THE PHYSICAL ENVIRONMENT (RITTER)

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The Physical Environment

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TABLE OF CONTENTS

Licensing

1: Essentials of Geography

- 1.1: Getting Ready for Chapter 1
- 1.2: The Discipline of Geography
  - 1.2.1: Principles of Geography
  - 1.2.2: Geography as a Spatial Science
  - 1.2.3: The Continuum of Geography
  - 1.2.4: Geography and the Scientific Method
- 1.3: Tools of the Geographer
  - 1.3.1: Maps
  - 1.3.2: Aerial Photographs and Remote Sensing
  - 1.3.3: Geographic Information System
  - 1.3.4: Models in Geography
  - 1.3.5: Graphs and Statistics
  - 1.3.6: The Global Positioning System (GPS)
- 1.4: Locational Systems
  - 1.4.1: Latitude and Longitude
  - 1.4.2: Geographical Zones
- 1.5: Time
- 1.6: Future Geographies
- 1.7: Review and Additional Resources

2: The Earth System

- 2.1: The Earth System
  - 2.1.1: Birth of the Solar System
  - 2.1.2: The Sun
  - 2.1.3: Earth Origin
  - 2.1.4: Size and Shape
  - 2.1.5: The Earth in Space
  - 2.1.6: Seasons
  - 2.1.7: Day Length and Seasons
  - 2.1.8: The Continents
  - 2.1.9: The Oceans
- 2.2: Looking Back - The Earth
- 2.3: Natural Systems
  - 2.3.1: Components of the Earth System
  - 2.3.2: Types of Systems
  - 2.3.3: Sources of Energy
  - 2.3.4: System Regulation
  - 2.3.5: Feedbacks
- 2.4: Looking Back - Natural Systems
- 2.5: Biogeochemical Cycle
  - 2.5.1: Nitrogen Cycle
  - 2.5.2: Oxygen Cycle

- 2.5.3: Carbon Cycle
- 2.5.4: The Hydrologic Cycle
- 2.6: Getting Ready for Chapter 2
- 2.7: Future Geographies- Feedbacks Driving Global Warming and Environmental Change
- 2.8: Looking Back
- 2.9: Review and Additional Resources

3: The Atmosphere

- 3.1: Atmospheric Composition
- 3.2: Atmospheric Structure
- 3.3: Greenhouse Effect
- 3.4: Future Geographies - Predicting Atmospheric Composition
- 3.5: Review and Additional Resources
- 3.6: Getting Ready for Chapter 3

4: Energy and Radiation

- 4.1: Energy and Heat
  - 4.1.1: The Nature of Electromagnetic Radiation
  - 4.1.2: Radiation as Particles
  - 4.1.3: Selective Absorption by the Atmosphere
- 4.2: Insolation
- 4.3: Radiation and Energy Balance of the Earth System
  - 4.3.1: The Radiation Balance
  - 4.3.2: The Energy Balance
- 4.4: Global Patterns of Insolation, Net radiation, and Heat
- 4.5: Getting Ready for Chapter 4
- 4.6: Global Patterns of Sensible and Latent Heat Transfer
- 4.7: Future Geographies - Radiative Forcing and the Earth's Heat Balance
- 4.8: Review and Additional Online Resources

5: Air Temperature

- 5.1: Temperature
- 5.2: Controls over Air Temperature
- 5.3: Explaining Patterns of Air Temperature
- 5.4: Getting Ready for Chapter 5
- 5.5: Future Geographies - Global Warming and Regional Temperature Patterns
- 5.6: Review and Additional Resources

6: Atmospheric and Ocean Circulation

- 6.1: Getting Ready for Chapter 6
- 6.2: Air Pressure
- 6.3: Controls over wind direction and speed
- 6.4: Cyclones and Anticyclones
- 6.5: Local Scale Wind
- 6.6: Regional Scale Winds - The Monsoon
- 6.7: Global Scale Circulation
- 6.8: Wind and Pressure Aloft
- 6.9: Ocean Circulation and Atmospheric Circulation
- 6.10: Future Geographies - Atmospheric Pressure and Winds

- 6.11: Review and Additional Resources

7: Atmospheric Moisture

- 7.1: Getting Ready for Chapter 7
- 7.2: Phases of Water
  - 7.2.1: Evaporation
  - 7.2.2: Transpiration
  - 7.2.3: Humidity
  - 7.2.4: Condensation
- 7.3: Adiabatic Temperature Change and Stability
- 7.4: Clouds and Precipitation
  - 7.4.1: Fog
  - 7.4.2: Clouds
  - 7.4.3: Precipitation Process
- 7.5: Global Patterns of Precipitation
  - 7.5.1: The Equator to the Subtropics
  - 7.5.2: Midlatitudes to the Poles
- 7.6: Future Geographies - Global Precipitation Patterns
- 7.7: Looking Ahead
- 7.8: Review and Additional Resources

8: Weather Systems

- 8.1: Getting Ready for Chapter 8
- 8.2: Air Masses
- 8.3: Fronts
- 8.4: Wave Cyclones (Cyclogenesis)
- 8.5: Weather and Wave Cyclones
- 8.6: Severe Weather
  - 8.6.1: Thunderstorms
  - 8.6.2: Lightning
  - 8.6.3: Tornadoes
  - 8.6.4: Hurricanes
- 8.7: Future Geographies - Severe Weather and Global Warming
- 8.8: Review and Additional Resources

9: Climate Systems

- 9.1: Getting Ready for Chapter 9
- 9.2: The Elements of Climate
- 9.3: Climate Classification
- 9.4: Low Latitude Climates
  - 9.4.1: Tropical Rain Forest
  - 9.4.2: Tropical Monsoon Climate
  - 9.4.3: Tropical Wet/Dry (Savanna) Climate
  - 9.4.4: Tropical Steppe Climate
  - 9.4.5: Tropical Desert Climate
- 9.5: Midlatitude and Subtropical Climates
  - 9.5.1: Mediterranean or Dry Summer Subtropical Climate
  - 9.5.2: Midlatitude Desert Climate
  - 9.5.3: Midlatitude Steppe

- 9.5.4: Humid Subtropical Climate
- 9.5.5: Humid Continental Climate
- 9.5.6: Marine (Humid) West Coast Climate
- 9.6: High Latitude Climates
  - 9.6.1: Subarctic Climate
  - 9.6.2: Tundra Climate
  - 9.6.3: Ice Cap Climate
- 9.7: Urban Climate
- 9.8: Future Geographies - The Evidence for Climate Change
- 9.9: Review and Additional Resources

10: The Hydrosphere

- 10.1: The Hydrosphere
- 10.2: The Hydrologic Cycle
- 10.3: The Water Balance
  - 10.3.1: Computing a Soil - Moisture Budget
  - 10.3.2: Soil Moisture Seasons
- 10.4: Future Geographies - Water Resources and Climate Change
- 10.5: Review and Additional Resources

11: Soil Systems

- 11.1: Soil Development
- 11.2: Horizon Development Processes
- 11.3: Soil Properties
- 11.4: Soil Profiles
- 11.5: Factors Affecting Soil Development
- 11.6: Soil Forming (Pedogenic) Processes
- 11.7: Soil Orders
- 11.8: Review and Additional Resources

12: Biogeography of the Earth

- 12.1: Fundamentals of Biogeography and Ecology
  - 12.1.1: Biogeography and ecological systems
  - 12.1.2: Habitat Occupation
  - 12.1.3: Principle of Limiting Factors
- 12.2: Ecology of Vegetation and Plant Succession
- 12.3: Energy Flow Through Ecosystems
- 12.4: Review and Additional Resources

13: Earth Biomes

- 13.1: Patterns of the Biosphere
- 13.2: The Forest Biome
  - 13.2.1: Tropical Forests
  - 13.2.2: Midlatitude Forests
  - 13.2.3: Northern Forests
- 13.3: Savanna Biome
- 13.4: Grassland Biome
- 13.5: The Desert Biome

- 13.6: Tundra Biome
- 13.7: Review and Additional Resources

14: Earth Materials and Structure

- 14.1: The Earth's Interior
- 14.2: Forces that Shape the Surface of the Earth
- 14.3: Orders of Relief
- 14.4: Minerals
- 14.5: Rocks
  - 14.5.1: Rocks and the Rock Cycle
  - 14.5.2: Igneous Rocks
  - 14.5.3: Sedimentary Rocks
  - 14.5.4: Metamorphic Rocks
- 14.6: Review and Additional Resources

15: Tectonics and Landforms

- 15.1: Plate Tectonics and Continental Drift
- 15.2: Plate Boundaries
- 15.3: Crustal Deformation
  - 15.3.1: Folding and Faulting
  - 15.3.2: Types and Geographic Patterns of Faults
  - 15.3.3: Tsunamis
- 15.4: Review and Additional Resources

16: Volcanic Processes and Landforms

- 16.1: Features of Volcanoes
- 16.2: Distribution of Volcanoes
- 16.3: Types of Volcanoes and Landscapes
- 16.4: Volcanic Hazards
- 16.5: Review and Additional Resources

17: Weathering, Erosion, and Mass Movement

- 17.1: Weathering
- 17.2: Mass Movement
- 17.3: Water Erosion
- 17.4: Review and Additional Resources

18: Fluvial Systems

- 18.1: The Stream System
- 18.2: Channel Geometry and Flow Characteristics
- 18.3: Geologic Work of Streams
- 18.4: Stream Gradation
- 18.5: Landforms of Alluvial Rivers
- 18.6: Fluvial Processes in Dry Regions
- 18.7: Review and Additional Resources

19: Glacial Systems

- 19.1: Glaciation
- 19.2: Geologic Work of Glaciers
- 19.3: Landforms of Continental Glaciation
- 19.4: Landforms of Alpine Glaciation
- 19.5: Digging Deeper-The Fate of Permafrost in a Warming World
- 19.6: Review and Additional Resources

20: Eolian Systems

- 20.1: Eolian Processes
- 20.2: Depositional Forms
- 20.3: Review and Additional Resources

21: Ocean and Coastal Systems

- 21.1: Water in Motion
- 21.2: Coastal Landforms and Processes
- 21.3: Types of Coasts
- 21.4: Review and Additional Resources

Index

Glossary

Detailed Licensing

Licensing

A detailed breakdown of this resource's licensing can be found in ***Back Matter/Detailed Licensing***.

CHAPTER OVERVIEW

1: Essentials of Geography

Figure 1.1: Glaciated valley in the Front Range, Colorado Rocky Mountains (Courtesy Michael Ritter)

Geography touches every aspect of our lives. At its simplest, geography is concerned with where something is at, why it's there, and how it relates to things around it. Geography influences where we live, affects our economic prosperity, has dictated the outcome of significant historical events, and shapes our local, regional, and global relationships with each other. This textbook focuses on physical geography and can answer many questions that you might have about the natural world and how it relates to your life. Ever wondered why present-day volcanoes occur on the west coast of the United States but not on the east coast? Why tornadoes seem to be unique to the United States? Why palm trees are found in Florida and pine trees in Maine? Where to go for a break from cold winter weather, or to escape a hot summer day? Physical geography can answer these questions, and more.

In this chapter you'll be introduced to the discipline of geography and what it means to study the Earth from a geographic perspective. You will become familiar with the array of tools geographers possess to investigate the Earth system. We'll conclude by looking at how geographers are well suited to address issues related to current trends in environmental change.

Learning Objectives

By the end of the chapter you should be able to:

- Explain why geographers describe their discipline as a spatial science and uniquely qualified to tackle issues related to environmental change.
- Construct a diagram showing how hypotheses are developed and become theories in physical geography.
- Compare and contrast qualitative and quantitative map data.
  Explain what a map projection is.
- Choose the appropriate type and scale of map for its intended purpose.
- Use latitude and longitude to determine location.
- Explain how a global positioning system works.
- List and give examples of remote sensing techniques.
- Differentiate between standard time and daylight saving time.
- Explain how a GIS is used to solve problems in physical geography.
- Explain how models are used in physical geography.
- Calculate the mean and range to describe a set of data.

1.1: Getting Ready for Chapter 1
1.2: The Discipline of Geography
1.2.1: Principles of Geography
1.2.2: Geography as a Spatial Science
1.2.3: The Continuum of Geography
1.2.4: Geography and the Scientific Method
1.3: Tools of the Geographer

1.3.1: Maps
1.3.2: Aerial Photographs and Remote Sensing
1.3.3: Geographic Information System
1.3.4: Models in Geography
1.3.5: Graphs and Statistics
1.3.6: The Global Positioning System (GPS)
1.4: Locational Systems
1.4.1: Latitude and Longitude
1.4.2: Geographical Zones
1.5: Time
1.6: Future Geographies
1.7: Review and Additional Resources

1.1: Getting Ready for Chapter 1

The Essentials of Physical Geography

Each chapter of "The Physical Environment" begins with a look at how previous chapters relate to the current chapter, includes a pretest to assess your learning, and helpful hints to prepare you for the coming chapter. As this is the first chapter of the textbook, there is no pretest. There are a few things you can do to get ready for reading and studying this chapter and the remainder of the book.

Figure 1.1.1: Tourists admire the grandeur of the Grand Canyon (Courtesy US National Park Service, Source)

1. **Get organized**. Getting organized to study is the most important thing you can do. Start by getting and using a planner, whether it be a paper or digital one. Keeping up with assigned reading can be challenging and so setting a regular routine can help you get your work done and reduce your stress level. Organize your study space to make your work time as efficient as possible.

   More of us are using laptops as our portable work environment. Consider using cloud computing applications like Google Docs or Evernote for taking notes and have them accessible no matter where you are. If your university has server space for students, consider using it to store important documents to prevent losing them in case your computer crashes. Check out this ultimate guide for students.

2. **Handwritten or digital notes?** Decide whether you want to take written notes or type them. Some like to take them by hand as they are either slow at typing or the material tends to "stick" better. Others are more efficient at typing. Another approach is to first write your notes by hand and then type them.
3. **Start reading.** Start by looking at the learning objectives or outcomes if they are provided. These are the key things you should know once you have completed the chapter. Take note of key points as you come to them. Be discriminating and don't try to take notes on everything. If your instructor has mentioned the point during their lecture, then it's important.
4. **Identify trouble spots.** Make note of points that you don't understand to ask your instructor as soon as possible. Don't procrastinate in asking for help. Write out a list of questions so you use your instructor's time efficiently and effectively. Send your questions via email if you cannot schedule a time to meet with them.
5. **Summarize the material.** Summarize the reading in your own words at the end of a chapter or section. If you can do this in a meaningful way, then you're more likely to retain it.
6. **Routine review.** After you move on to the next chapter, don't forget to go back and review your notes on previous chapters. Routinely reviewing your notes will make studying for tests much less stressful.

References:

"How to Effectively Take Notes While Reading" https://www.ehow.com/how_4878351_eff...s-reading.html (Last visited 10/14/09)

SECTION OVERVIEW

1.2: The Discipline of Geography

1.2.1: Principles of Geography

1.2.2: Geography as a Spatial Science

1.2.3: The Continuum of Geography

1.2.4: Geography and the Scientific Method

1.2.1: Principles of Geography

Geography is the study of the distributions and interrelationships of earth phenomena. Geography is different from other disciplines in that it doesn't have a particular "thing" it studies. Botanists study plants, while geologists are interested in features of earth like mountains, river, and rock structures. Geography is defined by its approach or methodology. Geographers describe their discipline as a **spatial science**. By "space" we aren't talking about celestial space. Geographers are concerned with answering questions about how and why phenomena vary across the surface of the Earth. For instance, geographers investigate patterns of vegetation as they relate to distributions of climate, soils, and topography.

Geographers recognize the dynamic nature of Earth's physical systems. The physical geography of Earth changes in response to variations in weather and climate, the shifting of continents, and and the sculpting of coastlines by wave action. By recognizing the Earth system is dynamic, geographers take time into consideration when looking at the spatial patterns of Earth phenomena. Therefore, geographers are playing important roles in understanding the effects of climate change on earth systems. The role of geographers in assessing patterns of environmental change is a theme that reoccurs throughout this book.

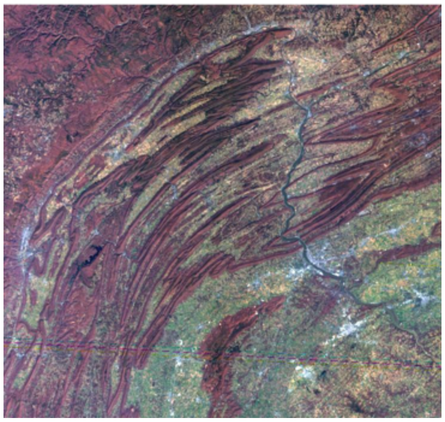


Figure 1.2.1.1: Folded Appalachian Mountains Linear folds of the Appalachian Mountains can be easily seen in this satellite image. (Source: NASA/GSFC/JPL, MISR Team)

Geographers study both the form and processes acting at the surface of the earth, the principal domain of geographic study. Examine the landscape of the Appalachian mountain range in North America in the satellite image illustrated in Figure 1.2.1.1and compare them to Mt. Saint. Helens found in the Cascade Mountain Range. The Appalachian mountains appear as a series of linear folds in the earth surface. The Cascades on the other hand are much taller than the Appalachians and contain many peaks that are conical in shape, as exemplified by Mt. Saint Helens. If both are mountain systems, why do they differ so greatly in form? Their difference arise from the processes that created them. The Appalachian Mountains were created by folding of the earth's crust. The conical shaped peaks of the Cascades are volcanoes. Many of these form where crustal plates collide, causing rock to melt deep beneath the earth, and finally erupting onto the surface to build the mountains we see today.

Figure 1.2.1.2: Mt. Saint. Helens, Cascade Mountain Range, USA (Source: USGS)

Think about what information was required to answer the question as to why these two mountain systems are so different. To understand their form we needed to investigate their geologic history to determine the processes that created them. Geographers must rely on information provided by other sciences to help understand the form and distribution of Earth phenomena. This is why geography has been called an "integrative science". It draws on the knowledge of many disciplines to understand the natural patterns within the earth system.

Geographers also study how human activities shape, and are shaped by, the natural environment. Geographers are actively engaged in research about the relationship between agriculture practices, water erosion, and flooding. Others are uncovering the impact of air pollution on ecosystems, and how global warming will affect the physical geography of earth. These studies are a part of the "human-environment" tradition in geography, which was the precursor to modern environmental studies.

Video: Watch Geographer Joseph Kerski explain "Why Geography Education Matters"

1.2.2: Geography as a Spatial Science

The key question facing most sciences is "how" and thus focus on the process whereby something comes about regardless of time or place. Geography is described as a spatial science because it focuses is on "where" things are and why they occur there. Geographers seek to answer all or more than one of four basic questions when studying our environment. These relate to location, place, spatial pattern, and spatial interaction. Let's look at how a physical geographer answers these questions about a desert.

Figure 1.2.2.1: Location of the Sonoran Desert (Courtesy USGS, Source)

Location: Location is defined as "the position in space" of something. Latitude and longitude is a convenient way to locate something's position. The Sonoran Desert is located at a latitude and longitude of 33°40'N, 114°15'W. This defines the Sonoran Desert's *absolute location.* It actually covers an area of 311,000 square kilometers (120,000 sq mi) between 25° to 33° North and longitude 105° to 118° West. We can also define the Sonoran Desert in relation to a known location, called its *relative location*. "The Sonoran Desert wraps around the northern end of the Gulf of California, from northeastern Baja California through southeastern California and southwestern Arizona to western Sonora." (Wikipedia)

Place. Geographers describe place as "... the human and natural phenomena that give a location its unique character ..." (Gershmel, 2009). A geographer may want to know how the Sonoran Desert compares to the Sahara desert. To answer this question, a physical geographer will collect data to compare their temperatures and precipitation, and contrast the vegetation, soils and fauna found there.

Spatial Pattern. Geographers are especially interested in the arrangement or patterns of earth phenomena. We might want to know - "What is the distribution of deserts on the Earth?". By examining a map of world climates we find deserts in the dry interiors of the subtropics and midlatitudes.

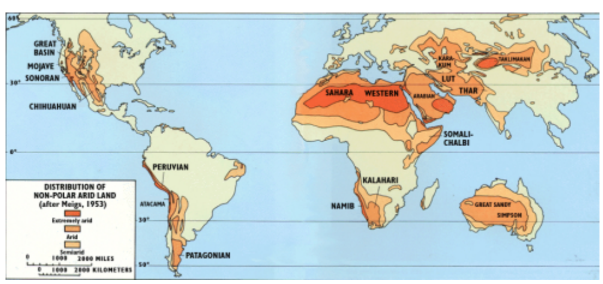


Figure 1.2.2.2: Distribution of Non-Polar Deserts (Courtesy USGS, Source)

Spatial Interaction. Finally, geographers are interested in how elements of the earth system interact with one another to create geographic patterns. A geographer might ask - "How do mountains interact with weather systems to affect the distribution of deserts?" By looking at maps of mountain systems, wind and precipitation patterns and, maps of climate we find that mountains oriented perpendicular to the flow of wind create moist conditions on the windward side and dry conditions on the leeward side. The dry leeward side is described as being in the "rain shadow". In many parts of the world deserts, like the Sonoran Desert of the United States is found in the rain shadow.

Figure 1.2.2.3: The Sonoran Desert near Maricopa, Arizona. (Courtesy Wikipedia, Source)

Fundamentally, geographers are concerned with where something is at, why it's there, and how it relates to things around it. They address this through defining where their object of inquiry is located, what the place is like, uncovering its distributional pattern, and understanding how it interacts with its environment. Our interest in understanding the geography of earth goes back centuries and will continue to intrigue us far into the future.

Video: The Geospatial Revolution, Courtesy Penn State Public Broadcasting

1.2.3: The Continuum of Geography

Geography is a wide ranging field that incorporates a number of diverse subject areas. Broadly speaking, geography can be divided into human geography and physical geography. **Human geography** deals with spatial aspects of human activities and culture. **Physical geography**, our topic here, focuses on the geographical attributes of the natural environment. The diagram below illustrates the **continuum of geography**. Though the discipline can be broken down into two separate areas of study, physical geography and human geography, they are actually seen as blending with one another along a geographic continuum (Figure 1.2.3.1).

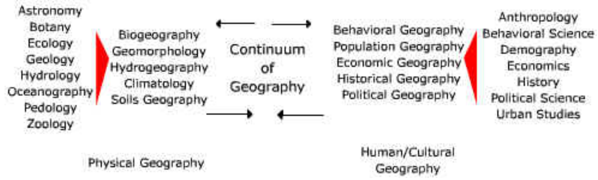


Figure 1.2.3.1: The Continuum of Geography

As we move toward the center of the diagram we enter a zone where the subject matter of the two meet and intermingle. At the center is where the synthesis of the physical environment with the human/cultural environment occurs. In so doing we create a holistic view of *earth systems*. The study of environmental issues like global warming, response of humans to natural hazards, and deforestation requires this kind of synthesis or examination of relationships between society and the natural environment to understand them.

Figure 1.2.3.2: Measuring lichen diameter to date glacial moraines. (Courtesy Michael Ritter)

> *Borrowing a technique from archeology and paleontology, physical geographers use lichen growth rate and diameters to estimate the age of debris flows, recent moraines, and other rocky deposits.*

Each subdiscipline draws on the knowledge provided by a variety of disciplines outside of geography. For instance, to study earth phenomena like the distribution of soils we have to draw on the expertise of such disciplines as soil science, botany, and climatology because soil properties are a function of vegetation, energy, and moisture. Geography, therefore, is a very integrative science.

Physical geography and earth science share much in common. Physical geography places earth science content in a spatial context. This video by the American Geological Institute illustrates why earth science (and by extension physical geography) is important to all of us.

Video: Why Earth Science, Courtesy American Geosciences Institute

1.2.4: Geography and the Scientific Method

The steps in geographic inquiry are embodied in the "scientific method". The **scientific method** consists of systematic observation, formulation, testing and revision of hypotheses. If a hypothesis withstands the scrutiny of repeated experimentation and review it may be elevated to a theory. Theories may undergo revision as new data and research methods are improved.

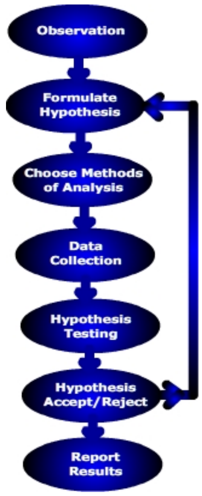


Figure 1.2.4.1: The Scientific Method

The scientific method includes:

- Observation
- Hypothesis Formulation
- Choose methods of analysis
- Data collection
- Analysis: Hypothesis testing
- Hypothesis acceptance or rejection
- Report results

Let's look at a very simple example of how you as a geographer could use the scientific method.

Observation. During a trip through the Cascade Range of Oregon you notice that the western slope tends to have more lush vegetation than the eastern slope and wonder why. Our experience tells us that vegetation requires moisture to live, and more lush vegetation is found where precipitation is abundant. Could it be that the western slopes are rainier than the eastern slopes given the spatial variation in vegetation?

Figure 1.2.4.2: View of western slope of Cascade Range mountains (Source: Flickr)

Figure 1.2.4.3: Near Condon, OR, east slope of Cascade Range (Courtesy NRCS Photo Gallery)

Hypothesis formulation. A **hypothesis** is referred to as "an educated guess". That is, upon recognizing a particular pattern displayed by earth phenomenon, the geographer offers a "guess" or explanation as to what caused it. Previous research serves as the foundation for constructing hypotheses. Given our initial observation and past experience we suggest that there is a relationship between slope orientation and precipitation.

A hypothesis is stated in a clear and concise way so that it can be tested through data collection and analysis.When constructing a hypothesis, scientists actually formulate two hypotheses related to their problem. The *null hypothesis* is a statement of no relationship. This is the hypothesis we will either reject or not reject. The null hypothesis (Ho) for our problem is:

H_o: There is no relationship between slope orientation and precipitation.

The *alternative hypothesis* is a statement of relationship. The alternate hypothesis is:

H_a: There is a relationship between slope orientation and precipitation.

Determine the methods used to test our hypothesis is the next step. There are a variety of quantitative and qualitative methods to test our hypothesis. One could calculate the average precipitation for the western and eastern slopes and apply a difference of means test (t-test).

Data collection. In order to test our hypothesis we must collect a sample of data. For most cases, a sample set of 30 will suffice. *Primary data* can be collected in the field and analyzed, or secondary data that has already been published can be used. Precipitation data is available from a variety of public and private sources.

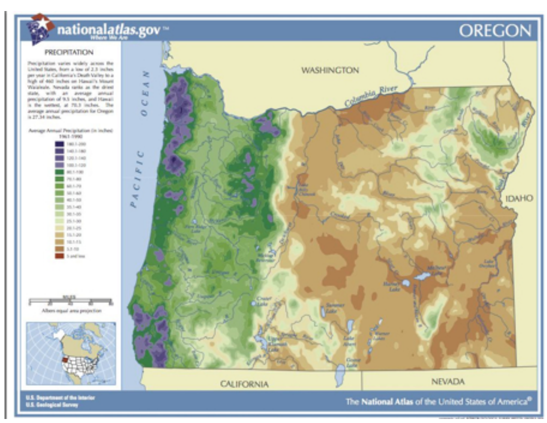


Figure 1.2.4.4: Precipitation in Oregon. Note linear purple areas of of high precipitation along western slopes of the mountains.

Analysis: Testing the hypothesis. A geographer often starts their analysis using some way to visualize the spatial pattern of precipitation. A map showing the geographic pattern of precipitation can be created if data from several places have been obtained. Or a graph of precipitation with the y-axis scaled for precipitation and x-axis for distance between locations along a transect. Statistics describing the data are usually calculated. The mean or average of each data set (west side and east side of the mountains) are determined and finally the hypothesis is tested using the difference of means test.

Hypothesis Acceptance/Rejection (Explanation). After testing our hypothesis we will either accept or reject our null hypothesis. In reality, we can't prove our hypothesis correct, we can only disprove it based on our analysis. That is, we reject the null hypothesis that there is no difference in precipitation based on the data that we have collected. If new data or better data collection techniques are available in the future, they may lead us to conclude that we cannot reject our null hypothesis. Hence it is hard to prove a hypothesis is correct as new information and understanding may present itself in the future.

Report Results. If we can accepted out hypothesis then we can report our results so others can scrutinize our work and test our hypothesis under different circumstances.If our null hypothesis is rejected we can turn to our alternative hypothesis or restate the null hypothesis in a different way. Thus, applying the scientific method can be an iterative process. If our work can be replicated many times under different circumstance the hypothesis can be elevated to a theory. A **theory** can be a hypothesis or group of hypotheses that has been validated through repeated experiments and coming to the same conclusion.

Assess your basic understanding of the preceding material by "Looking Back: The Discipline of Geography" or continue reading.

SECTION OVERVIEW

1.3: Tools of the Geographer

1.3.1: Maps

1.3.2: Aerial Photographs and Remote Sensing

1.3.3: Geographic Information System

1.3.4: Models in Geography

1.3.5: Graphs and Statistics

1.3.6: The Global Positioning System (GPS)

1.3.1: Maps

A map is the fundamental tool of the geographer. With a map, one can illustrate the spatial distribution (i.e., geographic pattern) of almost any kind of phenomena. Maps provide a wealth of information. The information collected to create a map is called **spatial data**. Any object or characteristic that has a location can be considered spatial data. Maps can depict two kinds of data. **Qualitative map data** is in the form of a quality and expresses the presence or absence of the subject on a map, like the kind of vegetation present occupying a region. **Quantitative map data** is expressed as a numerical value, like elevation in meters, or temperature is degrees celsius. There are many different kinds of maps that serve quite different purposes.

Types of Maps

Reference Maps

Reference or navigational maps are created to help you navigate over the earth surface. These kinds of maps show you where particular places are located and can be used to navigate your way to them. A street map or the common highway road map falls into this category.

Thematic Maps

Thematic maps are used to communicate geographic concepts like the distribution of densities, spatial relationships, magnitudes, movements etc. World climate or soils maps are notable examples of thematic maps. There are five common techniques for depicting geography data on a thematic map. The most common is a **choropleth map** that uses color to show variations in quantity, density, percent, etc. within a defined geographic area. Each color usually depicts a range of values.

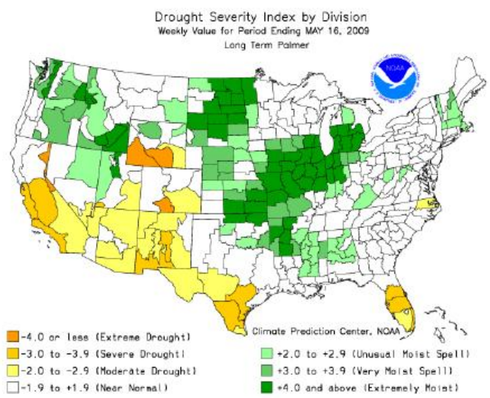


Figure 1.3.1.1: Palmer Drought Index (Source: NOAA Climate Prediction Center)

Defined areal units are colored on the Palmer Drought Index map in Figure 1.12 to show the pattern of dryness across the United States. Using administrative units presents a less realistic picture of the pattern of the distribution of natural phenomena. To overcome this, a variant of the choropleth map, the **dasymetric map** was created. This type of map employs special statistical methods and extra information to combine areas of similar values to depict geographic patterns on the map. The USDA's Plant Hardiness Zone Map is a dasymetric map.

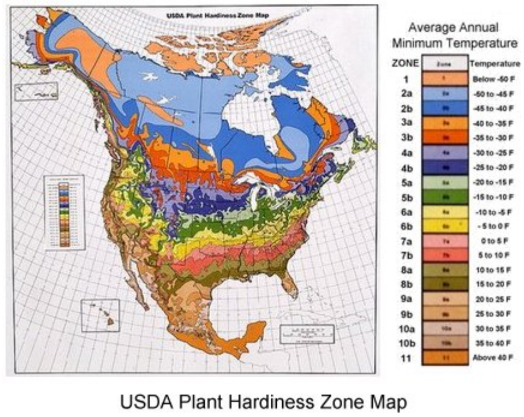


Figure 1.3.1.2: USDA's Plant Hardiness Zone Map

An **isarithmic map** uses isolines, lines that connect equal values, to illustrate continuous data such as elevation, air pressure, and precipitation. **Topographic maps** use contour lines to show elevation (height above sea level). **Contour lines** connect points of equal elevation above a specified reference, usually as sea level. The heavy brown contour lines with the elevation printed on them are called **index contours**. **Intermediate contours** are the lighter brown lines between index contours. Sometimes dashed lines called s**upplemental contours** are used in areas of very low relief. **Benchmarks** are locations where the elevation has been surveyed. Benchmarks are denoted on a map with the letters "BM", "X" or a triangle with the elevation printed beside.

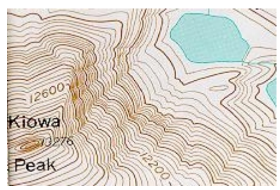


Figure 1.3.1.3: Sample Topographic map (Source: USGS Monarch Lake)

Not only are natural features like mountains, valleys, streams and glaciers portrayed, but cultural features as well, like houses, schools, streets, and urbanized areas. Examine a topographic symbol sheet (pdf file) from the USGS to see how a variety of features are symbolized on a topographic map.

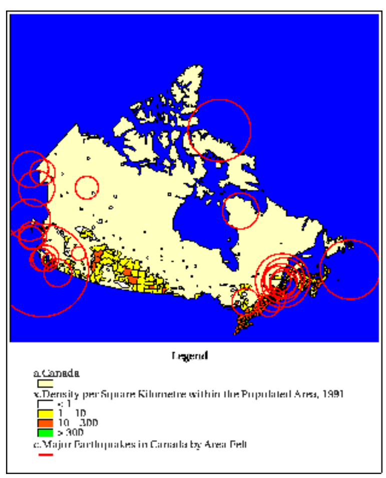


Figure 1.3.1.4: Major earthquakes felt in Canada. (Source: NAISMap WWW-GIS)

Proportional or **graduated circle maps** are another way of depicting geographic information on a map. Figure 1.3.1.4is a map that shows population density of Canada as colored polygons and the distribution of major earthquakes felt throughout the country. Graduated circles indicate the area over which the earthquakes were felt. This map was created using a geographic information system which has the capability of overlying different kinds of spatial data to show the relationships between them.

Dot maps use dots to illustrate the presence of the phenomenon on a map. A dot may equate to one or several units of measurement. Dot maps are especially useful in visualizing the frequency of occurrence or density of a mapped variable.

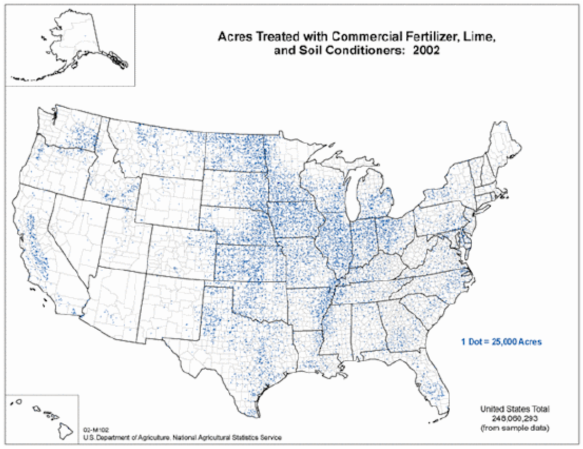


Figure 1.3.1.5: Dot map of agricultural chemical use (Source: USDA)

Isolines

Isarithmic maps use isolines to depict the geographic pattern of earth phenomena. An **isoline** is a line that connects points of equal value. For instance, the brown **contour lines** on a topographic map connect points of equal elevation. **Isobars** are used to show the distribution of air pressure . Some common isolines encountered in physical geography are:

- *isotherm:* a line connecting points of equal temperature.
- *isohyet:* a line that connects points of equal precipitation
- *isophene:* a line representing points where biological events occur at the same time, such as cops flowering.
- *isopleth*: a line connecting points of equal numerical value, like population
- *isotach:* a line of equal wind speed.
- *isobath*: a line representing points of equal water depth.

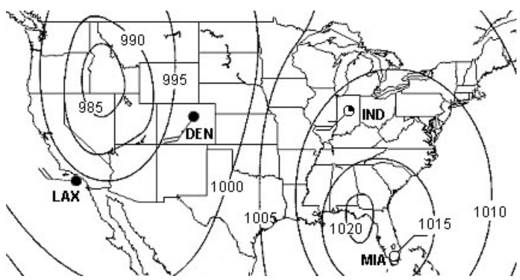


Figure 1.3.1.6: Isobars on a weather map depicting pressure pattern over United States (Courtesy NASA)

A few "rules" apply to isolines. First, there is a set interval between consecutive isolines called the **isoline interval**. For example, the map in Figure 1.3.1.6uses isobars to depict the disribution of air pressure. A 5 millibar interval was used to drawn them. Second, two different isolines cannot cross each other. If they did, it would mean two different values are at the same location. Third, values inside a closed isoline are either higher or smaller than those outside.

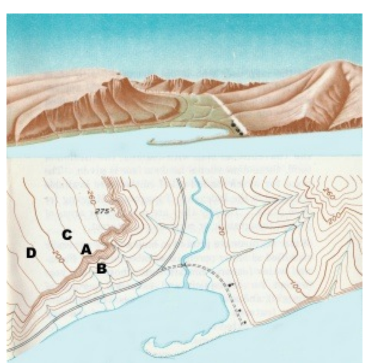


Figure 1.3.1.7: The land surface and how its depicted on a topographic map. (Courtesy USGS)

Because the interval between isolines is constant, their spacing gives an visual indication of the change that occurs over a given distance, called a **gradient**. The more closely spaced the isolines, the larger is the gradient. For example, the spacing of contour lines between A-B on the topographic map shows a much steeper hillslope gradient than does the spacing of the contour lines between points C-D.

Map Scale

Map scale is the relationship between distance on a map and distance in the real world. There are several ways to specify map scale. Often we find the scale of a map expressed in words like, "one inch equals one mile". You've most likely seen map scale depicted with a graphic, like a bar divided up into segments. The length of a segment represents some distance on the earth. We can specify scale as a representative fraction as well. These fractions often appear as follows:

1:24000

The fraction means that one unit of measurement on a map represents 24000 units in the real world. It's important to remember that the same units of measurement are on either side of the colon. That is, 1 inch represents 24000 inches, or 1 centimeter represents 24000 centimeters. To calculate the distance between two points, one simply measures the map distance and multiplies it by the number of "real world" units. For example, if the measured distance between two points on a map with a scale of 1:62500 is 2.4 inches, then the real world distance is 2.4 times 62500 or 150000 inches. It's hard to think how far that really is so convert it to miles. To do so simply take 150000 and divide by the number of inches in a mile which is 63360. So, the distance between the two points is about 2.37 miles.

Scale Categories

Map scales are grouped into small, medium and large categories. **Large scale maps**, such as 1:24000 scale maps show a smaller area in great detail. They are useful for showing the locations of buildings and other features important to engineers and planners. **Medium scale maps**, (1:62500) are good for agricultural planning where less detail is required. **Small scale** maps have the least detail but show large areas. These are useful for extensive projects at regional levels of analysis. You can easily see the impact of map scale on the information in figures $1.3.1.8a$through $1.3.1.8c$below.

Figure $1.3.1.8a$:

Scale 1:24000
1 inch = 2000feet
Area Shown: 1 square mile

(Source: U.S.G.S. Topographic Maps, 1969)

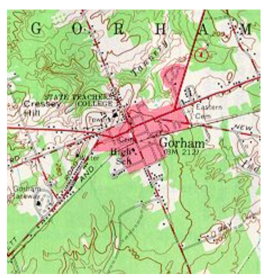


Figure $1.3.1.8b$:

Scale 1:62500
1 inch = nearly 1 mile
Area Shown: 6 3/4 square miles

(Source: U.S.G.S Topographic Maps, 1969.)

Figure $1.3.1.8c$:

Scale 1:250,000
1 inch = nearly 4 miles
Area Shown: 107 square miles

(Source: U.S.G.S. Topographic Maps, 1969)

? Concept Check 1.3.1.1

Notice in Figure $1.3.1.8a$(above) that black squares have been used to depict individual buildings in the downtown of Gorham. Why hasn't this been done in Figure $1.3.1.8c$?

Answer

At the reduced scale of 1:62500, it is impossible to show the same level of detail as that of a map of a larger scale (1:24000). Small features like individual buildings in the downtown are too small at this scale to show each of them. If a cartographer tried, the downtown area would be covered in black. Instead, a pinkish color is used to depict urban area.

Map projections

A map projection is a method of portraying the curved surface of the Earth on a flat planar surface of a map. Projections are created to preserve one or several measurements of the following qualities:

- Area
- Shape
- Direction
- Bearing
- Distance
- Scale

Each projection handles the conversion of these metric properties from the curved surface of a globe to the flat surface of map differently.

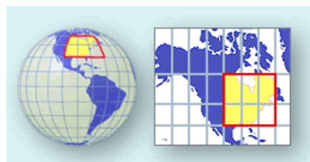


Figure 1.3.1.9: Visualizing a map projection (Courtesy USGS. Source)

The purpose of the map is of primary importance in choosing a projection to illustrate spatial patterns of Earth phenomena. For instance, the Mercator projection was long used for navigation or maps of equatorial regions. The cylindrical Mercator projection mathematically projects the globe onto a cylinder tangent to the Equator. Large areas become distorted which increases toward away from the Equator. Distances are true only along the Equator, special scales are provided for other latitudes for measurement.

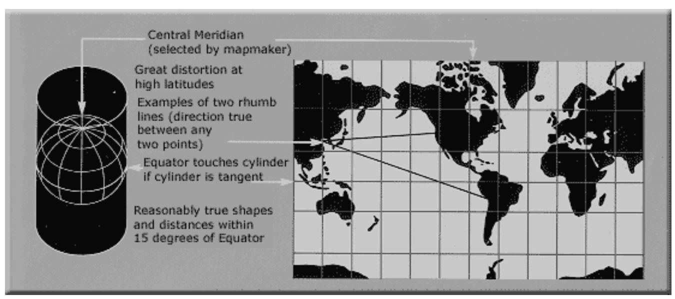


Figure 1.3.1.10: Cylindrical Mercator projection (Courtesy USGS - Source)

The Robinson projection uses tabular coordinates rather than mathematical formulas to make earth features look the "right" size and shape. A better balance of size and shape result is a more accurate picture of high-latitude lands like Russia, Soviet and Canada. Greenland is truer to size but compressed.

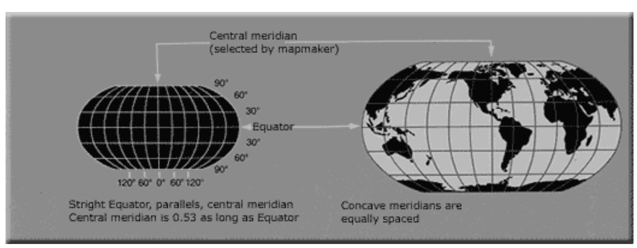


Figure 1.3.1.11: Robinson projection (Courtesy USGS - Source)

For more on projections see: Map Projections from the United States Geological Survey.

1.3.2: Aerial Photographs and Remote Sensing

Aerial Photographs

For years, geographers have used aerial photographs to study the Earth's surface. In many ways air photographs are better than maps. They provide us with a real world view of the earth's surface, unlike a map which is a representation of the real world. Aerial photographs can be used to make the same measurements that we make on a map, as they too are a scaled image of the surface.

Figure 1.3.2.1: Air photograph of Fair Glacier, Colorado. (Source: USGS)

Figure 1.3.2.1 shows the rugged terrain one finds in the Front Range of the Colorado Rocky Mountains. North is at the top of the photograph. Alpine glaciers are found in favorable sites for snow and ice accumulation. Few of these glaciers are very active under present day conditions though. The glacier is easily identified by its white color. Surrounding the glacier on its western, southern, and eastern sides are the walls of a cirque in which it sits. A cirque is a bowl-shaped landscape feature common to mountainous regions which have been glaciated. The glacier formed in the area to the bottom of the picture and extended itself towards the north. The dark triangular - shaped feature to the north of the glacier is Triangle Lake.

Remote Sensing and Satellite Imagery

To get a much larger view of the earth's surface features, geographers have turned to using remotely sensed data from satellites. Satellite sensors scan the surface and break it down into picture elements or pixels like those displayed on your computer monitor. Each pixel is identified by coordinates known as lines (horizontal rows), and samples (vertical columns). As the satellite scans the ground, it transmits this information to earth-based receivers, the same way a television station broadcasts a signal to your television. The digital data received is processed in a variety of ways: simulated natural color, "false" color, signal filtering, enhanced contrast, etc.

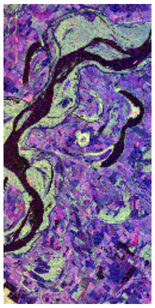


Figure 1.3.2.2: SIR-C/X-SAR image of the Mississippi River (Source: NASA Jet Propulsion Lab)

Figure 1.3.2.2 shows a portion of the Mississippi River that lies north of Vicksburg along the Arkansas-Louisiana-Mississippi state borders. The image was created from data obtained by Spaceborne Imaging Radar – C/X-band Synthetic Aperture imaging system aboard the space shuttle Endeavor. These images help scientists assess flooding potentials and land management along the river. Much of the area in purple is agricultural land. Areas occupied by water appear in black while the bright green areas are forested. The long narrow lakes bordering the river are called oxbow lakes and are created when the river changes course, abandoning the old channel for a new one. NASA has a detailed discussion (optional reading) about imaging radar online. Read how remote sensing is used to evaluate drought, desertification and the effect of war on Mozambique.

1.3.3: Geographic Information System

Advanced computer technology has placed new tools in the hands of geographers to not only create maps much more efficiently, but to analyze spatial data in map form as well. A geographic information system is a computer-based technology that enters, analyzes, manipulates, and displays geographic information. It is a marriage between computer-based cartography and database management.

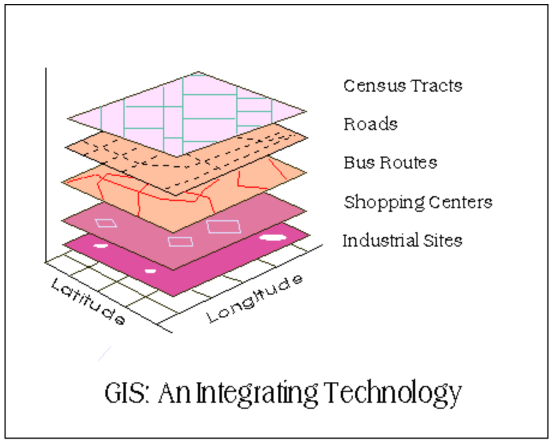


Figure 1.3.3.1: GIS layers (Source: The Geographer's Craft, UC-Boulder. GIS: Context, Concepts, and Definitions by Kenneth E. Foote and Margaret Lynch)

A simple way of visualizing a geographic information system is to think of a set of overhead transparencies. On each transparency is a map of a particular set of data. Examine Figure 1.3.3.1. The bottom transparency is the most important as it has the coordinate system (latitude and longitude) upon which we can align or register the other layers of information. The second layer is a map of industrial sites, the third shopping centers and so on. By layering the information one on top of the other, a geographer can show the relationship and degree of connectivity between various land uses and transportation routes. Transportation geographers can then plan new routes between population centers found on the census tract map layer and business locations. Geographic Information Systems are being employed to study a number of geographic issues like flood hazard mapping, earthquake hazard studies, economic market area analysis, etc.

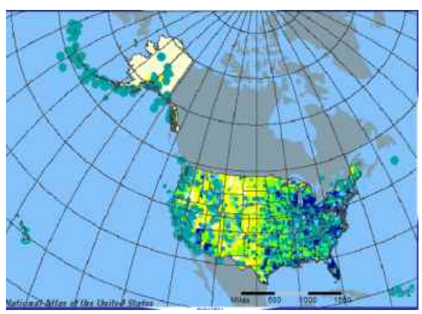


Figure 1.3.3.2: Earthquakes 1568 - 1996 and population density 2000, the National Atlas. (Courtesy USGS)

Figure 1.3.3.2 is a map constructed using a GIS from the online National Atlas of the United States. Layers of data, earthquakes 1568 - 1996 and population density 2000, are turned on and off with digital buttons. The map product from the GIS permits us to visualize those population centers most threatened by earthquake activity.

Video: GIS Specialists at Work (Courtesy of GadBall.com)

1.3.4: Models in Geography

A ***model*** is simply a representation of a real thing. You have seen and used models in the past, like a globe which is a model of the earth. Geographers construct models to analyze geographic processes because the real object of study may be too large to examine, the processes which created it operate over too long of a time frame, or experimentation might actually harm or destroy it. For instance, physical geographers construct *physical models* like stream tables to investigate the impact of hydrological processes on the earth. A stream table is more or less like a shallow sink filled with earth material similar to the land surface of interest. Water is applied to the material to see what effect varying amounts of water have on the erosion of the surface. Models may be simple *conceptual models* such as a box and arrow diagram showing the flows of energy between compartments of an ecosystem. Climate scientists use elaborate *mathematical or numerical models*. These could be complex numerical statements programmed into a *computer model* representing the impact of increasing carbon dioxide content of the atmosphere on global temperature.

Figure 1.3.4.1: Soil Scientists examine model of plots to investigate soil erosion (Source: Ben Nichols, U.S.D.A. Natural Resources Conservation Service)

Video: Climate in a Box (Courtesy NASA)

1.3.5: Graphs and Statistics

Graphs

Graphs are a visual way to portray the relationship between a set of variables. Graphs can easily show the spatial pattern and discern a cause and effect relationship between earth phenomena. The variable plotted on the x-axis is the cause of the variable plotted on the y-axis. A good example of how graphs can be used for the analysis of relationships in physical geography is to plot the change in temperature range across latitudes. The Y-axis of Figure 1.3.5.1has been scaled for temperature range and the X-axis for latitude. Note that temperature range appears to increase with latitude as one travels from the equator (0^o) toward the pole (90^o). Notice how the points seem to line up in a straight line. From the graph there appears to be a strong relationship between latitude and temperature range. From this graph we can say that (at least) latitude is a causal factor of temperature range.

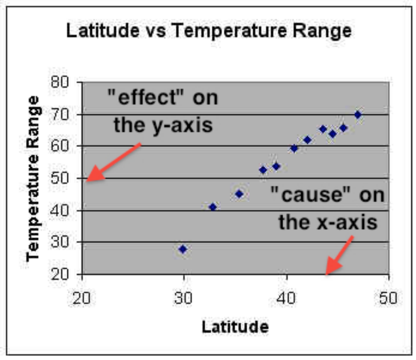


Figure 1.3.5.1: Graph of Latitude vs. Temperature Range

Statistics

A statistic is a quantity that is computed from a sample of data. Statistics are used for analyzing and interpreting numerical information. Statistics are all around us and we all use them from time-to-time. Statistical methods refers to "the collection, presentation, analysis and interpretation of numerical data for the purpose of making more correct decisions" (Parl, B., 1967). Statistical methods are generally grouped into two categories descriptive statistics and statistical inference.

Descriptive statistics attempt to simplify masses of data into a single number to communicate an existing condition or phenomena in the data. You will encounter two common descriptive statistics in this book. The **mean** (average) is the sum of the observations divided by the number of observations in the data set. The **range** is the difference between the highest and lowest value in a set of a data set. Choosing the right statistic, or statistics greatly influences our ability to accurately describe the spatial and temporal patterns of the natural world.

Descriptive statistics can be deceiving. Imagine trying to compare the climate of two places to a friend who hasn't visited either. Let's say location A has a summer temperature of 80^o F and a winter temp of 20^o F. Location B has a summer temperature of 65^o F and winter temperature of 45^o F. Notice when we average the summer and winter temperatures for each their average temperature for the year is the same, 50^o F. There appears to be no difference in climate between the two locations because both have the same average temperature. However, if we compute the seasonal range in temperature, 60^o F for location A and 20^o F for location B there appears to be a great deal of difference between the two. We should use both the average and temperature range to accurately describe climate.

Table 1.1 Comparison of Average and Range

Location A	Location B
Summer Temperature = 80^o F	Summer temperature = 65^o F
Winter temperature = 20^o F	Winter temperature = 45^o F
Average = 50^o F	Average = 50^o F
Range = 60^o F	Range = 20^o F

Statistical inference "is a method concerned with the analysis of a subset of data leading to predictions (or inferences) about an entire set of data" (Goodman, 1996). An inference is an educated guess or estimate. One cannot make a definitive statement of what the correct answer is but couches the conclusion in a degree of uncertainty. Inferential statistics are employed to test the hypotheses we create about the relationship between phenomena.

Correlation and regression analysis are two widely used statistical techniques. **Correlation** analysis attempts to express the degree to which variation in one variable is associated with the variation in another. Developing from correlation, **regression** enables us to estimate a mathematical statement which describes the relationship between two variables. These techniques are beyond the scope of this book.

1.3.6: The Global Positioning System (GPS)

The Global Positioning System consists of three parts:

1. Earth orbiting satellites,
2. control and monitoring stations across the Earth, and
3. GPS receivers owned by individuals.

A set of 24 satellites orbiting the Earth every 12 hours broadcasting their position and time. A ground-based receiver listens to the signals from four or more satellites, comparing the time transmissions of each with its own clock. Given that signal travels at a known rate of speed, the receiver can calculate the distance between the satellite and receiver. Combining the position of the satellite at the time of transmission with the distance, the receiver is able to determine its location.

Figure 1.3.6.1: The constellation of GPS satellites (Courtesy USGS)

Differential GPS uses a base station of an exact known location and a mobile unit to determine position. GPS determines location by computing the difference between the time that a signal is sent by a satellite and the time it is received by a GPS receiver. The base station calculates its position from satellite signals and compares this location to the known location. The base station broadcasts the range errors they're seeing from GPS satellites to the remote receiver. The mobile receiver uses these correction messages, correlated with the satellite signals its receiving, to determine position.

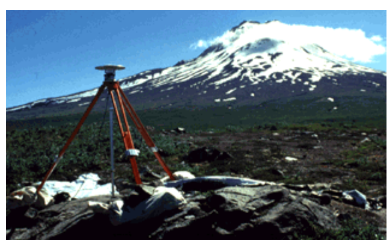


Figure 1.3.6.2: GPS ground receiver on the flank of Augustine Volcano (Cook Inlet, Alaska) Courtesy USGS

GPS is being employed in a variety of ways. GPS is widely used for ground, air, and sea navigation. It is used to produce highly accurate maps and record land deformation caused by earthquakes and volcanic eruptions. GPS is showing up in a number of commercial products available to the public from standalone units to automobiles, cell phones, and digital cameras interfaces. A popular use of gps units is geocaching, a high-tech "treasure" hunting game.

Assess your basic understanding of the preceding material by "Looking Back: Tools of the Geographer" or continue reading.

CHAPTER OVERVIEW

1.4: Locational Systems

The fundamental work of a geographer begins by describing location. Locational reference systems have been created to accurately identify the location of earth phenomena.

1.4.1: Latitude and Longitude
1.4.2: Geographical Zones

1.4.1: Latitude and Longitude

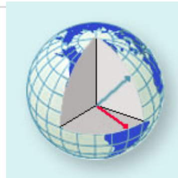


Figure 1.4.1.1: The Geographic Grid: Latitude and Longitude (Courtesy The National Atlas)

Latitude and longitude comprises a grid system of lines encircling the globe and is used to determine the locations of points on the earth. Lines of ***latitude***, also called *parallels*, run east - west. Latitude lines always run parallel to each other, and hence, they are always an equal distance apart. Latitude lines never converge or cross.

Figure 1.4.1.2: The Equator (Courtesy The National Atlas)

Lines of latitude measure distance north or south of the equator. The latitude of a particular location is the distance, measured in degrees, between that place and the equator along a meridian, or line of longitude. The **equator** is 0^o latitude, and the North and South Poles are located at 90^o north and 90^o south latitude respectively. In other words, values for latitude range from a minimum of 0^o to a maximum of 90^o.

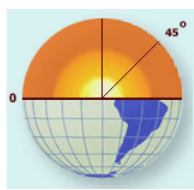


Figure 1.4.1.3: Measuring Latitude. (Courtesy The National Atlas)

If the earth were a perfect sphere (which it isn't), the distance, or the length, of 1^o of latitude would be constant everywhere. In reality, the earth is slightly flattened at the poles, so the length of 1^o of latitude at the poles is slightly more than at the equator. At the equator, the length of 1^o of latitude is equal to 110.6 km (68.7 mi.) and at the poles, the length of 1^o of latitude is equal to 111.7 km (69.4 mi.). For our purposes, we will assume the length of one degree of latitude is 111 km.

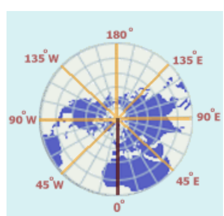


Figure 1.4.1.4: Longitude (Courtesy The National Atlas)

Lines of **longitude**, also called *meridians*, run north - south. Meridians are farthest apart at the equator, and converge at the North and South Poles. Lines of longitude measure distance east or west of the prime meridian. The longitude of a particular location is the distance along a parallel, measured in degrees, between that place and the prime meridian. The prime meridian passes through the old Royal Observatory at Greenwich, England, and is sometimes referred to as the Greenwich meridian. Since meridians are farthest apart at the equator and converge at the poles, the distance in kilometers (or miles) of 1^o of longitude varies from a maximum at the equator, to a minimum at the poles. At the equator the approximate length of 1^o is approximately 111 km (69 mi.). At 60^o north and south latitudes, the length of 1^o of longitude is approximately 55.5 km (34.5 mi.), or half what it is at the equator.

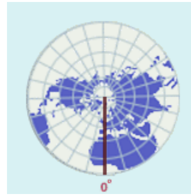


Figure 1.4.1.5: The prime meridian (Courtesy The National Atlas)

The **prime meridian**, which runs through Greenwich, England, is referred to as 0^{o} longitude. Points are measured east or west of the prime meridian until one reaches the opposite side of the prime meridian, which is referred to as the International Date Line. This is considered 180^{o} longitude, and is the highest value which longitude can take. In other words, values for longitude range from a minimum of 0^{o} to a maximum of 180^{o}.

An infinite number of parallels or meridians can be drawn on a globe. Thus, parallels and meridians exist for any point on the earth. Generally, only selected parallels and meridians are marked on maps and globes, and these are usually spaced equal distances apart. Parallels and meridians always intersect each other at right angles. In order to locate a particular point on the earth, a latitude and a longitude measurement is necessary. As stated above, these measurements are in degrees, but sometimes measurements smaller than degrees are necessary. In this case, minutes and seconds are used.

When we travel, we usually like to take the shortest route between two locations. If you pass a plane through the *center* of a sphere, the intersection of the plane and the surface of the sphere creates a **great circle**. Planes passing through any other part of a sphere without going through the center create **small circles**. An arc of a great circle is the shortest distance between two points on a sphere and therefore is the preferred route for planes traveling great distances, like crossing an ocean. The concept of great and small circles relates to meridians (longitude) and parallels (latitude). Meridians are half of a great circle (180^{o}) whose ends are at the North and South poles. Parallels of latitude are small circles, except for the equator which is a great circle.

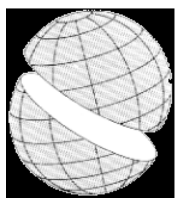


Figure 1.4.1.6: Great Circle (Source: Wikipedia)

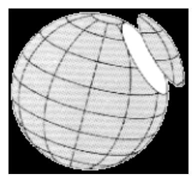


Figure 1.4.1.7: Small Circle (Source: Wikipedia)

For more information about other locational systems, start "Digging Deeper Into Locational Systems: USPLS and UTM" or continue reading

Dig Deeper into Locational Systems

United States Public Land Survey (USPLS)

Latitude and longitude gives us an easy way of locating points on the Earth. Instead of a point, we may wish to identify land areas. In the United States, the United States Public Land Survey (USPLS), conceived by Thomas Jefferson, is used to identify parcels of land. The USPLS is actually a means of describing parcels of land, but like latitude and longitude, the USPLS is basically a grid that can be used to identify location.

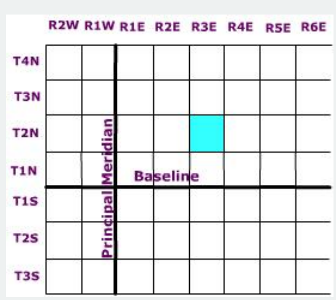


Figure 1.4.1.8:USPLS Townships and Ranges

Across the United States, several **principal meridians** (lines of longitude) have been selected to define "columns" of **ranges** every six miles either east or west of a particular principal meridian. In a similar fashion, "rows" of **townships** are delimited every six miles either north or south of a particular **baseline**, that coincides with a line of latitude. This creates a grid work of townships and ranges encompassing 36 square miles in area. Actually, an individual cell in this grid is sometimes referred to simply as a township.

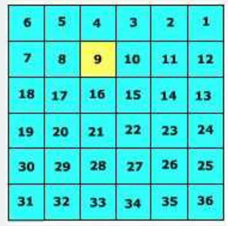


Figure 1.4.1.9: USPLS Sections

A township is subdivided into 36 1 square mile **sections**. Sections are numbered beginning at the upper right and working left to section 6, then down to 7, and then right across to section 12 ending with 36 sections as shown in Figure 1.4.1.9.

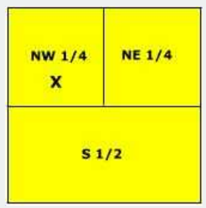


Figure 1.4.1.10: Subdivision of a section

Each section is 640 acres in size and can be further subdivided into smaller units by either halving or quartering the section (Figure EG.16) and described according to direction. For instance, the letter X is located in the NW 1/4, S9, T2N, R3E.

All United States Geological Survey topographic maps show the township, range, and section information on them. the figure below is a portion of the Whitewater, WI 1:24000 USGS topographic map. Township and Range information is found printed in red along the bottom and left margins (R 17E, T3N). Section boundaries are printed in red and their number designation is printed in the center of the section.

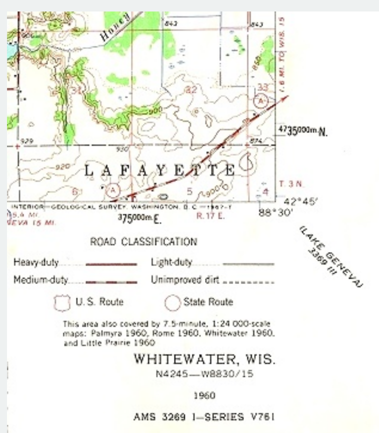


Figure 1.4.1.11: USPLS coordinates on topographic map.

The Universal Transverse Mercator (UTM) Grid

Though a spherical coordinate system like latitude and longitude is convenient for large areas, it is cumbersome for small areas. The need for accurate measurements within small areas was realized with the increasing range of artillery during the First and Second World Wars. This spurred the development of rectangular coordinate grid systems as plane rectangular geometry formulas were simpler than spherical geometry formulas upon which latitude and longitude is derived from. The Universal Transverse Mercator (UTM) Grid is one such system.

The Universal Transverse Mercator Grid divides the world into 60 north-south zones, each covering a strip 6° wide in longitude between 84N and 80S. Poleward the Universal Stereographic grid (UPS) is used. These longitude zones are numbered (called the "zone number") from Zone 1, between 180° and 174° west longitude, progressing eastward to Zone 60, between 174° and 180° east longitude. Each longitude zone is subdivided into a latitude zone is 8 degrees high north and south of the equator, and lettered starting from "C" at 80° S, increasing up to "X" (called the "zone designator"). The letters "I" and "O" are omitted because of their similarity to the digits one (1) and zero(0). X spans 12° of latitude.

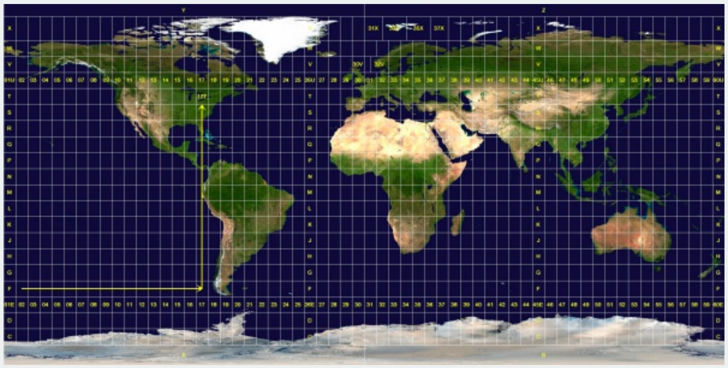


Figure 1.4.1.12: The UTM Zones (Source Wikimedia Commons) The grid reference is read "right, up", and written with the longitude zone first. The example identified by the arrows is "17T".

Each longitude zone is subdivided into an eastern and western half by drawing a line down the middle called the "central meridian". A point can be described by its distance east of the origin, called its "easting" value. The central meridian is assigned a false easting of 500,000 meters to insure positive coordinates. Any easting value greater than 500,000 meters indicates a point east of the central meridian. Any easting value less than 500,000 meters indicates a point west of the central meridian. A point's north-south origin depends on the hemisphere it is in. In the northern hemisphere, the origin is the equator and all distances north (or ‘northings’) are measured from the equator. In the southern hemisphere the origin is the south pole and all northings are measured from there. When writing UTM coordinates, the easting is always first and the northing is after it.

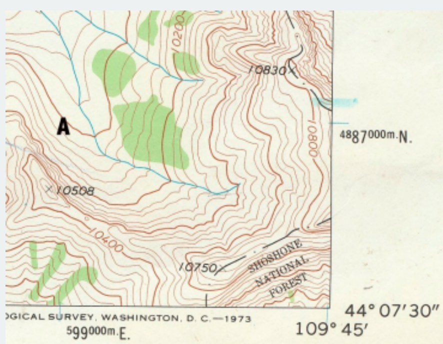


Figure 1.4.1.13: UTM coordinates on topographic map.

The UTM grid is printed on all U.S. Geological Survey (USGS) maps as blue tick marks in the margins, or as full grid lines. The spacing of the tick marks or grid lines depends on the scale of the map. Point A on the topopgraphic map is located at 599000 E., 4887000 N.

1.4.2: Geographical Zones

Natural systems of climate, vegetation, and soil change substantially as one travels from the equator to the pole due largely to the latitudinal variation in energy input to the earth system. The early Greek scholar Aristotle was the first to divide the Earth into zones based on climate. His "torrid zone", thought to be too hot for human habitation, lay between 23.5^o N and 23.5^o S. Aristotle thought that the "temperate zones" between 23.5^o N - 66.5^o N and 23.5^o S - 66.5^o S were the only livable zones. From the arctic (66.5 N) and and antarctic circles (66.5 S) to the the poles (90 N and S) were the uninhabitable "frigid zones".

Figure $1.4.2.1a$: Torrid Zone

(Image Source: WikiMedia)

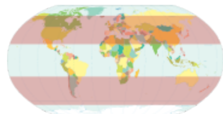


Figure $1.4.2.1b$: Temperate Zones

(Image Source: WikiMedia)

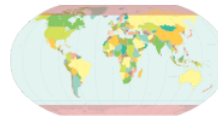


Figure $1.4.2.1c$: Frigid Zones

(Image Source: WikiMedia)

Geographers continue to use latitudinal variation of climate characteristics as a way of dividing the Earth into fairly homogeneous geographical zones. These zones are:

Equatorial: 10^o N - 10^o S

Tropical: 10^{o}N - 25^{o}N and 10^{o}S - 25^{o}S

Subtropical: 25^{o}N - 35^{o}N and 25^{o}S - 35^{o}S

Midlatitude: 35^{o}N - 55^{o}N and 35^{o}S - 55^{o}S

Subarctic: 55^{o}N - 60^{o}N

Subantarctic: 55^{o}S - 60^{o}S

Arctic: 60^{o}N - 75^{o}N

Antarctic: 60^{o}S - 75^{o}S

North Polar: 75^{o}N - 90^{o}N

South Polar: 75^{o}S - 90^{o}S

The equatorial zone is characterized by warm temperatures and nearly uniform day length throughout the year. The boundary of the tropical zone lies close to the Tropic of Cancer (23.5^{o}N) and Capricorn (23.5^{o}S), the latitudinal limit where the Sun is directly over head at noon at different times of the year. The subtropical zone includes Aristotle's home of Greece, and seasonal changes in temperature become more pronounced. The temperate midlatitude zone is noted for is variable weather conditions. Large annual swings in temperature are characteristic of the subarctic and subantarctic zone where extensive areas of cold air form during winter and milder conditions prevail during summer. The coldest zones are the Arctic and Antarctic, where the Sun never rises above the horizon for several months at a time. Much of the light that does reach the surface is reflected off the light colored surfaces of the North (sea ice) and South (mostly glacial ice) poles. The coldest zones are the North and South Polar. Like the Arctic and Antarctic Zones, the Sun never rises above the horizon for many months of the year. The coldest temperatures are near the South Pole, far from any moderating influence of an ocean and the little light that does make it to the surface is reflected from glacier ice.

1.5: Time

Early agricultural societies found that local noon could be determined by observing the changing length of the shadow cast by a stick placed placed perpendicular to the ground. *Local noon* is the time at which the shadow is the shortest length cast. Romans used this principle to design their sundials and called their noon position of the Sun the "meridian" (*meridiem* - the Sun's highest point of the day). It was difficult to compare time as one traveled to different localities as each city adjusted its clocks to their own local noon. Because the Earth rotates toward the east, towns to the east experienced solar noon earlier while those to the west later.

Standard time

As cross-country travel and communication became faster and more efficient, a standardized system of global time was required. Given the Earth rotates once throughout a 24 hour period, 24 standard times zones were agreed upon at the 1884 International Prime Meridian Conference. The local solar time at Greenwich, England was designated the prime meridian. Each time zone extends 7.5o on either side of a central meridian. For years the global standard for reporting time was **Greenwich mean time (GMT)**. GMT is now referred to as **Universal Time Coordinated (UTC)** or *Coordinated Universal Time* but the prime meridian is still the reference for standard time. It uses the 24-hour time (military) notation based on the local standard time at the prime meridian of 0^{o} longitude. Midnight corresponds to 00:00 UTC and noon to 12:00 UTC. (For more conversions, see Table 1.3 UTC Conversion Table)

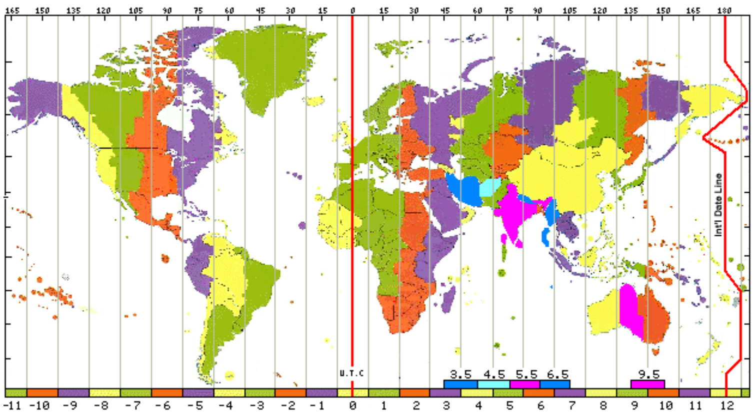


Figure 1.5.1: UTC zones (Image Courtesy NASA MSFC)

International Date Line

Ferdinand Magellan and crew in 1519 set out on their westward journey from Spain to circumnavigate the Earth. Upon their return three years later, they discovered that their meticulously kept logs were off by one day. This was one of the first recorded experience with changing global time. This earlier experience would ultimately lead to the establishment of the international date line. The **International Date Line** is an imaginary line the separates one day from another. It roughly follows the 180^{o} meridian form the North Pole to the South Pole through the Pacific ocean, deviating around some territories. Crossing the line when traveling east one turns their calendar back a full day. Traveling west one moves their calendar forward one day. The Prime Meridian lies opposite of the International Date Line.

Daylight Saving Time

Many countries observe **daylight saving time** - the practice of setting clocks forward one hour in the spring and back one hour in the fall. First proposed by Benjamin Franklin, the notion of extending daylight one hour into the evening didn't catch hold until World War One as a means of energy savings. Some countries,territories, and states in the U.S. do not observe daylight saving time.

1.6: Future Geographies

The Geographer's Role in Understanding Environmental Change

During the summer of 2005, the United States was pounded by a record number of hurricanes, some the most intense to ever strike the mainland. The southwest desert of the United States continues in the grip of one of the longest periods of drought. For the first time in centuries, the fabled arctic northern route is open between North America and Asia. Are these events caused by climate change due to global warming? If so, the future physical geography of planet Earth may be drastically and irreversibly changed if current global warming predictions are realized.

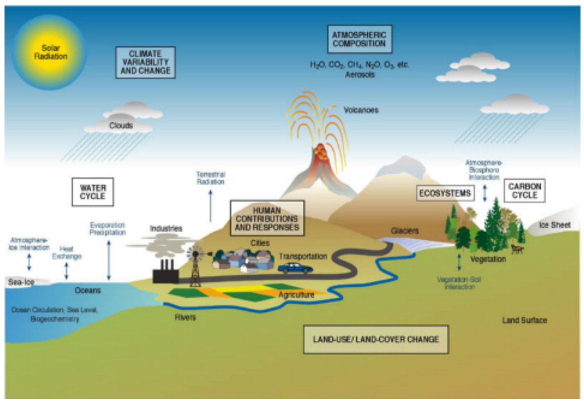


Figure 1.6.1: Major Components needed to understand the climate systems and climate change. (Source: US Climate Change Science Program).

Environmental change caused by global warming involves a complex set of interactions between the subsystems of the earth system and human activities. These interactions vary across geographic scales. The timing and impact of future warming will not be the same for all regions of the Earth. Research methodologies that consider place and scale are therefore essential in understanding future environmental changes.

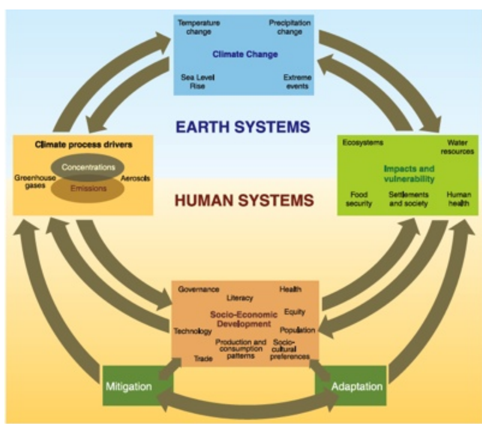


Figure 1.6.2: Schematic Framework of anthropogenic climate change drivers, impacts, and responses. (Courtesy IPCC)

The continuum of geography permits a holistic view of earth systems analysis. Geographers are therefore perfectly positioned to answer questions concerning global warming and environmental change. Geographers are engaged in all aspects of environmental change research, from field monitoring glacier movements to computer modeling of future climates. Straddling both social and physical sciences, geographers play an important role in unwinding the social and economic drivers behind climate change.

Observing environmental change

Geographers bring their unique talents to recording changes in earth systems. Geographical positioning systems (GPS) provide precise measurements of environmental change. For example, isostatic rebound of the earth's surface after the last ice age complicates measurements of melt from the expansive ice sheets that cover present-day Greenland and Antarctica. Recently, several GPS stations were deployed around the Greenland ice sheet to measure minute changes in earth surface elevation as a result of rebound. This data is being combined with that from sensors measuring elevation changes, glacial outflow rates and the mass balance to provide a more complete assessment of the sheets' melting.

Figure 1.6.3: A one-meter tall station (above) was installed last Thursday near Ilulissat to measure how much the earthâ€™s crust rebounds as the ice sheet melts. (Courtesy Thomas Nylen (UNAVCO), Source)

Databases for analyzing the effects of climate change are large and complex. As databases documenting environmental changes across the earth are developed, geographers will provide the tools for teasing out spatial and temporal signals in the observations. Geographic Information Systems are well-suited for handling complex databases to map the potential spread of diseases, ecosystem changes, and sea-level rise as a result of global warming.

Analyzing environmental change

Geographer's have a number of tools and skills to analyze impact of environmental change on earth systems. Geographers are actively engaged in projects to identify and understand patterns of deforestation and habitat fragmentation. Geographer Eric Larsen has studied the decline of aspen trees in Yellowstone for several years. Though climate change was first suspected, he and ecologist William Ripple, realized that aspens outside the park flourished. If climate change was responsible, trees inside and outside the park would have suffered a decline. Analyzing cores from trees within the park, they found that most were 70 years old, aspens had apparently stopped regenerating around the 1930s

Figure 1.6.4: Reintroduced wolf in Yellowstone Park. (Courtesy NPS.)

Between the late 1880s until the mid-1900s, more than bounty hunters killed 100,000 wolves in Wyoming and Montana. By the 1970s, the wolf was classified as an endangered species. A controversial reintroduction program brought 31 gray wolves back to the Yellowstone ecosystem. It appears that the removal of a top predator, allowed browsing elk populations to flourish and devastate young aspens. With the reintroduction, diversity and stability of the ecosystem appears to be on the rise.

Explaining environmental change

Geographers can play a significant role in hypothesis and theory development. Geographers are particularly suited for building numerical models of the complex coupling between the earth's surface and atmosphere above. Their strong field orientation and integrated methods will help hone the parameterization of climate models.

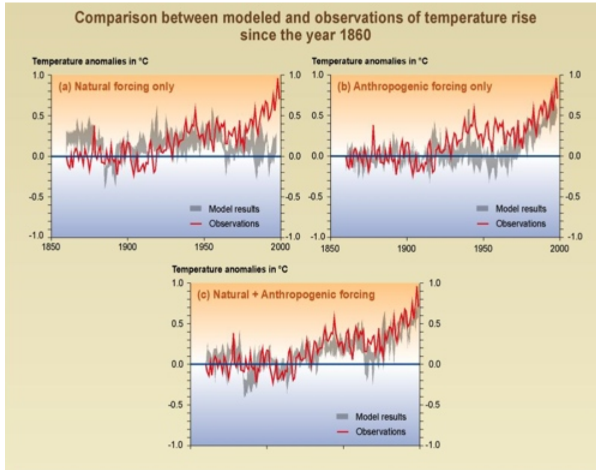


Figure 1.6.5: Comparison between modeled and observed temperature rise without human factors, with human factors and both. (Courtesy IPCC)

Geography's human-environment tradition provides a foundation for answering some of the most vexing issues of the global warming. The crux of the global warming issue is identifying the "fingerprint" of human activities in creating the enhanced greenhouse effect. For example, models that attempt to explain the warming experienced over the last several decades using only natural factors fail to adequately explain the actual pattern temperature. When human factors that influence warming are added, a much better correspondence with reality is uncovered.

Because geography uniquely straddles both physical and social sciences, geographers play an important role will play a role in future policy formulation and decision making. Geographers are well-suited for evaluating the costs and benefits of various global warming mitigation strategies.

Predicting environmental change

Climate models have demonstrated that the impact of global warming will vary across the earth. Geographers have been at the forefront of predicting the potential changes that our environment will undergo. Based on recent analyses, Geographer Jack Williams found that, we're headed for major change -- fast. He suggests areas that currently have a tropical climate will become warmer, pushing vegetation and animal life northward. Williams believes these changes will lead to the spread of insect-borne diseases like Malaria, increased catastrophic natural disasters and greater risks to human well-being. Temperatures rising just a few degrees will affect where particular plant and animal species will thrive. The question is if they will be able to migrate or adapt to a rapidly changing climate. If not, some face extinction.

Williams work predicts that many current climates may entirely vanish by the year 2100. He foresees "no-analog" communities of plants and animals arising from "novel" climates. No-analog communities consist of species that exist today but in differ net combinations from those presently inhabiting the earth. The species exist today, they have just been "reshuffled" into new combinations not found at the present. Such no-analog combinations have been found recorded in fossil pollen assemblages extracted from lake sediments dating from the late-glacial periods in North America. These seemingly odd past combinations of species are thought to be a product of of "novel" or no-analog climates, characterized by higher-than-present temperature seasonality. Professor Williams recognizes that with current trends in global warming, such new communities of species may be in our future. His climate models project the disappearance of many existing climates in tropical highlands and near the poles. Large swaths of the tropics and subtropics may develop new climates unlike anything seen today.

In coming chapters we'll examine the future geography of earth as predicted by geoscientists of all kinds and particularly physical geographers. You'll explore how earth's gaseous composition is predicted to change, how and where temperature changes occur, the impact of rising oceans, and the displacement of ecosystems. Though dire conditions are predicted, the challenges posed can be addressed ... and geographers will be at the forefront.

1.7: Review and Additional Resources

Review

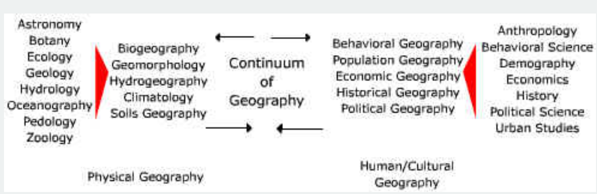
Recording GPS data into a PDA
Courtesy NRCS

Figure 1.7.1

Use the excersizes below to review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **Geography**
  the study of the distributions and interrelationships of earth phenomena
- **Spatial science**
  how geographers describe their discipline. Geographers are concerned with answering questions about how and why phenomena vary across the surface of the Earth
- **Location**
  "the position in space" of something
- **Place**
  "... the human and natural phenomena that give a location its unique character ..." (Gershmel, 2009)
- **Spatial Pattern**
  the arrangement or patterns of earth phenomena
- **Spatial Interaction**
  how elements of the earth system interact with one another to create geographic patterns
- **Human Geography**
  spatial aspects of human activities and culture
- **Physical Geography**
  the geographical attributes of the natural environment
- **Continuum of Geography**
  illustrated by diagram:



The Continuum of Geography

- **Hypothesis**
  an educated guess
- **Theory**
  a hypothesis or group of hypotheses that has been validated through repeated experiments and coming to the same conclusion
- **Maps**
  the fundamental tool of the geographer. With a map, one can illustrate the spatial distribution of almost any kind of phenomena.
- **Spatial data**
  the information collected to create a map
- **Qualitative map data**
  in the form of a quality and expresses the presence or absence of the subject on a map, like the kind of vegetation present occupying a region
- **Quantitative map data**
  expressed as a numerical value, like elevation in meters, or temperature is degrees celsius
- **Choropleth map**
  uses color to show variations in quantity, density, percent, etc. within a defined geographic area
- **Dasymetric map**
  employs special statistical methods and extra information to combine areas of similar values to depict geographic patterns on the map
- **Isarithmic map**
  uses isolines, lines that connect equal values, to illustrate continuous data such as elevation, air pressure, and precipitation
- **Topographic Map**
  use contour lines to show elevation
- **index contour**
  The heavy brown contour lines with the elevation printed on them
- **Intermediate contour**
  the lighter brown lines between index contours
- **supplemental contour**
  used in areas of very low relief
- **Benchmark**
  locations where the elevation has been surveyed. Benchmarks are denoted on a map with the letters "BM", "X" or a triangle with the elevation printed beside
- **graduated circle map**
  a way of depicting geographic information on a map
- **Dot map**
  use dots to illustrate the presence of the phenomenon on a map

- **Isoline**

  a line that connects points of equal value
- **Contour line**

  on topographic map, connect points of equal elevation
- **Isobar**

  used to show the distribution of air pressure
- **gradient**

  the change that occurs over a given distance
- **Reference Map**

  Reference or navigational maps are created to help you navigate over the earth surface
- **Thematic Map**

  used to communicate geographic concepts like the distribution of densities, spatial relationships, magnitudes, movements etc.
- **Map Projection**

  a method of portraying the curved surface of the Earth on a flat planar surface of a map
- **Map Scale**

  the relationship between distance on a map and distance in the real world
- **Large scale map**

  show a smaller area in great detail
- **Small scale map**

  have the least detail but show large areas
- **Air Photograph**

  provide us with a real world view of the earth's surface
- **Remote Sensing**

  used via satellites to get a much larger view of the earth's surface features. As the satellite scans the ground, it transmits this information to earth-based receivers.
- **Geographic Information System**

  a computer-based technology that enters, analyzes, manipulates, and displays geographic information.
- **Models**

  a representation of a real thing
- **Statistic**

  a quantity that is computed from a sample of data.
- **Graph**

  a visual way to portray the relationship between a set of variables.
- **Global Positioning System**

  consists of three parts: 1) Earth orbiting satellites, 2) control and monitoring stations across the Earth, and 3) GPS receivers owned by individuals.

- **Latitude and Longitude**

    Latitude and longitude comprises a grid system of lines encircling the globe and is used to determine the locations of points on the earth

- **Prime meridian**

    0^o longitude

- **Great Circle**

    If you pass a plane through the center of a sphere, the intersection of the plane and the surface of the sphere creates this

- **Small Circle**

    Created by planes passing through any part of a sphere without going through the center.

- **Universal Transverse Mercator Grid (UTM)**

    a plane coordinate grid system named for the map projection on which it is based

- **Geographical Zones**

    Geographers continue to use latitudinal variation of climate characteristics as a way of dividing the Earth into fairly homogeneous geographical zones.

- **Greenwich mean time (GMT)**

    the global standard for reporting time. It uses the 24-hour time (military) notation based on the local standard time at the prime meridian of 0^o longitude. Midnight corresponds to 00:00 UTC and noon to 12:00 UTC

- **Universal Coordinated Time (UTC)**

    GMT is now referred to as Universal Time Coordinated (UTC) or Coordinated Universal Time but the prime meridian is still the reference for standard time.

- **International Date Line**

    an imaginary line the separates one day from another

- **Daylight saving time**

    the practice of setting clocks forward one hour in the spring and back one hour in the fall

? Review Questions 1.7.1

Define what geography is and explain how the study of geography differs from other physical and social sciences.

Answer

Geography is the study of the distributions and interrelationships of earth phenomena. Geography is described as a spatial science. Geographers integrate information about human and natural processes to **explain the pattern** and relationships of earth phenomena. It is this spatial approach that distinguishes geography from other disciplines.

What is the significance of the "geographic continuum".

Answer

The geographic continuum represents the continuum of study within geography. Though geography can be broadly separated into human and physical geography, geography is actually a continuum as human activities and the natural environment cannot be separated from one another. As one approaches the center of the continuum, we see the intermingling of human and physical geography as environmental science.

Describe the steps of geographic inquiry.

Answer

- **Observation** - data collection.
- Analysis - statistical manipulation of data; mapping; graphing; modeling.
- Explanation - Using knowledge of process to explain the analysis of observed phenomena.
- Prediction - Forecasting possible future scenarios

What is the difference between a large and small scale map?

Answer

A large scale map, like 1:24000, covers a small area but show more detail than a small scale map. A small scale map, like 1:62500, shows a larger area, but little detail can be portrayed.

What is a model in geography? Give an example.

Answer

A model is a representation of something. For instance, a globe is a model of the Earth. Models may be mathematical statements that represent climate processes.

Describe how graphs are used in geographic research.

Answer

Graphs are used to show the relationships between earth phenomena. They can illustrate changes between earth processes and properties over distance and time.

What are descriptive statistics?

Answer

Descriptive statistics like the mean, median, and mode characterize the nature of a set of data as a single number.

What is a geographic information system? Suggest how a GIS can be used to address geographic problems.

Answer

A geographic information system is a method where by "layers" of geographic data are overlaid to show the spatial correlation of earth processes and properties. Soil, topography, and vegetation data layers could be overlaid to assess erosion potential.

Compare and contrast air photos and satellite imagery as tools of the geographer.

Answer

Air photos give us a real world view of the earth’s surface, unlike a map which is a representation of the real world. Aerial photographs can be used to make the same measurements that we make on a map, as they too are a scaled image of the surface. Satellite imagery due to the location of the sensor, can give us a larger view of the earth. A variety of satellite imagery display techniques exist, like simulated natural color, or "false" color, each being useful in their own way for studying earth surface processes and properties. High-resolution imagery is also useful in detailed, close-up viewing.

Describe how latitude and longitude are measured on a globe.

Answer

Latitude is measured in angular degrees north or south of the equator. Lines of latitude are called "parallels" as they parallel each other from the equator (0^o latitude) to the pole (90^o latitude. Lines of longitude are measured in angular degrees east or west of the prime meridian (0^o latitude). Lines of longitude, or "meridians", are furthest apart at the equator and converge at the poles.

? Self-assessment Quiz 1.7.1

1. A small scale map
   - A. might have a representative fraction of 1:24000
   - B. shows a small portion of the earth's surface
   - C. makes features look large
   - D. none of the above
2. Live vegetation appears _____ on a false-color infra-red image.
   - A. red
   - B. green
   - C. black
   - D. blue
3. Which of the following incorporates the smallest land area?
   - A. A township
   - B. A range
   - C. A section
   - D. All are equal area
4. If you were half way between the equator and the north pole and one quarter of the way around the earth west of the prime meridian you will be at:
   - A. 45 N; 90 W
   - B. 45 N; 180 W
   - C. 45 N; 90 E
   - D. 45 N; 180 E
5. Which of the following is not a model?
   - A. a globe
   - B. a physical equation
   - C. a weather forecasting program
   - D. all the above are models
6. Which of the following tells us more about the temperature extremes of a climate?
   - A. the average annual temperature
   - B. the range of annual temperature
   - C. a correlation statistic
   - D. they all will give us the same information
7. Which of the following types of maps is used to show the distribution of world soils?
   - A. a topographic map
   - B. a relief map
   - C. a thematic map
   - D. any of the above
8. Lines of latitude
   - A. converge at the poles
   - B. are measured north or south of the prime meridian
   - C. are parallel to each other
   - D. all the above
9. Lines connecting points of equal elevation are called
   - A. topographic lines
   - B. elevation lines
   - C. isobars
   - D. contour lines
10. You measured 5.5 inches between two points on a 1:24000 scale map. The actual distance in miles is:

A. 25
B. 2.08
C. 240
D. 1100

Answer

1. D
2. A
3. C
4. A
5. D
6. B
7. C
8. C
9. D
10. B

Additional Readings and Resources

Use these links to further explore the world of geography.

Interactivities

Contour drawing - practice drawing contour line from VisualEntities

Contour Analysis - practice drawing isotherms (from WeatherWise)

Studying Oceans from Space (NASA)

Multimedia

USGS Public Lecture Series: "Science Through Imagery" (April, 2009) Description from the site: "Knee-high to Bird's Eye: Multi-scale Remote Sensing of Vegetation Dynamics. Dr. John Jones, an expert in remote sensing, discusses several projects in the Shenandoah National Park and the Everglades. Learn how science from satellites can help decision-makers address issues related to climate change, water resources, and habitat conditions."

"Careers in Geoscience" - (AGI) *from the Site* "The *Careers for Geoscientists* video introduces the breadth of scope of the geosciences, including atmosphere, oceans, and the solid-Earth. Through interviews with individual practicing geoscientists discussing current projects, the nature of a career working in the geosciences is revealed. A discussion of the opportunities and adventures of travel, working outdoors, and using state-of-the-art technology is presented through this rare glimpse into the work-a-day world of geoscientists."

"Using Space Technology to Understand Earthquakes" (NASA JPL Lecture series)

"Laser Mapping Technology Gives New Glimpse of Earth" (NPR) Dec. 28, 2004 *All Things Considered* report on airborne LIDAR.

"Mapping Technology Helps Direct Tsunami Aid Efforts" (NPR) Dec. 29, 2004 *All Things Considered* report on LandScan mapping technology.

"Mapping Shuttle Debris" (NPR) Feb. 11, 2003 *Morning Edition* report on the use of GPS to map the debris field of the space shuttle Columbia.

"One Earth, Many Scales: Lost in Space? Geography Training for Astronauts" *The Power of Place* (Annenberg Media) Preparation for a NASA Shuttle mission provides context for introducing key issues in physical geography and human-environmental interaction. (First segment of program - 11:50) (Windows Media Player required) Go to the Power of Place site and scroll to "One Earth, Many Scales: Lost in Space? Geography Training for Astronauts"

Readings

Location, Location, Location (NASA EOS)

Hantavirus Risk Maps (NASA EOS)

Visualization

Google Earth - 3-D interface to the Earth

Web Sites

Association of American Geographers

National Council for Geographic Education

Geography at About.com

National Geographic Magazine

Virtual Geography Department Project

CHAPTER OVERVIEW

2: The Earth System

Figure 2.1: Buffalo on Wetland. (Courtesy USFWS)

The Earth system is a complex interaction between its subsystems the atmosphere, hydrosphere, biosphere, and lithosphere. The Earth system around us today is the result of millions of years of evolutionary processes tending toward a stable equilibrium. At times, assaults from within and outside have stressed the system and forced changes. Here you will explore the types of systems found on Earth and the sources of energy that drive them.

Learning Outcomes

By the end of the chapter you should be able to:

- Explain the origin and shape of the Earth.
- Explain how the Earth's orientation to and revolution around the Sun cause seasons.
- Describe the basic features of the continents and oceans.
- Explain how earth "spheres" interact with one another within the Earth system.
- Explain how natural systems are regulated by feedback.
- Demonstrate through the use of a flow chart how positive and negative feedback effect system change.
- Compare and contrast, and provide examples of open and closed systems.
- Draw a simple diagram of the nitrogen, carbon, oxygen, and hydrologic cycles.
- Compare and contrast, and give examples of endogenic and exogenic sources of energy.
- Explain how feedbacks drive global warming and climate change.

2.1: The Earth System
- 2.1.1: Birth of the Solar System
- 2.1.2: The Sun
- 2.1.3: Earth Origin
- 2.1.4: Size and Shape
- 2.1.5: The Earth in Space
- 2.1.6: Seasons
- 2.1.7: Day Length and Seasons
- 2.1.8: The Continents
- 2.1.9: The Oceans

2.2: Looking Back - The Earth

2.3: Natural Systems
- 2.3.1: Components of the Earth System
- 2.3.2: Types of Systems
- 2.3.3: Sources of Energy

2.3.4: System Regulation
2.3.5: Feedbacks
2.4: Looking Back - Natural Systems
2.5: Biogeochemical Cycle
2.5.1: Nitrogen Cycle
2.5.2: Oxygen Cycle
2.5.3: Carbon Cycle
2.5.4: The Hydrologic Cycle
2.6: Getting Ready for Chapter 2
2.7: Future Geographies- Feedbacks Driving Global Warming and Environmental Change
2.8: Looking Back
2.9: Review and Additional Resources

SECTION OVERVIEW

2.1: The Earth System

A ***system*** is defined as a collection of interacting objects. The earth is a component of the **solar system**, which consists of the Sun and the celestial objects bound to it by gravity. Though Earth has relatively little interaction with the other planets, the Sun and the Earth's moon indeed do. The earth system receives receives energy from Sun, and gravitational attraction holds the Moon in an orbit around the Earth. The gravitational pull of the Moon on Earth's oceans creates tides as we'll see in Chapter 21. Let's begin an investigation of the earth system by examining the origin of the earth, its basic components, and its most important source of energy, the Sun.

2.1.1: Birth of the Solar System

2.1.2: The Sun

2.1.3: Earth Origin

2.1.4: Size and Shape

2.1.5: The Earth in Space

2.1.6: Seasons

2.1.7: Day Length and Seasons

2.1.8: The Continents

2.1.9: The Oceans

2.1.1: Birth of the Solar System

Earth is the third planet from the Sun, one of eight "classical" planets recognized by the International Astronomical Union in our solar system. A planet must orbit the Sun, be big enough that gravity pulls it into a round ball, and must have other things out of its orbital path. Pluto, defined as a planet until 2006 but was declassified as it orbits among the icy bits of the asteroid belt. In 2008 it was classified as a "plutoid", a kind of dwarf planet.

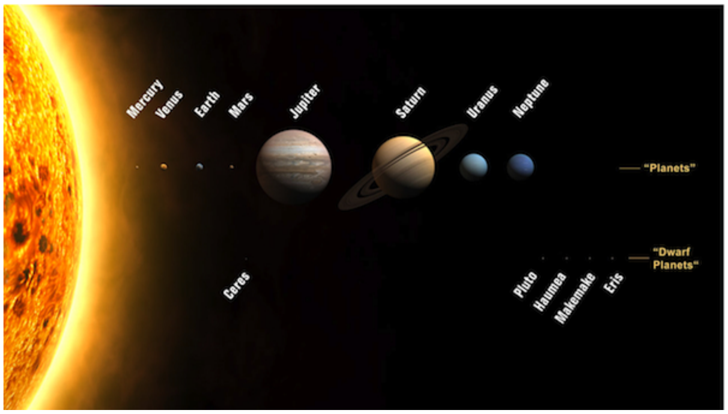
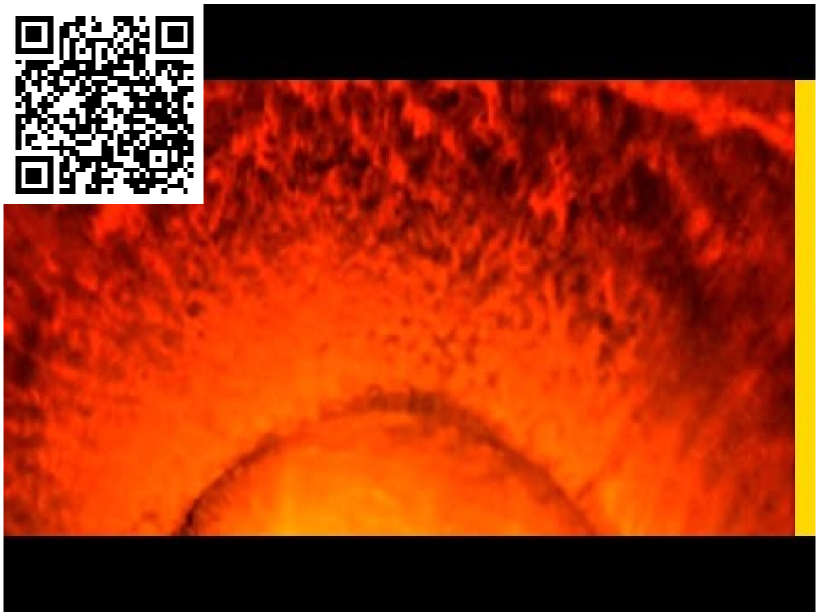


Figure 2.1.1.1: The Solar System. (Courtesy NASA (Source))

It is thought that the planet like Earth originated from the accretion of bits of solid matter left from the massive explosion of a star or supernova. Bits of material were scattered into space forming a slowly rotating cosmic gas cloud. Gravity slowly gathered the thinly spread atoms of the cosmic cloud. As the atoms moved closer together the gas became hotter and more dense. A new sun was born as hydrogen eventually became so tightly compressed and temperatures so high that nuclear burning began. A flattened rotating disc of gas and dust surrounded the young sun. Outer cooler parts of the disc or ***star nebulae*** began to condense to form the building blocks of future planets.

Figure 2.1.1.2: Image of the spiral galaxy NGC 4414 (Source: NSSDC NASA)



Video: "Birth of the Solar System" Courtesy National Geographic

2.1.2: The Sun

The Sun is a giant thermonuclear furnace with an internal temperature estimated to be 15 million degrees Celsius. Hydrogen nuclei collide at such an extremely high speed they fuse to form helium nuclei generating enormous amounts of heat in the core. The heat works its way to the luminous outer surface called the **photosphere**. Here temperatures fall to about 6000^{o}C generating a maximum wavelength of emission in the visible end of the electromagnetic spectrum. Above the photosphere lies the **chromosphere** and the **corona**. The chromosphere acts as a boundary between the cooler photosphere and hotter outermost layer the corona.

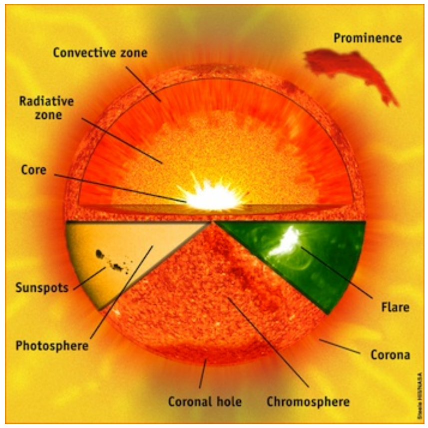


Figure 2.1.2.1: Structure of the Sun. (Courtesy NASA (Source))

Video: "Where does the Sun get it's energy?"

Sunspots are dark, cooler regions of strong magnetic fields on the photosphere whose activity varies through an eleven year cycle. **Solar flares** occur in the region of Sun spots, sending energized, charged particles at great speeds toward Earth. They form when the Sun's magnetic energy becomes unstable and collapses causing an explosive heating of gases.

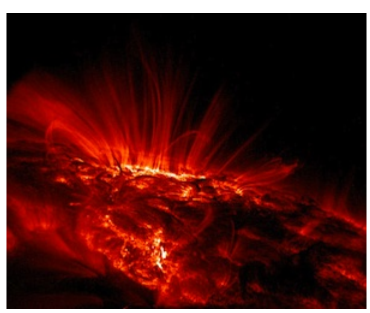


Figure 2.1.2.2: Glowing arcs of gas surrounding sunspots. (Courtesy NASA.)

A **solar prominence** is an arch of gas held above the Sun's surface by strong magnetic fields and lasting up to several months. Their eruptions release massive amounts of amounts of solar material.

Video: Striking a Solar Balance (Courtesy NASA Goddard Space Flight Center (Source))

This short film explores the vital connection between the Earth and the Sun. NASA's Glory mission and the Total Irradiance Monitor will continue nearly three decades of solar irradiance measurements. This crucial data will contribute to the long-term climate record.

The Solar Wind and Auroras

A continuous flow of charged particles (ions and electrons) from the Sun is discharged as a **solar wind**. At these extremely high temperatures, violent collisions of gases strip charged particles of electrons, and acquire enough speed to escape the gravitational pull of the Sun. As the solar wind streaks toward Earth the flow of particles strikes the Earth's magnetic field deforming it into a tear-drop shaped cavity called the **magnetosphere**. Inside the magnetosphere are ionized gases from the solar wind and the upper most part of the Earth's atmosphere.

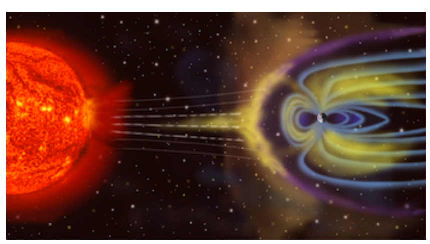


Figure 2.1.2.3: Magnetosphere shielding the Earth from the solar wind. (Courtesy NASA)

During periods of high solar activity, the solar wind is more dense, travels faster, and possesses more energy. Reaching the Earth's magnetic field it sets off amazing displays of light by exciting atmospheric gases. In the Northern Hemisphere the spectacular light shows are called the **aurora borealis** or northern lights. In the Southern Hemisphere they are called the **aurora australis**, or southern lights. Solar flares have a direct impact on modern society. They create geomagnetic storms that deposit excess energy on power grids and satellite components causing them to fail. Solar flares disrupt cell phone communication, television signals from satellites, corrode pipelines and disrupt global positioning systems. They also pose a radiation threat to astronauts orbiting in space.

Video: The Mystery of the Aurora (Courtesy NASAexplorer)

2.1.3: Earth Origin

It is believed that the Earth was created by the accretion of cold particles and originally had a homogeneous composition throughout. During the later part of the accretion phase, the Earth was likely heated by kinetic energy of objects colliding with the surface. Combined with the heat generated from radioactive decay of isotopes in the developing earth, the high temperature environment caused the entire planet to melt. Iron was pulled inward toward the core by gravity as lighter minerals - silicon, magnesium and aluminum - migrated upward, cooling to form the Earth's crust about 4.6 billion years ago.

Figure 2.1.3.1: Earth, the "Blue Marble". (Courtesy NASA Earth Observatory (Source))

As the planet cooled, solar radiation stripped away its original gasses to be replaced by those trapped beneath the surface and later released by volcanic venting also known as ***outgassing***. The volcanic vapors, like water vapor, vented into the evolving atmosphere and condensed to form clouds, and ice comets appear to have contributed water vapor to the atmosphere. However, the surface was still too hot for water to collect. That which fell to the surface as precipitation quickly vaporized and re-entered the atmosphere to condense once again. As the surface cooled, precipitation finally filled basins and depressions forming the first oceans. The Earth was now on its evolutionary way towards the planet we live on today. The tectonic forces creating the surface configuration of oceans and continents today will be taken up in Chapter 15.

2.1.4: Size and Shape

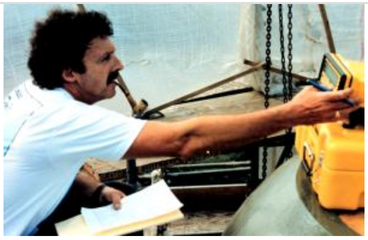


Figure 2.1.4.1: Taking readings from a GPS atop the US capitol building. (Courtesy NOAA. Source)

Those involved in the study of measuring the Earth, called ***geodesists***, don't know exactly what the true shape of the Earth is. We often describe it as a sphere but it's more like an ***oblate spheroid***. That is, Earth is wider in the middle and flatter at the poles than a perfect sphere. From pole-to-pole the distance is 12,713.6 km. The equatorial diameter Earth is about 7926 miles (12,756 km) while the polar diameter is 7900 miles (12,714 km). The equatorial circumference is approximately 24,900 miles (40,075 km). The equatorial bulge is due to the centrifugal force exerted on the Earth by its rotation.

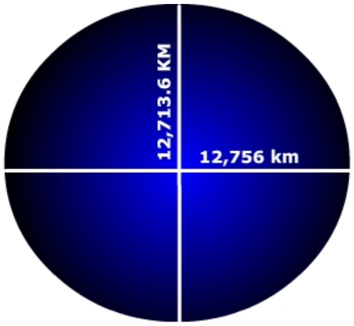


Figure 2.1.4.2: Oblate spheroid

On December 26th, 2004 subduction occurred between the India and Burma plates off the coast of Indonesia making for a slightly more compact Earth. The shift in Earth's crust resulted in a magnitude 9 earthquake and large tsunami that devastated South Asia. Interestingly, Earth became slightly more round and the North Pole shifted by about 2.5 cm (an inch) in the direction of 145 degrees East longitude (Science Daily, 2005).

From the top of Mt. Everest at 29,029 feet (8848 m) in the Himalayas, to the depths of the Mariana Trench in the Pacific at 36,198 feet (11,033 meters) below sea level, Earth has a total relief of about 12 miles. Though this seems to be a great distance, it's a mere blip when compared to the diameter of Earth.

2.1.5: The Earth in Space

Earth revolves around the Sun once every 365 1/4 days. The elliptical orbit of the earth varies from 91.5 million miles on January 3 called "**perihelion**", to 94.5 million miles on July 4 called "**aphelion**" for an average earth-sun distance of 93 million miles. The elliptical path causes only small variations in the amount of solar radiation reaching the earth.

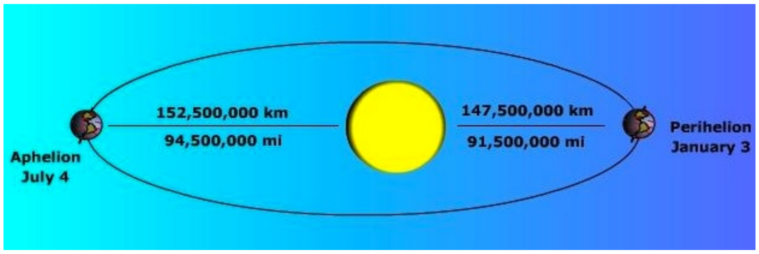


Figure 2.1.5.1: Earth's elliptical orbit

The Earth rotates at a uniform rate on its axis once every 24 hours. Turning in an eastward direction the Sun "rises" in the east and seemingly "travels" toward the west during the day. The Sun isn't actually moving, it's the eastward rotation towards the morning Sun that makes it appear that way. The Earth then rotates in the opposite direction to the apparent path of the Sun. Looking down from the North Pole yields a counterclockwise direction. From over the South Pole a clockwise direction of rotation occurs. You can demonstrate this by looking down at the North Pole of a counterclockwise rotating globe. Lift the globe while keeping it spinning in a counterclockwise direction and look at it from below.

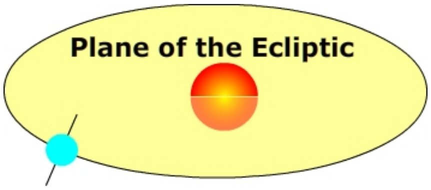


Figure 2.1.5.2: Plane of the Ecliptic

The ***plane of the ecliptic*** (also known as the "Earth-Sun plane") is a plane that cuts through the center of the Earth and the Sun in which the Earth revolves around the Sun. The Earth's axis of rotation (called the "***axial tilt***") is tilted 23 1/2 degrees from being perpendicular to the plane of the ecliptic. The axis remains pointing in the same direction as the Earth revolves around the Sun, pointing toward the star Polaris. As a result, the Earth's axis of rotation remains parallel to its previous position as it orbits the sun, a property called "***parallelism***".

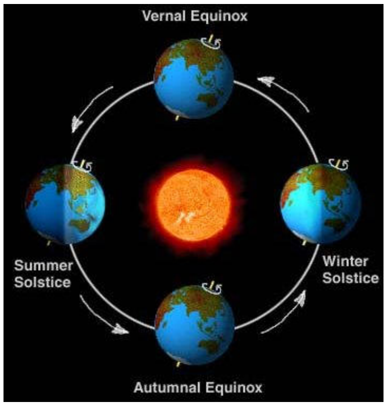


Figure 2.1.5.3: Orientation of Earth to Sun. (Courtesy NASA (Source))

The constant tilt and parallelism causes changes in the angle that a beam of light makes with respect to a point on Earth during the year, called the "***sun angle***". The most intense incoming solar radiation occurs where the sun's rays strike the Earth at the highest angle. During the summer months the Earth is inclined toward the Sun yielding high sun angles. During the winter, the Earth is oriented away from the Sun creating low sun angles.

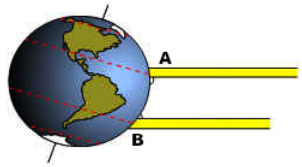


Figure 2.1.5.4: Effect of axial tilt on incoming solar radiation

Figure 2.1.5.4shows the orientation of Earth with respect to the Sun during the northern hemisphere summer and its affect on sun angle. The dashed lines are the Tropic of Cancer (23.5^{o}N) and Tropic of Capricorn 23.5^{o}S). The northern hemisphere is tilted into the sun yielding a higher angle (A) and warmer temperatures than in the southern hemisphere were low angle sun angles are striking (B).

2.1.6: Seasons

The tilt of the Earth and its impact on sun angle is the reason the Northern and Southern Hemisphere have opposite seasons. Summer occurs when a hemisphere is tipped toward the Sun and winter when it is tipped away from the Sun. The orientation of the Earth with respect to the Sun also determines the length of day. Together, the sun angle and day length determine the total amount of solar radiation incident at the Earth. To illuminate this point (pardon the pun), let's follow the Earth as it progresses through its orbit around the Sun. Watch the video below to help visualize the concepts below.

Video: How Earth's tilt Causes Seasons: How Being Earth's Tilt Causes Seasons

On about June 21st the Northern hemisphere is tipped toward the sun as shown in Figure 2.12 At noon, the ***subsolar point***, or place where the sun lies directly overhead at noon, is located at 23 1/2^{o} north latitude. This date is known as the ***summer solstice***, the longest day of the year for places located north of Tropic of Cancer. The 23 1/2^{o} parallel was so named because it is during the astrological sign Cancer when the Sun's rays strike at their highest angle of the year north of this line. The North pole tips into the Sun and tangent rays strike at the Arctic and Antarctic Circles. (A tangent ray is one that meets a curve or surface in a single point). This creates a 24 hour period of daylight ("polar day") for places located poleward of 66 1/2^{o} north. We find the South Pole tipped away from the Sun, sending places poleward of 66 1/2^{o} south into 24 hours of darkness ("polar night").

On Sept 23rd, the Earth has moved around the Sun such that the poles are neither pointing toward or away from the sun. On this day, the Sun is directly overhead 0 degrees, the equator, at noon. Tangent rays strike at the poles. It is the ***autumnal equinox*** and all places experience 12 hours of day light and 12 hours of darkness.

The ***winter solstice*** occurs on December 22nd when the Earth has oriented itself so the North Pole is facing away from, and the South Pole into the Sun. Again, tangent rays strike at the Arctic and Antarctic circles. Places poleward of 66 1/2^{o} north are in the grips of the cold, polar night. Places poleward of 66 1/2^{o} south experience the 24 hour polar day. The Sun lies directly over 23 1/2^{o} south. Occurring during the astrological sign of Capricorn, 23 1/2^{o} south latitude is called the Tropic of Capricorn.

Continuing to March 21st (i.e. ***spring equinox***) the Earth has positioned itself similar to that which occurs in September, only on the other side of the Sun. Once again tangent rays strike at the North and South poles, and the perpendicular rays of the Sun strike the Equator at noon. All places have equal day length (12 hours day;12 hours of night) as the circle of illumination cuts all latitudes in half.

So over the course of a year, the Sun's rays are only perpendicular to the surface (directly over head) at places between 23 1/2^{o} north and south. Places between the Tropic of Cancer and Capricorn experience two times when the Sun is directly over head over the course of a year. The sun angle does not vary much for places between 23 1/2^{o} north and south, a larger range in sun angle occurs poleward of these latitudes. The greater the variation in sun angle, the greater the variation in surface heating.

2.1.7: Day Length and Seasons

Day length is determined by the length of time the Sun is above the horizon. Day length changes through the year as the orientation of the Earth to the Sun changes. The **circle of illumination** is the imaginary circle that separate day from night.

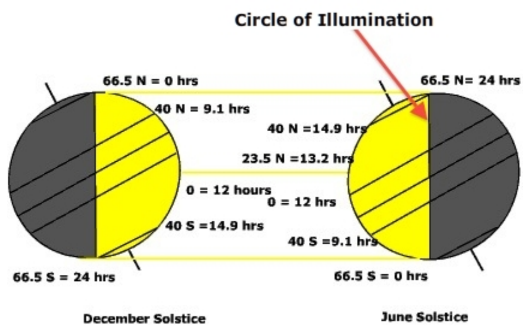


Figure 2.1.7.1: Variations in day length.

Figure 2.1.7.1 shows two extreme cases, the December and June solstices. Note during December that more of a given latitude in the Southern hemisphere is exposed to the Sun. This is the longest day of the year for those living poleward of the Equator. In June the opposite occurs with longer day length in the Northern hemisphere. Note that in both cases, the circle of illumination bisects the Equator (cuts it in half). The Equator is the only place on Earth that experiences equal day length every day of the year. The Earth's axis is neither inclined toward or away from the Sun on the equinoxes and so the circle of illumination cuts all latitudes in half resulting in equal day length for the entire Earth.

To summarize the changing seasonal conditions:

Table 2.1.7.1: Earth- Sun Relations and Season

	SPRING EQUINOX	**WINTER SOLSTICE**	**AUTUMNAL EQUINOX**	**SUMMER SOLSTICE**
Date	March 21	December 22	Sept. 23	June 21
Subsolar Point	0^o	23 1/2^o S	0^o	23 1/2^o N
Tangent Rays	North and South Poles	Arctic and Antarctic Circles	North and South Poles	Arctic and Antarctic Circles
Day length	12 hour day length everywhere	24 hours of darkness at North Pole; 24 hours day light at South Pole; 12 hours day light at Equator	12 hour day length everywhere	24 hours of darkness at South Pole; 24 hours day light at North Pole; 12 hours day light at Equator

2.1.8: The Continents

A **continent** is usually regarded as a large unbroken land mass completely surrounded by water, although some are not. There are several continent models, two of which are depicted in Figure 2.1.8.1 The seven continents model of North America, South America, Europe, Asia, Africa, Australia, and Antarctica are defined by physical and cultural conventions. Considered a separate continent in the seven continent model, Europe is a physical extension of Asia, together called the "Eurasian continent" in the six continent model. The Ural and the Caucasus mountains are used as the boundary between Europe and Asia. The island groups of the Pacific are grouped together as Oceania but are not parts of an actual continent.

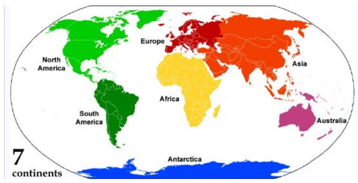


Figure 2.1.8.1a: Seven Continent Model
(Courtesy Wikipedia)

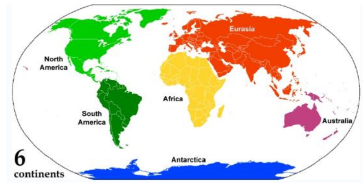


Figure 2.1.8.1b: Six Continent Model
(Courtesy Wikipedia)

Geologists view continents in a different way from geographers, a continent is defined as a portion of the fractured Earth's crust. Continental crust is composed primarily of granitic rock while oceanic crust is mostly basaltic rock. These fractured pieces are called "tectonic" or "lithospheric plates".

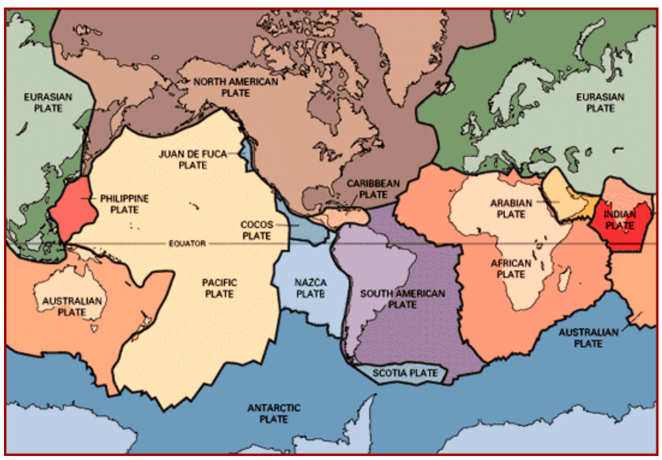


Figure 2.1.8.2: Earth's Tectonic Plates. (Courtesy USGS)

2.1.9: The Oceans

It's obvious why Earth is called the "Blue Planet" as 71 percent of the surface is covered by water, 97% of which is in oceans. Oceans appeared on Earth between 3 and 4 billion years ago from which sprang life. Ancient algal formations found in the water near Australia called stromatolites are thought to have been the early source for oxygen in the atmosphere.

Oceans & Seas

Five principal oceans the Pacific, Atlantic, Indian, Southern and Arctic comprise the "world ocean" that surround the Earth's continental land masses. The **Pacific Ocean** is the largest covering 166 million square kilometers (64 million square miles) of the surface with an average depth of 4200 meters (14,000 ft). At nearly half the size, the **Atlantic Ocean** occupies 83 million square kilometers (32 million square miles) with an average depth of 3900 meters (13,000 ft). With a similar average depth, the **Indian Ocean** is slightly smaller at approximately 73 million square kilometers (28 million square miles). The **Southern Ocean** surrounds Antarctica and was recognized in 2000 as an ocean by the International Hydrographic Organization. It encompasses roughly 20.3 million square kilometers (7.8 million square miles) with a typical depth between 4,000 and 5,000 meters (13,000 to 16,000 feet). The **Arctic Ocean** is the smallest covering 13 million square kilometers (5 million square miles) with an average depth of 930 meters (3250 ft). Some view the Arctic Ocean as a sea rather than ocean because of its small size.

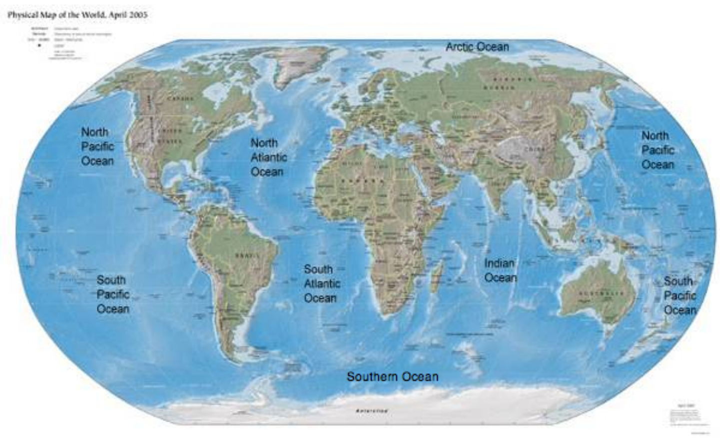


Figure 2.1.9.1: World's Oceans. (Base map courtesy CIA)

Seas are salt-water bodies smaller than oceans and partially enclosed by land. Major seas include the Mediterranean, Baltic, Bering, Black, Caribbean, Coral, North, Red, and Yellow. Unlike inland lakes that can be salt or fresh water, there is a constant exchange of water between ocean and sea. Several inland salt lakes like the Aral, Caspian, and Dead are erroneously named "seas".

The Nature of Ocean Water

Sea water makes up the largest store of water in the hydrologic cycle. It is comprised of nearly 60 chemical substances with common salt being the most abundant, 78% of the dissolved solids. Ocean salinity varies from 32 - 37 parts per thousand. Salinity is lower near land and in the polar regions (30 ppt).

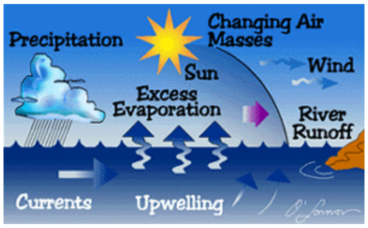


Figure 2.1.9.2: Controls over ocean salinity. (Courtesy Naval Meteorology Program and Oceanography Command "Seawater, Sound & Ice")

A number of factors determine ocean salinity. Salinity is lower where freshwater rivers enter the ocean. In the North Pacific precipitation exceeds evaporation thus diluting ocean water. Water is more saline in subtropical oceans where evaporation exceeds precipitation. The Atlantic ocean is the most salty while the Arctic ocean is the least.

The oceans exhibit three vertical temperature zones, 1) a surface layer of water, 2) a transition zone of decreasing temperatures with depth, and 3) the cold waters of the deep ocean. The zone of transition, known as the thermocline, is most noticeable where surface water is warmest. Polar water may have no thermocline as the surface temperature are very cold.

Learn more about the impact of human activities on ocean water by Digging Deeper: Ocean Acidification, or continue to the next topic.

Digging Deeper: Ocean Acidification

Oceans play an important role in the natural cycling of carbon dioxide through the Earth System (See: The Carbon Cycle). But the chemistry of the Earth's oceans is changing as a result of the absorption of anthropogenic carbon dioxide emissions. The ocean's absorb about 25% of the carbon dioxide released from human activities each year. The result is a decrease in pH and acidification of ocean water leading to severe consequences for ocean ecosystems.

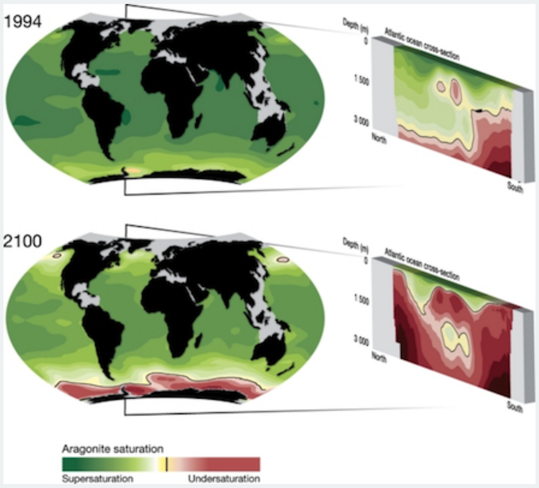


Figure 2.1.9.3: Ocean Acidification. (Courtesy UNEP) (Cartographer Hugo Ahlenius, UNEP/GRID-Arendal. Sources: Donner, S.D., Skirving, W.J., Little, C.M., Hoegh-Guldberg, O., Oppenheimer, M. 2005. Global assessment of coral bleaching and required rates of adaptation under climate change. Global Change Biology vol, 11, 2251-2265. Orr, James C. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, vol 437, 681-686.)

How ocean acidification happens

When carbon dioxide (CO_2) combines with ocean (H_2O) it forms H_2CO_3, carbonic acid. Most of this acid dissociates into hydrogen ions (H+) and bicarbonate ions (HCO_3-1). The increase in H+ ions reduces pH and raising the acidity of ocean water. Since the dawn of the industrial revolution, which was fueled by fossil fuel burning, the pH of Earth's oceans has decreased from 8.2 to 8.1. This doesn't sound like much, but realize that pH is measured on a logarithmic scale. The .1 change represents a 30% increase in acidity. This increase is 100 times faster than any change in acidity for at least the last 20 million years. Under current emission rates, pH will fall by 0.4 between now and 2100, a 3-fold increase in acidity.

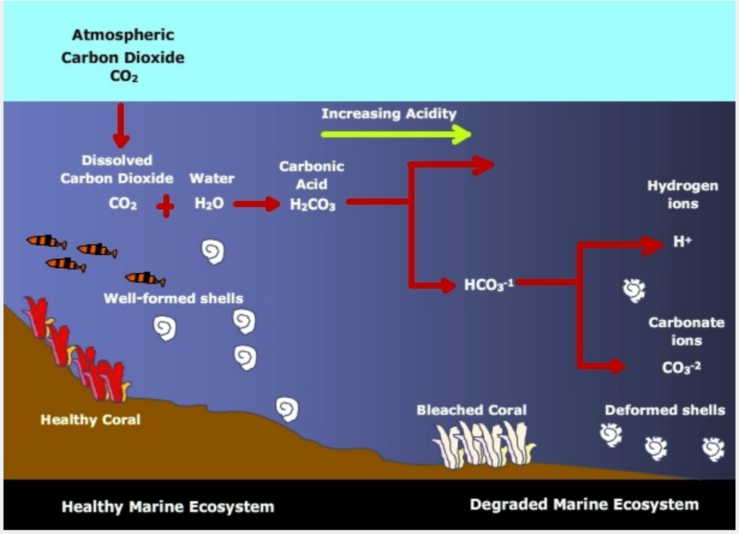


Figure 2.1.9.4: Ocean acidification process

Impacts of ocean acidification

The impact of acid acidification is wide ranging and potentially disastrous for the earth system. Ocean acidification causes or is linked to various impacts on the ocean and its ecosystems. Some of these are:

- *Decreasing uptake of atmospheric carbon dioxide as saturation level is approached.* Like other elements dissolved in a solution, water has a saturation point beyond which its "sink function" ceases to be effective at absorbing carbon dioxide. As a result, more CO2 is left in the atmosphere to fuel global warming.
- *Damage to coral reef ecosystems.* Coral reefs are found in two types of ocean habitat, warm water and cold water. Warm water coral reef are typically found at shallow depths and in tropical waters. Cold-water corals are found at much deeper depths and in subtropical to high latitude oceans. Ocean acidification has been shown to hinder the calcification of deep-sea, or cold-water, corals. It is estimated that by 2100, 70% of cold-water corals will be exposed to acidified ocean water. Though excessively warm water is often the cause, acidified ocean water has been linked to coral bleaching. The whitening caused by bleaching occurs when corals lose microscopic algae within their tissues that give corals their wonderful colors.

Figure 2.1.9.5: Distribution of Coral Reefs. (Courtesy: UNEP Cartographer:Hugo Ahlenius, UNEP/GRID-Arendal. Sources: UNEP World Conservation Monitoring Centre. 2005. Global Cold-Water Coral Distribution (points). Cambridge, UK: UNEP-WCMC UNEP World Conservation Monitoring Centre. 2005. coral1km_v7_2003. Cambridge, UK: UNEP-WCMC)

- *Slower growth rates for marine organisms with calcareous skeletons.* As carbonic acid forms from the uptake of atmospheric CO2, the hydrogen ion concentration increases limiting access to carbonate ions needed to form shells.

Figure 2.1.9.6: Krill and phytoplankton, the foundation of the marine food web. (Source: NOAA)

- *Disruption of marine food webs*. Impacts on phytoplankton and other sensitive species may disrupt marine food webs and in turn affect fisheries. Phytoplankton are organisms that float on or near the surface of water. Most are single-celled, like diatoms and dinoflagellates,and in the ocean serve as the foundation of the marine food web. Phytoplankton are the primary producers of the ocean, accounting for 95% of the ocean's primary productivity. They serve as food for zooplankton that include copepods, some species of shrimp, and larval forms of jellyfish, barnacles, mollusks, and fish. Small predators like shrimp, krill, sardines, etc feed on the zooplankton, and are in turn eaten by large predators which include birds, large fish, and marine mammals. Loss of the species at the foundation reverberates through the entire food web. Soon, fisheries important to many national economies founder resulting in a degraded marine ecosystem.

Future ocean acidification

Ocean acidification is projected to increase this century as atmospheric carbon dioxide continues to increase. The amount of acidification depends largely on future emissions as shown by the Intergovernmental Panel on Climate Change projections for various emission scenarios. The worse case scenario for ocean acidification is one in which the world continues to use carbon-based energy resources to fuel its economic, industrial, and transportation needs.

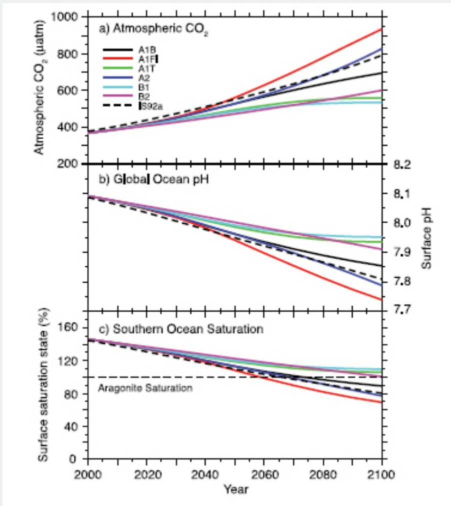


Figure 2.1.9.7: Future CO_2, pH and saturation state. (Source EPA)

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Oceans At Risk

Acid In The Oceans: A Growing Threat To Sea Life

Listen 8:15

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Audio Program: Acid in the Oceans: A Growing Threat to Sea Life (Courtesy NPR - *All Things Considered*)

The Ocean Floor

The deep-ocean floor has an average depth of 4000 meters (12,000 feet) with a significant variation in the depth. The ocean basins are cut by deep trenches and large mountains rise from the floor. The midocean ridge is the longest continuous chain of mountains on Earth winding its way along the sea floor through all the oceans. Its width average 1600 kilometers (1000 mi) with ridges rising an average of 1500 - 3000 meters (5,000 - 10,000 feet) above the floor. Along its spine, new sea floor is created and spreads apart by lava pouring out of rifts along the ocean ridge. Along the rugged volcanic topography of the ridge one finds dramatic undersea volcanoes called "black smokers".

Long narrow arc-shaped **trenches** cut across the deepest parts of the ocean floor. Trenches are found near active plate margins where earthquakes and volcanoes are common. Converging plates in subduction zones recycle rock along the ocean trenches. Ocean-flooring drilling along trenches and the midocean ridge indicates that rock is recycled over a period of 2 to 3 million years. The deepest trenches are found along the Pacific "Ring of Fire". Trenches are common along curved island arcs like the Aleutian Islands.

The vast submarine plains of the "ocean deep" are the abyssal plains. The abyssal plains cover 40% of the ocean floor with depths of 3000 - 6000 meters (10,000 - 20,000 ft). Wind deposition and volcanic eruptions have covered most in layers of brown and red clays. Some are covered with the remains of microscopic marine organisms known as ooze. The celebrated White Cliffs of Dover are uplifted ooze deposits.

Rising from the ocean floor one finds seamounts, mountains that do not reach the water's surface and typically formed from extinct volcanoes. Guyouts are flat-topped seamounts.

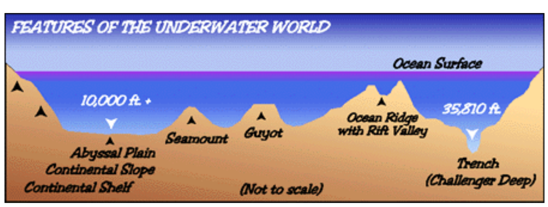


Figure 2.1.9.7: Features of the ocean floor. (Courtesy Naval Meteorology Program and Oceanography Command "The Underwater World")

Continental Margins

The continental margins are comprised of three topographic features. The ocean floor slopes gradually upward toward the continents forming the **continental rise**. Approaching the edge of the continent the slope of the ocean floor steepens into the

continental slope. At the top of the slope lies the **continental shelf**, a gently sloping platform of varying width. Along *passive margins* like the east coast of the United States, the continental shelf is wide. The continental shelf is much narrower along *active margins* bordered by mountains like that found along the west coast of the United States.

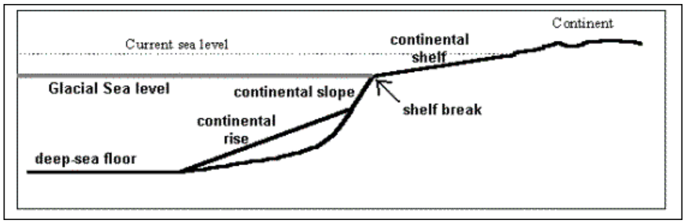


Figure 2.1.9.8: Topography of continental margins (Courtesy USGS Earthquakes Hazards Program - Southern California (Source))

2.2: Looking Back - The Earth

Assess your understanding of concepts related to this chapter section by answering the questions below before proceeding with this chapter.

Exercise 2.2.1

What process was largely responsible for earth's early atmosphere?

Answer

Outgassing, the release of gasses through processes like volcanic venting.

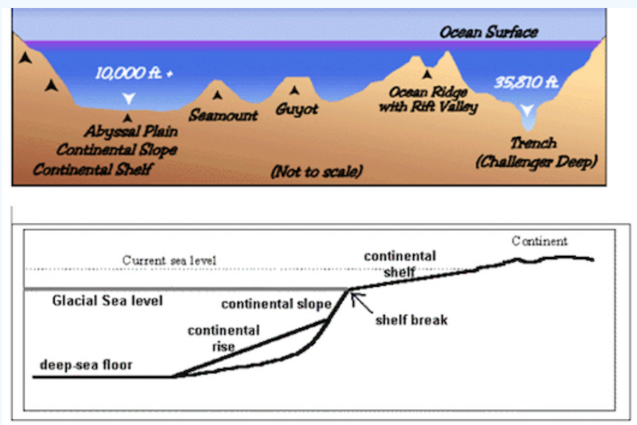
Define continent, sea, and ocean.

Answer

Continent, according to the 6-continent model it is large unbroken land mass completely surrounded by water. An *ocean* is a large body of salt water not enclosed by land. A *sea* is a large body of salt water partially enclosed by land.

Draw and label generic diagrams of the ocean floor and the continental margins on a seperate piece of paper.

Answer



Describe the shape of the Earth.

Answer

The shape of the earth is described as an oblate ellipsoid.

Construct this table in your notes, fill it out, then compare it to the correct answers.

	June Solstice	September Equinox	December Solstice	March Equinox
Date				
Orientation to Sun*				
Location of Vertical Rays				
Day Length - North Pole				
Day Length - South Pole				
Day Length - Equator				

Answer

	Summer Solstice	Atumnal Equinox	Winter Solstice	Spring Equinox
Date	June 22	Sept 23	Dec 22	Mar 23
Orientation to Sun*	NH towards Sun	Neither pole	SH towards Sun	Neither pole
Location of Vertical Rays	23.5 N	0 hours	23.5 S	0
Day Length - North Pole	24 hours	12 hours	0 hours	12 hours
Day Length - South Pole	0 hours	12 hours	24 hours	12 hours
Day Length - Equator	12 hours	12 hours	12 hours	12 hours

NH = Northern Hemisphere
SH = Southern Hemisphere

SECTION OVERVIEW

2.3: Natural Systems

At the beginning of this chapter we defined a ***system*** as a collection of interacting objects. The Earth and its atmosphere defines the Earth system. A system consists of three basic elements: (1) a functioning set of components, (2) a flow of energy which powers them, and (3) a process for the internal regulation of their functioning called ***feedback*** (Trewartha, et. al., 1977).

2.3.1: Components of the Earth System

2.3.2: Types of Systems

2.3.3: Sources of Energy

2.3.4: System Regulation

2.3.5: Feedbacks

2.3.1: Components of the Earth System

The ***Earth system*** is a complex functioning system that includes all the components of the various "spheres" like the solid Earth or ***lithosphere***, the gaseous envelope surrounding the Earth that is the ***atmosphere***, ***biosphere*** comprised of all living organisms and the **hydrosphere** or "water sphere".

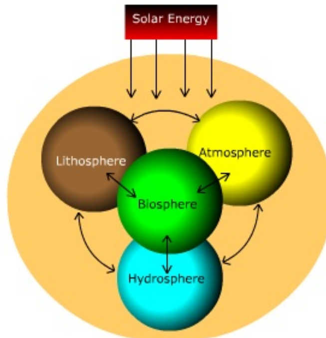


Figure 2.3.1.1: The Earth System (after Christopherson, 2005)

The Earth system diagram shows arrows representing flows of energy and mass that connect and intertwine the four spheres. At the top, solar energy drives many of the environmental processes operating in the four spheres. The Earth's internal heat engine and the gravitational attraction of the moon are additional sources of energy to power Earth systems. There is a constant cycling of energy and mass between the hydrosphere, lithosphere, atmosphere, and biosphere as indicated by the arrows.

2.3.2: Types of Systems

Systems can be classified as open, closed, or isolated. ***Open systems*** allow energy and mass to pass across the system boundary. A ***closed system*** allows energy but not mass across its system boundary. An ***isolated system*** allows neither mass or energy to pass across the system boundary.

Open Systems

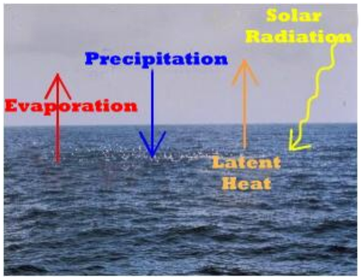


Figure 2.3.2.1: The ocean is an open system

The ocean is an example of an open system. The ocean is a component of the hydrosphere and the ocean surface represents the interface between the hydrosphere and the atmosphere that lies above. Solar radiation passes through the atmosphere and is absorbed by the ocean. The absorbed energy evaporates water from the ocean. As water vapor (mass) enters the atmosphere it carries with it the heat used to evaporate the water (called *latent heat*) and raises the air's humidity. If the humidity is high enough, condensation occurs, latent heat is released, and clouds are created. Continued condensation creates precipitation (mass) that falls back into the ocean. Hence, energy and heat (solar radiation, latent heat) as well as mass (water vapor and precipitation) passes across the boundary between the atmosphere and hydrosphere. All of the "spheres" of the earth system are considered open systems because energy and mass is exchanged between them.

Closed Systems

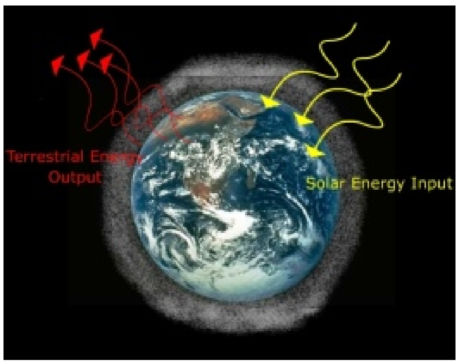


Figure 2.3.2.1: The Earth as a closed system

The earth system *as a whole* is a closed system. The boundary of the earth system is the outer edge of the atmosphere. Virtually no mass is exchanged between the Earth system and the rest of the universe (except for an occasional meteorite). However, energy in the form of solar radiation passes from the Sun, through the atmosphere to the surface. Earth in turn emits radiation back out to space across the system boundary. Hence, energy passes across Earth's system boundary, but not mass, making it a closed system.

The interface between systems is not always easy to identify, others more so. The interface between the hydrosphere and lithosphere at a shoreline is easy to recognize as a definite planar boundary between a solid and fluid. The interface between the atmosphere and hydrosphere is less easy to discern as the hydrosphere comprises both liquid water of the surface and water held in the air.

? Concept Check 2.3.2.1

What kind of system is a terrarium that has a tightly sealed glass lid? Why?

Answer

A terrarium is a ***closed system***. A terrarium is a glass container holding plants and under this scenario has a closed glass lid. The glass serves as the boundary to the system. Energy, like solar radiation and heat can be transmitted through the glass. Moisture (mass), like that which is evaporated from the soil inside the terrarium cannot escape. Therefore a terrarium is considered a closed system, one that allows energy but not mass to across its system boundary.

2.3.3: Sources of Energy

Forces that drive the Earth system derive their energy from a number of different sources. ***Exogenic processes*** are those driven by ***exogenic forces*** that primarily derive their energy from solar radiation. For instance, soil erosion is caused by the force of wind acting on bare ground. We can trace the energy that causes wind erosion to the receipt of solar radiation. How? Though we are jumping ahead ourselves, wind is a product of horizontal differences in pressure over distance caused by the unequal heating of the Earth's surface. Low pressure is created when heated air rises from the surface and then flows outward at a higher elevation. As air moves upward, the surface pressure decreases relative to the air around it. The variation in surface pressure causes air to move into the region of low pressure to replace that which is rising, thus creating a wind. Soil is detached when wind blows over an erodible surface. Water and glacial erosion are other examples of exogenic processes.

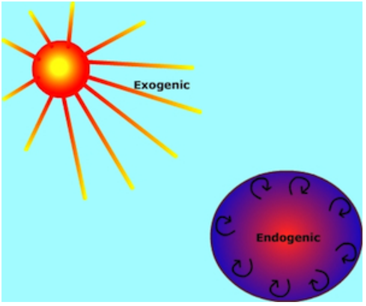


Figure 2.3.3.1: Sources of Energy

Endogenic processes are those that get their energy from ***endogenic forces*** originating deep within the Earth. Many of the great mountain systems like the Himalayas are a product of the collision of lithospheric plates. The movement of lithospheric plates is thought to result from convection currents in the mantle. Deep within Earth's mantle and lower crust, heat is generated by the radioactive decay of elements like uranium, thorium, and potassium. The heat is transferred upward to warm the mantle causing it to slowly circulate and tug on the plates above. The movement of plates fractures and folds rock, and their collision creates vast mountain chains and volcanic cones. (For more see: Some Unanswered Questions, *The Dynamic Earth*, USGS). So in the final analysis, endogenic forces tend to build things up while exogenic forces wear things down.

Figure 2.3.3.2: Texas dust storm during the Dust Bowl (1935). Wind erosion is a product of an exogenic source of energy. (Source: NOAA)

Figure 2.3.3.3: Mt. Paricutin, a cinder cone volcano is a product of an endogenic source of energy. (Source: USGS)

2.3.4: System Regulation

Most systems tend toward a state of equilibrium where system inputs are balanced by system outputs. Though natural systems change over long periods of time, on the scale of a human lifetime they appear to be static. In reality, the state of natural systems oscillates around a mean condition a state known as ***dynamic equilibrium***. For instance, the abundance and type of animal species in an ecosystem may fluctuate over a time, but the overall diversity remains constant. The Earth's atmospheric temperature has remained fairly constant through long periods of Earth history, even though at shorter time intervals, geologically speaking, the temperature has risen or fallen. If one or more controlling variables (climate, vegetation, soil, man) imposes a long-term stress to the system it will seek to establish a new state. A ***steady-state equilibrium*** is reached when the rates of system inputs and outputs are equal, and the amount of material stored in the system is constant over time.

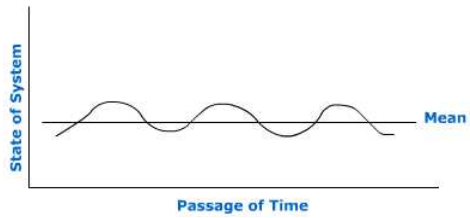


Figure 2.3.4.1: System equilibrium over time.

The state of the system is a result of feedback mechanisms between system components.

2.3.5: Feedbacks

Outputs generated by the functioning of a system component either encourages change in the system (***positive feedbacks***) or discourage change (***negative feedbacks***). Negative feedbacks act to regulate the system to keep it in a state of equilibrium. Figure $2.3.5.1$ is an example of how a positive feedback can encourage a system to change as it relates to the onset of glaciation. Though many theories have been proposed as to what caused the long periods of glaciation over the course of earth history, a change in the amount of solar radiation absorbed by the surface is common to many of them. One idea is that the orbit of the earth around the sun changed causing a decrease in the amount of solar radiation reaching the earth. This was accomplished by a change in the earth - sun distance or a change in the tilt of the earth's axis. Whatever the reason, a decrease in solar radiation reaching and being absorbed by the surface would have caused the air temperature to decrease. With colder temperatures increased snowfall likely occurred and less snow melted over the course of a year. The build of snow and subsequent change to ice enabled glaciers to form and grow. As the earth is covered with a light colored surface its reflectivity increases. With increased reflectivity, less solar radiation is absorbed. As less radiation is absorbed, cooler temperatures develop, snow duration increases, glaciers grow, and more of the earth is covered by the highly reflective surface of glaciers. The circuit indicated by the arrows in Figure $2.3.5.1$ is the positive feedback.

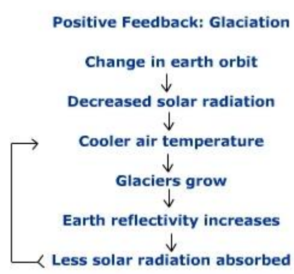


Figure $2.3.5.1$: Positive Feedback: Glaciation

A negative feedback discourages system change. An example of a negative feedback is used to support the notion of biospheric regulation of the atmosphere called the "Gaia Hypothesis" Some feel that the relatively stable conditions on Earth (atmospheric gas composition, temperature, etc) is due to the regulatory influence of the biosphere over the atmosphere. If some perturbation causes environmental conditions to shift, activities of the biosphere bring them back into balance. To illustrate this process they developed a simple model called "Daisy World". What we know is that the output of the sun has increased since the time our galaxy was formed. As a result, more solar radiation has been reaching the earth through time. However, over long periods of geologic time the air temperature has not changed all that much. Scientists argue that this has been accomplished through various biospheric regulatory mechanisms that alter the gaseous composition of the atmosphere and the nature of the earth surface. Their Daisy World model shows how the distribution of plants can modify the radiation balance of the Earth to regulate temperatures. Their model begins with a world that is covered with 50% dark and 50% light colored daisies. As the output of energy from the Sun increases, more energy is absorbed by the earth which in turn increases air temperature. The darker daisies absorb more sunshine than the light colored daisies because of their color. If the output of solar energy continues to increase, it becomes too much for the dark daisies to endure causing them to begin to die off. The with the lack of competition and their ability to reflect more light and endure higher temperatures, the light colored daisies flourish. As Daisy World becomes covered in a higher percentage of light colored daisies, the reflectivity of the surface increases. This results in a decrease in the absorption of sunshine and a reduction of temperature. Thus the change in the composition of plants in Daisy World dampens the effect of increased solar output. If it gets too cold, the dark daisies begin to flourish, increasing absorption of solar radiation and raising temperatures, causing the cycle to begin again. The negative feedback that is set up ultimately causes the system to reach an equilibrium.

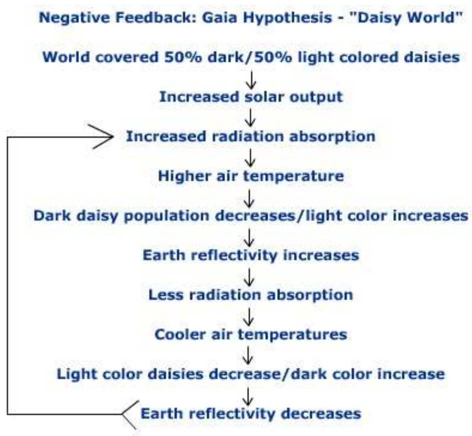


Figure 2.3.5.2: Negative Feedback: Daisy World model

All systems have ***leverage points***, points of vulnerability where an imposed stress yields maximum change. For instance, human intervention in the hydrologic cycle is best achieved at the river-flow stage (dam and reservoir building) as opposed to the precipitation stage (cloud seeding). A ***trigger*** (fire, species invasion, fertilizer runoff) sets off an environmental change. Once a change is initiated, the system responds by adjusting the energy and mass exchanges. If the stress is released, a period of recovery to its previous state occurs. Should the system be stressed beyond its ***threshold***, it will seek a new state of equilibrium.

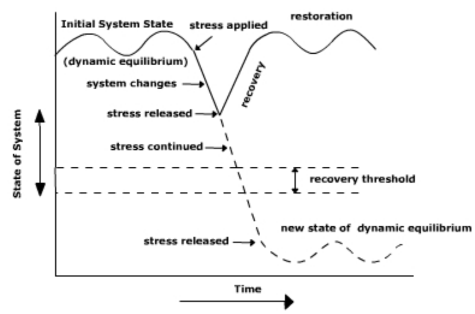


Figure 2.3.5.3: System changes due to an imposed stress. (After Drew, 1983)

Assess you basic understanding of the preceding material by "Looking Back: Natural Systems" or skip and continue reading.

2.4: Looking Back - Natural Systems

Assess your understanding of concepts related to this section by answering the questions below before proceeding with this chapter.

Exercise 2.4.1

List the three basic elements of a system.

Answer

(1) a functioning set of components, (2) a flow of energy which powers them, and (3) a process for the internal regulation of their functioning called feedback.

Define open and closed systems. Give an example of each from the Earth system.

Answer

Open systems allow energy and mass across their system boundary. The various "spheres" of the earth system like the biosphere are examples of open systems. Closed systems allow energy but not mass to cross their system boundary. The earth system as a whole is an example of a closed system.

Explain the difference between positive and negative feedback.

Answer

Positive feedback encourages system change towards a new state. Negative feedback reverses the direction of system change to return to it's original state.

Define system equilibrium.

Answer

System equilibrium is a state when the inputs and outputs of a system are in balance.

Define exogenic and endogenic sources of energy.

Answer

Exogenic source of energy comes from outside the earth system, notably solar radiation. An endogenic source is found within the earth system, notably the heat generated from the earth's core.

SECTION OVERVIEW

2.5: Biogeochemical Cycle

We have adopted a model of the Earth System as a set of interacting “spheres”, the atmosphere, hydrosphere, biosphere, and lithosphere. Being open systems, energy and mass are constantly cycled between them. The transport and transformation of substances through the Earth system are known collectively as **biogeochemical cycles**. These include the hydrologic (water), nitrogen, carbon, and oxygen cycles.

2.5.1: Nitrogen Cycle

2.5.2: Oxygen Cycle

2.5.3: Carbon Cycle

2.5.4: The Hydrologic Cycle

2.5.1: Nitrogen Cycle

Nitrogen comprises 78.08% of the atmosphere making it the largest constituent of the gaseous envelope that surrounds the Earth. Nitrogen is important in the make up of organic molecules like proteins. Unfortunately, nitrogen is inaccessible to most living organisms. Nitrogen must be “fixed” by soil bacteria living in association with the roots of particular plant like legumes, clover, alfalfa, soybeans, peas, peanuts, and beans. Living on nodules around the roots of legumes, the bacteria chemically combine nitrogen in the air to form nitrates (NO_3) and ammonia (NH_3) making it available to plants. Organisms that feed on the plants ingest the nitrogen and release it in organic wastes. Denitrifying bacteria frees the nitrogen from the wastes returning it to the atmosphere.

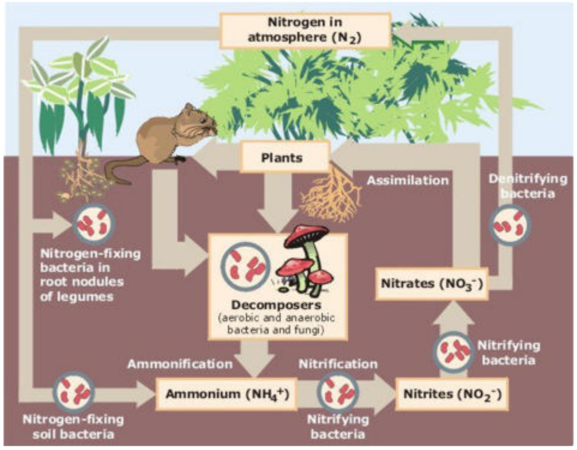


Figure 2.5.1.1: The Nitrogen Cycle (Courtesy EPA, Source: www.epa.gov/maia/html/nitrogen.html)

2.5.2: Oxygen Cycle

Oxygen is the second most abundant gas in Earth's atmosphere and an essential element of most organic molecules. Though oxygen is passed between the the lithosphere, biosphere and atmosphere in a variety of ways, photosynthesizing vegetation is largely responsible for oxygen found in the atmosphere. The cycling of oxygen through the Earth system is also accomplished by weathering of carbonate rock. Some atmospheric oxygen is bound to water molecules from plant transpiration and evaporation. Oxygen is also bound to carbon dioxide and released into the atmosphere during animal respiration.

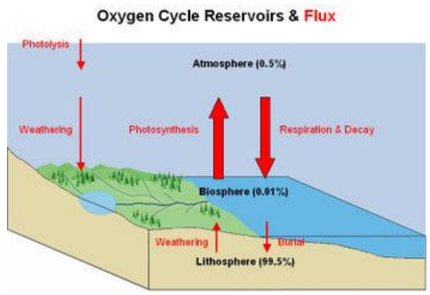


Figure 2.5.2.1: The Oxygen Cycle (Courtesy Wikipedia, Source: https://en.Wikipedia.org/wiki/Oxygen_cycle)

2.5.3: Carbon Cycle

Carbon is the fourth most abundant element in the Universe and is the building block for all living things. The conversion of carbon dioxide into living matter and then back is the main pathway of the carbon cycle. Plants draw about one quarter of the carbon dioxide out of the atmosphere and photosynthesize it into carbohydrates. Some of the carbohydrate is consumed by plant respiration and the rest is used to build plant tissue and growth. Animals consume the carbohydrates and return carbon dioxide to the atmosphere during respiration. Carbohydrates are oxidized and returned to the atmosphere by soil microorganisms decomposing dead animal and plant remains (**soil respiration**).

Another quarter of atmospheric carbon dioxide is absorbed by the world's oceans through direct air-water exchange. Surface water near the poles is cool and more soluble for carbon dioxide. The cool water sinks and couples to the ocean's thermohaline circulation which transports dense surface water toward the ocean's interior. Marine organisms form tissue containing reduced carbon, and some also form carbonate shells from carbon extracted from the air.

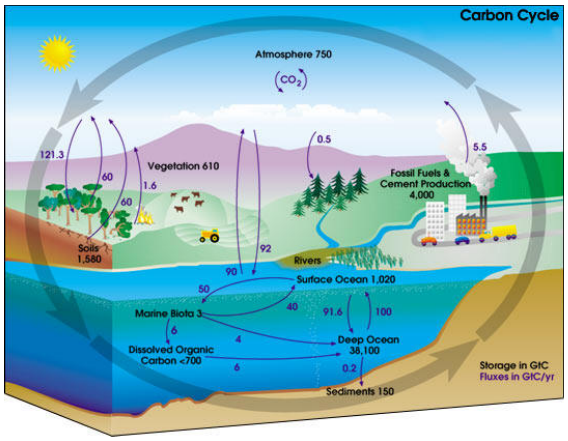


Figure 2.5.3.1: The Carbon Cycle
(Courtesy NASA, Source: earthobservatory.nasa.gov/Li...on_cycle4.html)

There is actually very little of the total carbon cycling through the Earth system at any one point in time. Most of the carbon is stored in geologic deposits - carbonate rocks, petroleum, and coal - formed from the burial and compaction of dead organic matter on sea bottoms. The carbon in these deposits is normally released by rock weathering.

Video: Keeping Up With Carbon (Courtesy NASA (Source))
Understanding how the carbon cycle is changing is key to understanding Earth's changing climate.

2.5.4: The Hydrologic Cycle

The ***hydrologic cycle*** refers to the movement of water through its various stores within the Earth system. The amount of water that cycles between the surface and the atmosphere is phenomenal. At any minute, nearly a billion tons of water is delivered to the atmosphere by evaporation and the same amount precipitated from it. The hydrologic cycle not only traces the movement of water through the Earth system, it is a path way for the movement of energy. Water is evaporated from tropical oceans where energy is abundant and is transported on the wind to high latitudes where energy is in short supply. There it condenses and gives off heat to the atmosphere. The exchange of energy from low latitudes to high latitudes helps maintain the energy balance of the Earth system.

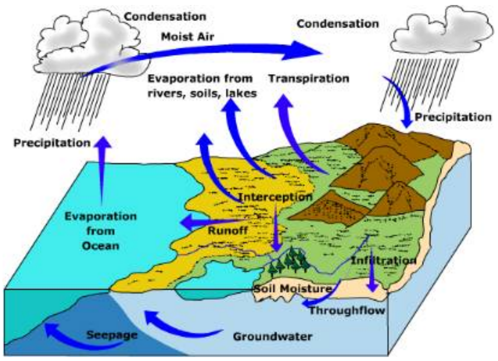


Figure 2.5.4.1: The Hydrologic Cycle

The cycle starts with evaporation from the surface, most of which comes from the tropical oceans. The water vapor later condenses into clouds in which precipitation forms. Water falling as precipitation may be intercepted by vegetation or fall directly onto the surface. Water intercepted by plants may ultimately fall to the ground and seep into it. Likewise, water falling directly on the surface may seep into the subsurface or runoff to nearby streams. Water seeping into the ground may become soil water or groundwater. Water in the soil may be taken up by plants then transpired to the air. Groundwater may seep into streams or return to the ocean along along a coast. Water found in streams may also empty into the ocean. A detailed discussion of the hydrologic cycle is found in Chapter 10: "The Hydrosphere".

2.6: Getting Ready for Chapter 2

In chapter 1 we examined what physical geography is, and how geographers study the geographic patterns found in earth systems. We have found that physical geographers are particularly well-suited for answering questions about how the future geography of planet Earth will evolve as a result of global warming and climate change. Though there are those who dispute that the current warming trends are part of a natural cycle, the vast majority of geoscientists and physical geographers agree that global warming is affecting the planet and it is caused linked to human activities. The evidence for global warming and its effects on physical and biological systems as shown in are mounting. Throughout the world, nearly 90%, and in most regions more, of the significant observed changes in physical and biological systems are consistent with warming. The earth system is quickly approaching a point when new geographies will appear.

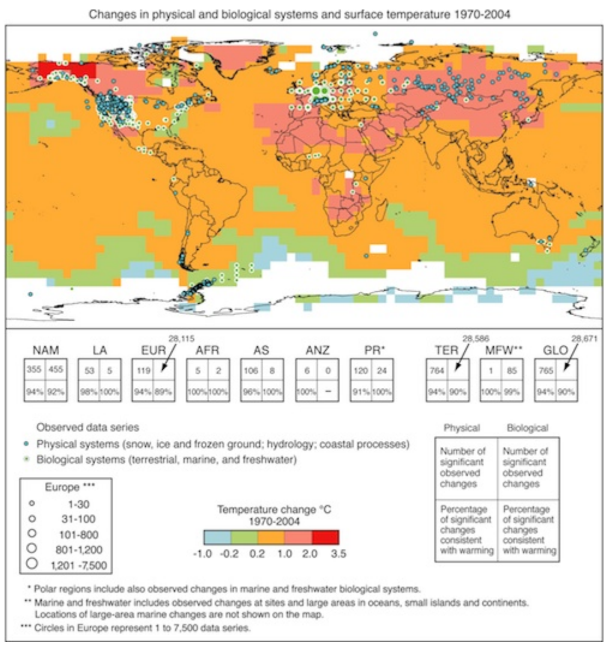


Figure 2.6.1: Changes in Physical and Biological Systems and Surface Temperature 1970-2004 (Source IPCC)

Chapter 2 concerns the earth system, what it is, how it formed, and the energy and material that cycles between the various system components. In this chapter we'll examine how the earth system formed and its present day functioning. We'll conclude the chapter by looking out how climate change may affect the functioning of the earth system.

What you should already know...

You should have a good understanding of how physical systems are visualized and modeled.

Quiz 2.6.1

1. Which of the following best describes geography?

   A. The study of where things are.
   B. The study of the distributions and interrelationships of earth phenomena.
   C. The study of the earth.
   D. The study of landforms and weather.

2. Live vegetation appears _____ on a false-color infra-red image.

   A. red
   B. green
   C. black
   D. blue

3. Which scale will show the most detail on a map?

   A. 1:24000

B. 1:62500
C. 1:100000
D. None of the above as the amount of detail will be the same no matter the scale.

4. If you were half way between the equator and the north pole and one quarter of the way around the earth west of the prime meridian you will be at:

A. 45 N; 90 W
B. 45 N; 180 W
C. 45 N; 90 E
D. 45 N; 180 E

5. Use the data set below to determine the correct annual average temperature (AT) and temperature range (TR).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
°C	-6.2	-3.3	3.1	10.6	16.5	21.9	24.8	23.3	18.2	11.8	3.8	-3.8

A. AT = 10.025; TR =18.6
B. AT = 18.6; TR =10.025
C. AT = 31; TR =10.025
D. AT = 10.025; TR =31

6. The prime meridian is located at

A. 90 W
B. 180 W
C. 0
D. 90 N

7. 45 degrees North latitude falls in the ________ geographic zone.

A. subtropical
B. midlatitude
C. subarctic
D. arctic

8. Lines of longitude

A. converge at the poles.
B. measured north or south of the prime meridian.
C. are parallel to each other.
D. all the above.

9. Lines connecting points of equal elevation are called

A. topographic lines.
B. elevation lines.
C. isobars.
D. contour lines.

10. You measured 5.5 inches between two points on a 1:24000 scale map. The actual distance in miles is

A. 25 miles
B. 2.08 miles
C. 240 miles
D. 1100 miles

Answer

1. B
2. A
3. A
4. A
5. D
6. C

7. B
8. A
9. D
10. B

About your score....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous chapter.

If you scored less than 70% you should consider reviewing the previous chapter and seeking help from your instructor.

2.7: Future Geographies- Feedbacks Driving Global Warming and Environmental Change

In this chapter we have learned that there are two types of feedbacks, positive feedbacks that drive system change and negative feedbacks that seek to keep systems in a state of equilibrium. Geoscientists like physical geographers are recognizing that positive feedback mechanisms may drive the Earth system past thresholds and towards a new state of equilibrium. In so doing, the distribution of climates and ecosystems may be irreversibly altered and a new physical geography of the Earth system will appear.

Examples of Feedbacks Driving Global Warming

Rising temperatures are expected to cause increased evaporation of water into the atmosphere, most of which will originate from oceans. The additional water vapor boosts the absorption of infrared radiation emitted by the earth resulting in more warming (a positive feedback). The increased warmth promotes more evaporation yielding an enhanced greenhouse effect. However, the addition of water may cause an increase in cloud cover resulting in a higher atmospheric albedo and reflection of incoming solar radiation. If this were to occur, the reduction in insolation would lead to cooling. Such contradictory consequences makes it difficult to determine what actually will occur in the future.

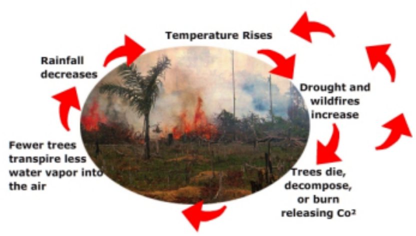


Figure 2.7.1: Tropical forest - climate change feedback (Courtesy NASA Source)

Throughout history, humans have cut forests to build structures, warm their homes, and cook their meals, and clear the land for agriculture. Removing forests removes a powerful sink for carbon dioxide. Leaving more CO_2 in the atmosphere enhances global warming and thus an increase in temperatures. As a result, temperature conditions that may be too warm to support healthy forest ecosystems. With less vegetation present, more carbon dioxide is left in the atmosphere causing more warming, another positive feedback driving the earth system toward ever warmer conditions. As temperatures increase, evaporation increases causing drier conditions and the threat of wildfires and forest destruction.

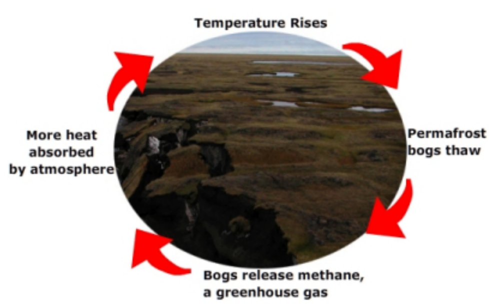


Figure 2.7.2: Permafrost - climate change feedback. (Image Courtesy USGS)

Geoscientists agree that the Arctic has been and will continue to be significantly impacted by global warming. Much of the land surface in the Arctic is underlain by permanently frozen ground called "permafrost". They uppermost "active layer" experiences seasonal thawing. Recent studies indicate that climatic warming my result in in a 12 to 15% reduction in the area covered by permafrost and a 15 to 30% increases in the thickness of the active layer. As temperature rises permafrost melts, releasing stored carbon, but just as importantly, methane. Increased warming results in more permafrost melting pushing the earth system ever forward into a future enhanced greenhouse environment.

Changes in Arctic ecosystems has already occurred as a result of global warming. Figures 2.7.3 a & b show two photographs from the same location in Alaska, showing the transition from tundra to wetlands over the last twenty years. When permafrost melts, water collects in small ponds on the surface increasing the heat gain nearly ten-fold. The additional heat continues to melt the underlying permafrost causing it to collapse and increasing the size of the pond. This positive feedback further degrades the permafrost.

Figure $2.7.3a$: Tundra (Courtesy: Torre Jorgenson/NOAA, Source)

Figure $2.7.3b$: Wetland (Courtesy: Torre Jorgenson/NOAA, Source)

As noted earlier in this chapter, carbon dioxide makes up a greater proportion of the atmosphere by volume, but methane absorbs energy much more efficiently. Increased warming at high latitudes may cause an increase in the release of methane from bogs or peatlands. Methane release from organic decomposition in wetlands coupled with carbon dioxide from melting permafrost will drive greenhouse gas levels higher, creating warmer temperatures.

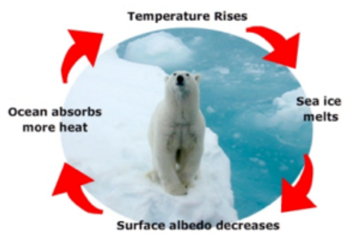


Figure $2.7.4$: Sea Ice - climate change feedback (Image Courtesy USGS)

Changes to the reflectivity of the surface (called the albedo) affects the amount of solar radiation absorb by the Earth. As Arctic sea ice melts it exposes open water which is less reflective (albedo decreases). The reduction in albedo allows more light to be absorbed by the ocean. As the ocean water warms, more heat is added to the air creating a positive feedback and driving Arctic temperatures ever higher. The reduction in sea ice is having a significant impact on arctic ecosystems.

Tipping Points and Environmental Change

Positive feedbacks drive the physical environment towards new physical states. In June of 2008, twenty years after his landmark testimony about global warming, NASA scientist Dr. James Hansen reiterated his warnings before the U.S. Congress. He cited several examples of earth systems reaching or nearing a tipping point. A *tipping level* (*point*) is a level at which "no additional forcing is required for large climate change and impacts." (Hansen, 2008). According to Hansen, a "point of no return" is reached when unstoppable and irreversible (on a practical time scale) occurs. A *tipping element* is a part of the earth system that has a tipping point, e.g., Arctic sea-ice loss, Sahara greening, Boreal forest dieback, permafrost and tundra loss. There is no one tipping point for the earth system as each element has its own point at which irreversible change will occur. For example, geoscientists believe that disintegration of the Greenland ice cap could occur if global temperature rises more than 2^{o}C (3.6^{o}F). For Arctic sea ice, the tipping point could occur with a rise of global mean temperature between .5^{o}C (.9^{o}F) to 2^{o}C (3.6^{o}F). Given the current amount of global warming, Arctic sea ice may have reached its tipping point.

Time is also an important factor in assessing whether a tipping point has been reached or a point of no return. Some, like Josefino Comiso of the NASA Goddard Space Flight Center, feel that the tipping point for perennial Arctic sea ice has already passed (National Geographic, 2007). David Barber, of the University of Manitoba is projecting that the North Pole will be ice free for the first time in history. For example, sea ice may completely disappear from the Arctic Ocean during the summer in a few years. This would represent a new state for the Arctic ocean. But temperature conditions could change in the relatively near future to permit sea ice to reform during the summer.

Assess you basic understanding of the preceding material by "Looking Back: Biogeochemical Cycles and Future Geographies" or skip and continue reading.

2.8: Looking Back

Biogeochemical Cycles and Future Geographies

Exercise 2.8.1

Describe the basic functioning of the hydrologic cycle.

Answer

The hydrologic cycle refers to the movement of water through its various stores within the Earth system. The cycle starts with evaporation from the surface which later condenses into clouds in which precipitation forms. Water falling as precipitation may be intercepted by vegetation or fall directly onto the surface. Water intercepted by plants may ultimately fall to the ground and seep into it. Likewise, water falling directly on the surface may seep into the subsurface or runoff to nearby streams. Water seeping into the ground may become soil water or groundwater. Water in the soil may be taken up by plants then transpired to the air. Groundwater may seep into streams or return to the ocean along along a coast. Water found in streams may also empty into the ocean.

Describe the basic functioning of the nitrogen cycle.

Answer

Nitrogen in the atmosphere must be "fixed" by soil bacteria living in association with the roots of particular plant like legumes, clover, alfalfa, soybeans, peas, peanuts, and beans. Living on nodules around the roots of legumes, the bacteria chemically combine nitrogen in the air to form nitrates (NO_3) and ammonia (NH_3) making it available to plants. Organisms that feed on the plants ingest the nitrogen and release it in organic wastes. Denitrifying bacteria frees the nitrogen from the wastes returning it to the atmosphere.

Describe the basic functioning of the oxygen cycle.

Answer

Photosynthesizing vegetation is largely responsible for oxygen found in the atmosphere. The cycling of oxygen through the Earth system is also accomplished by weathering of carbonate rock. Some atmospheric oxygen is bound to water molecules from plant transpiration and evaporation. Oxygen is also bound to carbon dioxide and released into the atmosphere during animal respiration.

Describe how carbon is cycled through the earth system.

Answer

Plants draw about one quarter of the carbon dioxide out of the atmosphere and photosynthesize it into carbohydrates. Some of the carbohydrate is consumed by plant respiration and the rest is used to build plant tissue and growth. Animals consume the carbohydrates and return carbon dioxide to the atmosphere during respiration. Carbohydrates are oxidized and returned to the atmosphere by soil microorganisms decomposing dead animal and plant remains (soil respiration). Another quarter of atmospheric carbon dioxide is absorbed by the world's oceans through direct air-water exchange. Surface water near the poles is cool and more soluble for carbon dioxide. The cool water sinks and couples to the ocean's thermohaline circulation which transports dense surface water toward the ocean's interior. Marine organisms form tissue containing reduced carbon, and some also form carbonate shells from carbon extracted from the air.

What are tipping points?

Answer

A tipping level (point) is a level at which "no additional forcing is required for large climate change and impacts."

2.9: Review and Additional Resources

Space Shuttle photograph of the Hawaiian Islands, the southernmost part of the long volcanic trail of the "Hawaiian hotspot" Courtesy USGS

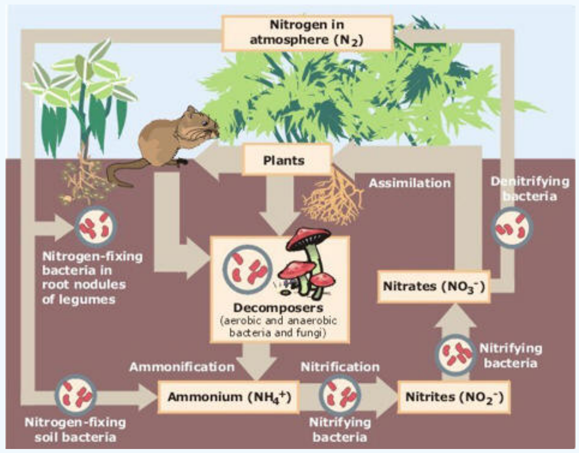
Figure 2.9.1

Assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Then, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts 2.9.1

- **System**
  a collection of interacting objects
- **Open system**
  allow energy and mass to pass across the system boundary.
- **Closed System**
  allows energy but not mass across its system boundary
- **Isolated system**
  allows neither mass or energy to pass across the system boundary
- **Lithosphere**
  the solid Earth
- **Hydrosphere**
  "water sphere"
- **Biosphere**
  all living organisms
- **Atmosphere**
  the gaseous envelope surrounding the Earth
- **Positive feedback**
  a process that aims to amplify or inhibit an action (moves towards extremes)
- **Negative feedback**
  self-regulatory system aiming to stabilize or establish equilibrium
- **Steady-state equilibrium**
  constant flow. constant over time

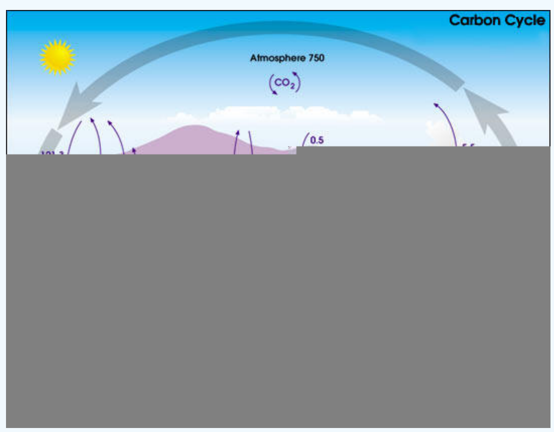
- **Dynamic equilibrium**
  a state of balance between continuing processes
- **Exogenic process**
  processes driven by ***exogenic forces*** that primarily derive their energy from solar radiation.
- **Endogenic process**
  processes that get their energy from ***endogenic forces*** originating deep within the Earth.
- **Nitrogen Cycle**



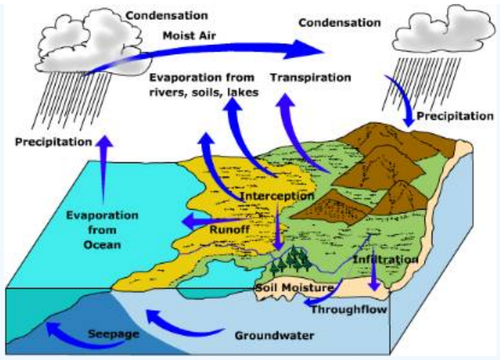
- **Oxygen Cycle**

oxygen cycle

- **Carbon Cycle**



- **Hydrologic Cycle**



the movement of water through its various stores within the Earth system

? Self-Assessment Quiz 2.9.1

1. The Earth system is considered
   A. an open system
   B. a closed system
   C. an isolated system
   D. None of the above
2. Which of the following was pulled inward to create the Earth's core during the later accretion phase?
   A. Magnesium
   B. Silicon
   C. Aluminum
   D. Iron
3. A change in a system property that encourages further system change is called
   A. a positive feedback
   B. a negative feedback
   C. a threshold
   D. an equilibrium trigger
4. Earth's shape is described as
   A. a true sphere.
   B. an oblate ellipsoid.
   C. a disk.
   D. none of the above.
5. The shortest distance between two points on a sphere is
   A. an arc of a great circle.
   B. an arc of a small circle.
   C. an oblate ellipsoid.
   D. a straight line.
6. Which of the following would act to keep a system in a state of equilibrium?
   A. a positive feedback
   B. a negative feedback
   C. a threshold
   D. an equilibrium trigger
7. The equatorial bulge is due to
   A. the gravitation attraction of the Moon.
   B. the gravitation attraction of the Sun.
   C. the centrifugal force of Earth rotation
   D. none of the above.

8. The hydrosphere is an example of
   A. an isolated system
   B. an open system
   C. a closed system
   D. none of the above
9. Though the atmosphere's temperature has varied throughout geologic history, much of the time it has been considered to be
   A. in a state of dynamic equilibrium
   B. in steady-state equilibrium
   C. in a non-equilibrium state
   D. in a geo-equilibrium state
10. Earthquakes are generated by ______ sources of energy.
   A. endogenic
   B. exogenic
   C. both endogenic and exogenic
   D. none of the above

Answer

1. B
2. D
3. A
4. B
5. A
6. B
7. C
8. B
9. A
10. A

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "Science on a Sphere: Earth System Overview" NOAA

Connections: "Dimming the Sun" Nova - air pollution's effect on solar radiation and global warming. Support site and program transcript. (2006)

Physical Geography Today: Real Time Geomagnetism monitoring - USGS

Multimedia

"The Precious Envelope" (Annenberg Media) *The World of Chemistry video series* "The Earth's atmosphere is examined through theories of chemical evolution; ozone depletion and the greenhouse effect are explained. (Material is somewhat dated but still useful.) Go to the The World of Chemistry site and scroll to "The Precious Envelope". One-time, free registration may be required to view film.

"Is Global Warming Nurturing Parasites?" *All Things Considered* June 20, 2002.

Earth Revolution NASA JPL

CHAPTER OVERVIEW

3: The Atmosphere

Figure 3.1: Earth's atmospheric layers revealing the troposphere (orange-red), stratosphere and above, July 31, 2011 (Image courtesy NASA/JSC Gateway to Astronaut Photography of Earth)

The atmosphere that envelops us reflects the complex interactions between the major spheres that comprise the Earth system. The gaseous composition of the atmosphere is being regulated by the biotic elements of the Earth system as well as the geological processes that have shaped our Earth. Volcanic eruptions release vast quantities of gases and particles into the air causing changes to the composition and heat dynamics of the atmosphere. Human activity has also had a profound impact on the composition of the atmosphere locally, regionally, and globally. In this chapter you will investigate the structure and composition of the atmosphere and its influence on physical systems of the Earth.

Learning Objectives

By the end of the chapter you should be able to:

- Draw a diagram of the layers of the atmosphere based on temperature change.
- List and explain the importance of the permanent and variable gases that comprise the atmosphere.
- Explain what the greenhouse effect is and how human activities influence global warming.
- Explain the difference between normal and environmental lapse rate.
- Explain the function of the ionosphere and ozonosphere.

See if you are prepared for this chapter by Getting Ready for Chapter 3: The Atmosphere.

3.1: Atmospheric Composition
3.2: Atmospheric Structure
3.3: Greenhouse Effect
3.4: Future Geographies - Predicting Atmospheric Composition
3.5: Review and Additional Resources
3.6: Getting Ready for Chapter 3

3.1: Atmospheric Composition

Our atmosphere is a dynamic mixture of gases that envelop the Earth. Two gases, nitrogen and oxygen, make up most of the atmosphere by volume. They are indeed important for maintaining life and driving a number of processes near the surface of the Earth. Many of the so called "minor gases" (known here as "variable gases") play an equally important role in the Earth system. These gases include those that have a significant impact on the heat budget and the availability of moisture across the Earth. The atmosphere is not a homogeneous mass of gases, but has a layered structure as defined by vertical temperature changes.

Two broad regions can be identified using air composition as a means to subdivide the atmosphere. The **heterosphere** is the outer most sphere where gases are distributed in distinct layers by gravity according to their atomic weight. Extending from an altitude of 80 km (50 mi), the lightest elements (hydrogen and helium) are found at the outer margins of the atmosphere. The heavier elements (nitrogen and oxygen) are found at the base of the layer.

The **homosphere** lies between the Earth's surface and the heterosphere. Gases are nearly uniformly mixed through this layer even though density decreases with height above the surface. The only exceptions is the "ozone layer" from 19 to 50 km (12 to 31 mi) and near surface variations in water vapor, carbon dioxide and air pollutants.

Constant Gases

Nitrogen, oxygen and argon are called the "**constant gases**" because their concentration has remained virtually the same for much of recent earth history. *Nitrogen* (78%)is a relatively inert gas produced primarily by volcanic activity. It is an important component of protein in meat, milk, eggs and the tissues of plants, especially grains and members of the pea family. It cannot be ingested directly by organisms but made available to plants, and then to animals, by compounds in the soil. Most atmospheric nitrogen enters the soil by nitrogen-fixing microorganisms.

Oxygen (21%) is important for plant and animal respiratory processes. It is also important to chemical reactions (oxidation) that breakdown rock materials (chemical weathering). Without oxygen, things cannot burn either. Free oxygen in the atmosphere is a product of plant photosynthesis. Plants take up carbon dioxide and in the process of photosynthesis release oxygen.

Argon (0.93%) is a colorless, odorless relatively inert gas, the reason it use to electric light bulbs, fluorescent tubes. It is used to form inert atmosphere for arc welding, and growing semiconductor crystals.

Variable Gases

The so called "**variable** gases" are those present in small and variable amounts. These include carbon dioxide, methane, ozone, water vapor, and particulates among others. Even though they represent a tiny portion of the atmosphere as a whole, they exert a great control over our environment.

Carbon dioxide

Carbon dioxide(CO_2) makes up only 0.036% of the atmosphere by volume. Carbon dioxide is essential to photosynthetic processes of plants. Huge quantities of carbon are stored in plant tissue, deposits of coal, peat, oil, and gas. Carbon dioxide is taken in by plants and during photosynthesis is combined with water and energy to form oxygen and carbohydrates. The stored carbohydrates are used to fuel plant respiration and growth. Carbon is also stored in limestone rocks that have formed by the compaction of carbonate-rich shells of ocean life. Because vegetation takes in so much carbon dioxide, we often refer to plants as a "sink" for it.

Carbon dioxide in the atmosphere varies throughout the year, decreasing slightly during the summer as plants leaf out, and then increases during the winter as plants go dormant and photosynthesis decreases. The zigzag pattern of carbon dioxide measurements taken at Mauna Loa, Hawaii in Figure $3.1.1$ below illustrates this seasonality.

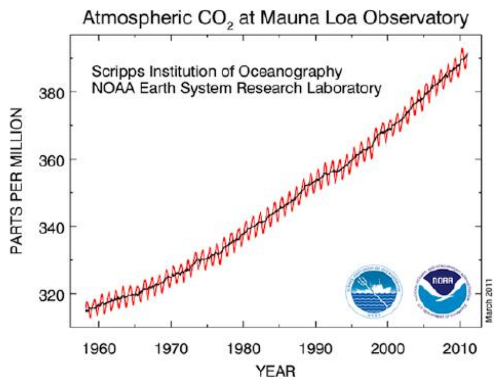


Figure 3.1.1: Temporal Variation of Carbon Dioxide (Source: NOAA ESRL)

The seasonal changes in the geography of uptake and release of carbon dioxide during 2004 is shown in Figure 3.1.2 by NOAA's CarbonTracker. The black and white dots are locations where CO_2 data is collected. A computer model based on this data and a knowledge of surface sources and sinks generates the patterns for the entire globe. Again, the large season to season variation is due to plant life. Blue colors over the northern hemisphere during July in the midlatitudes result from forests and crops soaking up large quantities of CO_2. Intense red areas of CO_2 release during July, August, and September in the southern hemisphere is largely due to biomass burning. Some burning is natural, such as the dry savanna grasses ignited by lightning strikes. Most is due to people burning fields in preparation for planting, or burning of forests for new agricultural land.

Video: NOAA's Carbon Tracker (Courtesy NOAA Earth System Research Laboratory)

Methane

Methane (CH_4) is a greenhouse gas contributing to about 18% of global warming and has been on the rise over the last several decades. Though methane makes up far less of the atmosphere (.0002%) than carbon dioxide, it is 20 times more potent than CO_2 as a greenhouse gas. Methane is a product of the decomposition of organic matter, with major natural sources being that which occurs from wetlands, termites, the oceans, and hydrates.

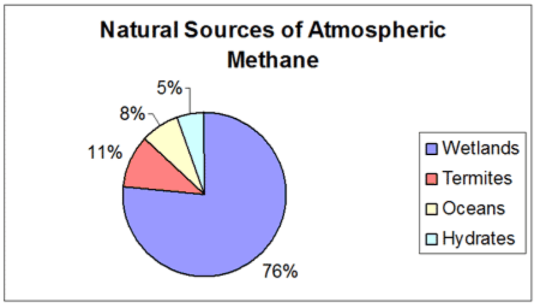


Figure 3.1.2: Natural Sources of Methane (Courtesy US EPA: Source)

A major source of methane is from termites. Termites eat wood and produce methane as a result of the breakdown of cellulose in their digestive tracts. They are thought to be responsible for 11% of the methane in the atmosphere (some estimates are as high as 20% - 40%). The clearing of the rain forests greatly impacts termite populations and in turn the methane content of the atmosphere. When a patch of rain forest is cleared, termite populations explode due to the ample food source that is left behind.

Figure 3.1.3: Transplanting Rice in India (Source: G. Bizzarri, FAO)

Human activities have contributed to the rise of methane in our atmosphere. Landfills, rice paddy agriculture, natural gas systems, and livestock production appear to be significant contributors of anthropogenic sources of methane.

Ozone

Ozone (O_3) is both beneficial and harmful to life on Earth. Much of the ozone in the atmosphere is found in the stratosphere. Here, ozone absorbs UV light from the Sun preventing it from reaching the surface. Without this blanket, humans would be exposed to serious sun burn and potential risk of skin cancer. Ozone is also found in the lowest layer of the atmosphere, the troposphere. Here ozone can act as an eye and respiratory irritant. Ozone also causes cellular damage inside the leaves of plants causing brown splotches, impairing carbon dioxide uptake and disrupting the photosynthetic apparatus. Such damage can cause economic losses through reduced crop yields. It also damages the carbon "sink" role of vegetation leaving more carbon dioxide in the atmosphere to enhance the greenhouse effect and potential global warming.

Human-produced compounds such as chlorofluorocarbons and halides containing chlorine and bromine destroy ozone, and have disrupted the fragile stratospheric ozone layer over Antarctica and the Arctic. Ozone depletion over Antarctica occurs during the spring when sunlight returns to the South Pole and the temperatures are still very cold.

Video: Exploring Ozone (Courtesy NASAexplorer)

Water Vapor

Water vapor is an extremely important gas found in the atmosphere. It can vary from 4% in the steamy tropics to nearly nonexistent in the cold dry regions of the Antarctic. Water vapor is a good absorber of Earth's outgoing radiation and thus is considered a greenhouse gas. When water vapor is converted to a liquid during condensation, clouds are formed. Clouds are good absorbers of radiation given off by the Earth's surface. The absorption of this energy raises the temperature of the air. But clouds are generally light-colored and hence reflect incoming solar radiation off their tops. The reflected light is sent back to space, never reaching the ground to warm the Earth. Thus clouds can have either a warming or a cooling effect on air temperature. It has been thought that these effects balance one another out but National Public Radio's All Things Considered report suggests that this might not be true, forcing climatologists to rethink the issue.

Particulates and Aerosols

Atmospheric particulates and aerosols are very small particles of solid or liquid suspended in the air. Particulates and aerosols play several important roles in atmospheric processes. Particulate matter includes dust, dirt, soot, smoke, and tiny particles of pollutants. Major natural sources of particulates are volcanoes, fires, wind-blown soil and sand, sea salt, and pollen. Human sources such as factories, power plants, trash incinerators, motor vehicles, and construction activity also contribute particulates to the atmosphere.

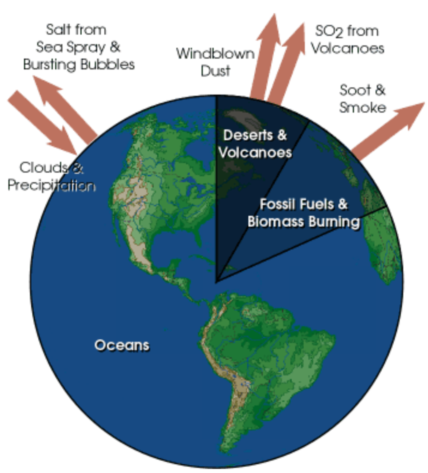


Figure 3.1.4: Sources of particulates and aerosols. (Courtesy NASA Earth Observatory (Source))

Particulates are very effective at altering the energy and moisture balances of the Earth system. Particulates diffuse sunlight reducing the amount and intensity of solar radiation reaching the Earth's surface. The most spectacular sunrises and sunsets are a result of light being refracted from particulates in the atmosphere. Particulates will also reflect sunlight back out to space, never letting it reach the surface. Decreasing significant amounts of incoming solar radiation can cause global temperatures to decrease. The eruption of Mt. Pinatubo in 1991 caused a .5° C decrease in global temperatures. However, particulates can absorb longwave radiation emitted by the Earth, causing the atmosphere to warm as well. Particulates serve as condensation nuclei for water. In order for water to change from a gas to a liquid, a nucleus upon which water vapor can attach itself is nearly always required. Without particulates, little water would condense to form clouds and precipitation.

Figure 3.1.5: Sunset over the Atlantic (Source: NOAA)

NASA scientists using satellite data and computer models found black soot from incomplete combustion may be contributing to changes in sea ice, snow and atmospheric temperatures near the North Pole. They found the timing and location of rising temperatures and loss of sea ice during the end of the 20th century is consistent with a significant rise in human produced aerosols. Their models suggest that one third of the soot comes from South Asia, one third from biomass burning, and the rest from Russia, Europe, and North America. Soot deposited on snow and sea ice decreases the surface reflectivity causing more sunshine to be absorbed. Airborne soot warms the Arctic atmosphere and affects weather patterns and clouds.

Video: Climate Change and Aerosols

Dr. Jim Haywood, Aerosol Research scientist at the Met Office talks about climate change and aerosols.

Assess you understanding of the preceding material by "Looking Back: Atmospheric Composition" or skip and continue reading

? Looking Back - Atmospheric Composition

Assess your understanding of concepts related to this chapter section by answering the questions below before proceeding with this chapter. Click the "Answer" to reveal the correct answer.

Define homosphere and heterosphere

Answer

Homosphere: Sphere that lies between the surface and heterosphere where gases are uniformly mixed. Heterosphere: Outermost "sphere" of the atmosphere where gases are distributed into distinct layers.

List the "permanent (constant)" gases.

Answer

nitrogen, oxygen, argon

Which greenhouse gas is more effective at heating the atmosphere, carbon dioxide or methane?

Answer

Methane

Which gas filters UV light in the stratosphere, carbon dioxide, ozone, or methane?

Answer

Ozone.

Soot increases or decreases reflectivity resulting in melting when deposited on snow?

Answer

Decreases

3.2: Atmospheric Structure

If we examine the vertical structure the atmosphere in different places we will find it varies in height, being lowest at the poles and highest at the equator. The varying height is due to the spatial variation in heating of the Earth's surface and thus the atmosphere above. This fact makes it difficult to define exact heights for the layers of the atmosphere. The solution is to subdivide the atmosphere not on the basis of fixed heights, but on temperature change. Figure 3.2.1 illustrates the way in which the atmosphere is divided using temperature change as the primary criterion.

Troposphere and Tropopause

The ***troposphere*** is the layer closest to the Earth's surface. The graph of temperature change indicates that air temperature decreases with an increase in altitude through this layer. Air temperature normally decreases with height above the surface because the primary source of heating for the air is the Earth. The rate of change in temperature with altitude is called the ***environmental lapse rate of temperature (ELR)*** The ELR varies from day-to-day at a place, and from place to place on any given day. The ***normal lapse rate of temperature*** is the average value of the ELR, 0.65^{o} C /100 meters. That is, at any particular place and on any given day the actual ELR may be larger or smaller, but on average has a value of 0.65^{o} C /100 m. So if I went outside today it could be 0.62^{o} C /100 m and then tomorrow it might be 0.68^{o} C /100 m. The ELR also varies from place to place on a given day. That is, at Chicago, Illinois it might be 0.65^{o} C /100 m and on the same day it could be 0.62^{o} C /100 m over London, England.

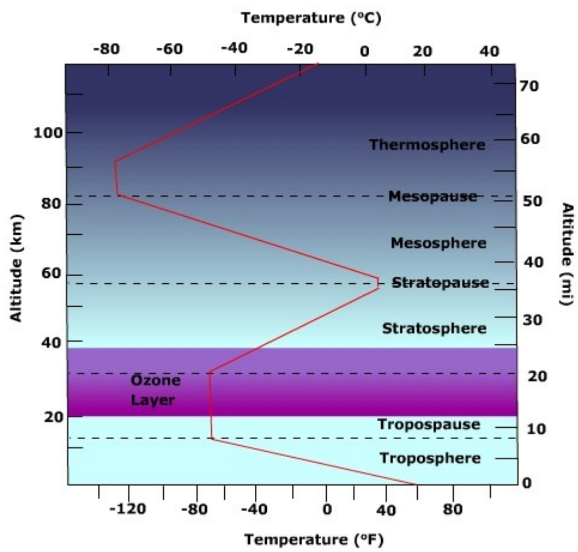


Figure 3.2.1: Structure of the Atmosphere

Under the right conditions, the air temperature may actually increase with an increase in altitude above the Earth. When this occurs we are experiencing an ***inverted lapse rate of temperature***, or simply an ***inversion***. Shallow surface inversions are typical over the snow covered surfaces of subarctic and polar regions, and sometimes occur when high pressure cells inhabit a region.

The ***tropopause*** lies above the troposphere. Here the temperature tends to stay the same with increasing height. The tropopause acts as a "lid" on the troposphere preventing air from rising upwards into the stratosphere.

Stratosphere

Above the tropopause lies the stratosphere. Note in Figure 3.2.1 that the temperature of the air does not change with an increase in elevation. If a layer of air exhibits no change in temperature with an increase in elevation we typically refer to it as an *isothermal layer* i.e. layer of equal temperature. Through most of the stratosphere the air temperature increases with an increase in elevation creating a temperature inversion. The inverted lapse rate of temperature is due to the presence of stratospheric ozone which is a good absorber of ultra-violet radiation emitted by the Sun. As energy penetrates downward, less and less is available for lower layers and hence the temperature decreases toward the bottom of the stratosphere. The downward reduction of heat transfer due to solar energy absorption from above is offset by the heat given off by the Earth creating the isothermal layer at the bottom of the stratosphere. At the top of the stratosphere lies the stratopause. Like the tropopause, the stratopause is an isothermal layer that separates the stratosphere from the mesosphere.

Mesosphere and beyond

It is the properties of the previously discussed layers that affects most of what we study in physical geography. Processes acting in layers above the stratopause have relatively little impact on our elemental study of Earth near-surface processes. In the **mesosphere** air temperatures begin to decrease with increasing altitude. 99.9 percent of the gases that comprise the atmosphere lie below this level. The air of the mesosphere is thus extremely thin and air pressure very small. With very few molecules like ozone capable of absorbing solar radiation, especially near the top of the layer, the air temperature decreases with height. The mesopause separates the mesosphere from the thermosphere above.

Figure 3.2.1 shows air temperature increasing with increasing altitude in the **thermosphere**. Here, energetic oxygen molecules absorb incoming solar radiation raising the layer's temperature. Because solar activity determines the temperature of the layer, temperature at the top of the layer is warmer than that near the bottom of the thermosphere. Even though the temperatures are quite high in the thermosphere, the heat content of the layer is very low due the low density of air at this level.

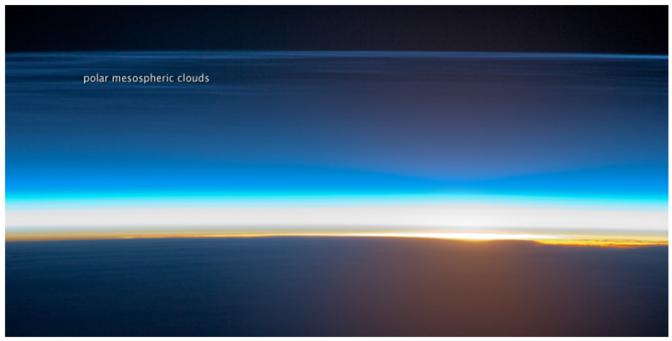


Figure 3.2.2: Polar Mesospheric clouds. (Courtesy NASA EOS, Source)

Polar mesospheric clouds are also known as noctilucent or "night-shining" clouds as they are usually seen at twilight. These clouds form at high latitudes and high altitudes (76 - 85 kilometers) near the boundary of the mesosphere and thermosphere.

Functional layers

Two layers, the **ionosphere** and ozonosphere are identified when using function as the criterion for subdivision. The ionosphere is not really a layer of the atmosphere, but an electrified field of ions and free electrons. The ionosphere absorbs cosmic rays, gamma rays, X-rays, and shorter wavelengths of ultraviolet radiation. The spectacular display of auroral lights is generally found in this region.

The **ozonosphere**, also called the "ozone layer", is the concentrated layer of ozone found in the stratosphere. Ozone (O_3) absorbs ultraviolet light between 0.1 - 0.3μm. The ozone layer absorbs 97 - 99% of the Sun's ultraviolet light that can be harmful to life on earth. Though relatively constant through millions of years, seasonal fluctuations of ozone especially over the Arctic and Antarctic are common. The ozone layer is thinner at the equator and thicker at the poles. Ozone concentrations are highest in the spring and generally lowest during the autumn.

Video: Reveal Earth's Atmosphere (Courtesy National Geographic)

Assess your basic understanding of the preceding material by "Looking Back at Atmospheric Structure" or skip and continue reading.

Looking Back at Atmospheric Structure 3.2.1

Explain what normally happens to air temperature as one moves upward through the troposphere.

Answer

Temperature decreases.

Define the normal and environmental lapse rate of temperature.

Answer

The normal lapse rate of temperature is the average decrease in temperature with an increase in elevation. The environmental lapse rate is the decrease in temperature with an increase in elevation at any given time.

What happens to air temperature as one moves upward through the stratosphere?

Answer

Generally increases.

Define "temperature inversion".

Answer

A temperature inversion is a situation in which air temperature increases with increasing elevation.

Describe the "functional layers" of the atmosphere and explain what do they do?

Answer

The ionosphere absorbs cosmic rays, gamma rays, X-rays, and shorter wavelengths of ultraviolet radiation. The ozonosphere absorbs 97% of the Sun's ultraviolet light that can be harmful to life on earth.

3.3: Greenhouse Effect

Carbon dioxide and methane are two of a number of so called "greenhouse gases". Greenhouses gases are responsible for the relatively warm temperature of the atmosphere. Without the blanket of greenhouse gases, the Earth would be a frozen ball of ice. The gases of our atmosphere are known as "selective absorbers" of radiant energy. That is, a particular gas absorbs and emits energy well at some wavelengths but not at others. Solar radiation (shortwave) passes through most of the atmospheric gases without being absorbed to a significant extent. However, longwave radiation emitted from the Earth's surface and directed toward the sky is readily absorbed by greenhouse gases. When absorbed, the temperature of the atmosphere increases. Some of this absorbed energy is emitted to space while some is emitted back towards the Earth. This is the basis for the **greenhouse effect**.

Though all atmospheric scientists agree there is a greenhouse effect, not all agree on the impact that human beings are having on it. In particular, many cannot agree that the warming we are currently experiencing is a product of human activities. Analysis of ice cores has shown a significant variation in the carbon dioxide content of our atmosphere which has affected global air temperatures since the great ice sheets marched across warmer periods associated with higher greenhouse gases and cooler with less. But for the last several decades, greenhouse house concentrations are up and the earth's atmosphere has been warming. The consensus is that human contributions of greenhouse gases are the reason.

3.4: Future Geographies - Predicting Atmospheric Composition

It is undeniable that the climate of Earth has seen numerous changes over time. Our current climate is undergoing changes in unprecedented ways for modern times. Measurements of atmospheric temperature show a clear upward trend while many regions are gripped in years-long drought. Most geoscientists concur that the current warming trend is related to human activities. Some disagree and suggest it is a natural fluctuation similar to that which the earth has experienced in the past.

To understand how climate has changed in the past, and more importantly, what will happen in the future, geoscientists must rely on models. Models are merely representations of the real world and are constrained by our understanding of earth processes. Scientist must make assumptions to fill in gaps where understanding or data is lacking. As a result, the output of a model inherently has a degree of uncertainty associated with it.

Predicting the changes in gaseous composition of the atmosphere is a difficult exercise. How the gaseous composition of the atmosphere will change in the future depends a great deal on the impact of human activities and our ability to control emissions. In addition to changes brought about by humans, increasing temperatures as a result of an enhanced greenhouse effect will impact the concentration of various gases in earth's atmosphere.

Prediction versus Projection

Uncertainty over how population will grow, economies develop, and technological advancement makes it difficult at best to predict the future composition of the atmosphere. Bodies like the Intergovernmental Panel on Climate Change (IPCC) make projections based on models. Though quite sophisticated, models of earth systems are constrained by our knowledge of environmental processes. The unpredictability of human advancement and the state of our understanding of climate dynamics leaves uncertainty in these projections. Thus geoscientists use statistics and their expert judgment for factors that elude quantification to determine the likelihood for the outcome of their model projections.

Future concentrations will not necessarily be geographically defined due to the fluid nature of the atmosphere. The exception may be water vapor, due to the unequal distribution of available water to evaporate into the air. However, the sources of future contributions to the gaseous composition of the atmosphere are certainly geographically distributed, especially those from human activities. The race toward economic development will shift the largest contributors to the developing world.

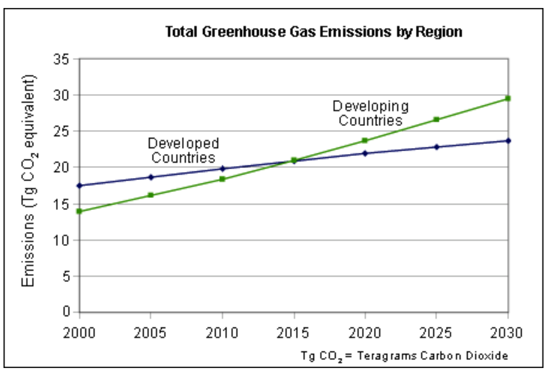


Figure 3.4.1: Greenhouse emissions by region (Source: EPA)

IPCC Storylines and Scenarios

The Intergovernmental Panel on Climate Change (IPCC) is recognized by many as the foremost authority on climate change. Their most recent analysis of climate change (2007) utilized four different "storylines" that represent the range of driving forces and emission behind climate change. Each storyline posed several different scenarios, grouped as "families" to examine the outcome of models that use similar assumptions about the driving forces, and some that do not.

Table 3.4.1 IPCC Storylines

A1 Storyline (Homogenous World - market focus)	**A2 Storyline** (Heterogeneous World - market focus)	**B1 Storyline** (Homogeneous World - environmental focus)	**B2 Storyline** (Heterogeneous World - environmental focus)

• Very rapid economic growth. • Substantial reduction in regional per-capita income. • Global population peaks mid-century then declines. • Rapid introduction of new, and efficient technology.	• Emphasis on self-reliance & preserving local identities. • Slow per-capita economic growth and technological change. • Continuously increasing global population.	• Global population peaks mid-century then declines. • Rapid change to information & service economy. • Reduction in material intensity. • Introduction of resource-efficient and clean technologies.	• Continuously increasing global population, slower than A2. • Less rapid creation of new energy technologies than B1 & A1. • Local and regional emphasis on environmental and social justice issues.

Projected increases in greenhouse gases

Projected increases from the four story lines are shown in Figure 3.4.2. All but the A2 show an increase in CO_2 followed by a decrease or leveling in CO_2 emissions the coming century. The A2 scenario show an increasing rate of emissions through time. In some sense, this is the "worst case scenario" with a continuously increasing population using more resources, slow technological change, and lack of global unity in tackling these issues.

At the opposite end of the spectrum is the "utopian" B1 scenario. The B1 scenario assumes low fertility with low mortality and central migration rates, global population peaks mid-century, then continually decreases toward 2100. Resource-efficient and renewable technology adoption diffuses rapidly through the world economy. The greening of material production and energy use helps lower carbon dioxide emissions from industry and transportation.

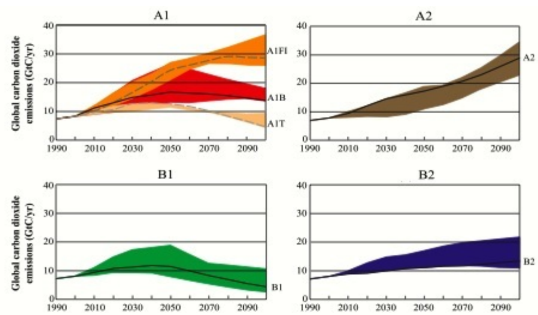


Figure 3.4.2: Projected carbon dioxide emissions (Source: IPCC)

The A2 and B1 scenarios represent two ends of the spectrum of possible outcomes. But in both cases, the importance of global population change and attendant demand for resources has a strong impact on emissions of greenhouse gases and stress on the physical environment. It may be just as likely for the changes in the composition of the atmosphere to lie somewhere between these extremes. The A1 market-driven scenarios of decreasing population growth coupled with rapid expansion of technology can yield reductions of greenhouse gases as well.

The IPCC does not suggest the likelihood of any particular outcome. They should be seen for what they are, scenarios, what could happen given particular conditions. Thus they serve policy makers with a kind of roadmap to the future, however uncertain it might be.

Video: Projecting Future Climate Change. The late Professor Stephen Schneider explains the factors that influence uncertainty in predicting future climate. (Source)

Assess you understanding of the preceding material by Looking Back at the Greenhouse Effect, and Future Geographies or skip and continue reading.

? Looking Back at the Greenhouse Effect and Future Geographies 3.4.1

Describe how the greenhouse effect works.

Answer

Gases such as carbon dioxide and methane absorb radiation emitted by the earth and warm, raising the temperature of the air.

List the four IPCC Scenarios and their world type/focus.

Answer

A1- Homogenous world - market focus. A2 - Heterogeneous world - market focus. B1 - Homogenous world - environmental focus. B2 - Heterogeneous world - environmental market focus.

3.5: Review and Additional Resources

Review

Space Shuttle photograph of the Hawaiian Islands, the southernmost part of the long volcanic trail of the "Hawaiian hotspot" Courtesy USGS

Figure 3.5.1

Assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

? Important Terms and Concepts

- **Heterosphere**
  the outer most sphere where gases are distributed in distinct layers by gravity according to their atomic weight
- **Homosphere**
  lies between the Earth's surface and the heterosphere. Gases are nearly uniformly mixed through this layer even though density decreases with height above the surface
- **Constant Gases**
  Nitrogen, oxygen and argon are called the "constant gases" because their concentration has remained virtually the same for much of recent earth history
- **Variable Gases**
  those present in small and variable amounts. These include carbon dioxide, methane, ozone, water vapor, and particulates among others.
- **Ozone**
  O_3 is both beneficial and harmful to life on Earth
- **Carbon dioxide**
  (CO_2) makes up only .036% of the atmosphere by volume. Carbon dioxide is essential to photosynthetic processes of plants.
- **Methane**
  (CH_4) is a greenhouse gas contributing to about 18% of global warming and has been on the rise over the last several decades. Methane is a product of the decomposition of organic matter, with major natural sources being that which occurs from wetlands, termites, the oceans, and hydrates.
- **Particulates (and aerosols)**
  very small particles of solid or liquid suspended in the air

- **Water Vapor**
  an extremely important gas found in the atmosphere.
- **Environmental lapse rate (ELR)**
  The rate of change in temperature with altitude
- **Normal lapse rate of temperature**
  the average value of the ELR, .65^{o} C /100 meters
- **Inverted lapse rate of temperature (inversion)**
  when the air temperature actually increase with an increase in altitude above the Earth
- **Troposphere**
  the layer closest to the Earth's surface
- **Tropopause**
  lies above the troposphere. Here the temperature tends to stay the same with increasing height.
- **Stratosphere**
  Above the tropopause lies the stratosphere. Through most of the stratosphere the air temperature increases with an increase in elevation creating a temperature inversion
- **Mesosphere**
  air temperatures begin to decrease with increasing altitude
- **Thermosphere**
  above the mesosphere. air temperature increasing with increasing altitude
- **Ionosphere**
  not really a layer of the atmosphere, but an electrified field of ions and free electrons
- **Ozonosphere**
  also called the "ozone layer", is the concentrated layer of ozone found in the stratosphere
- **Greenhouse effect**
  longwave radiation emitted from the Earth's surface and directed toward the sky is readily absorbed by greenhouse gases. When absorbed, the temperature of the atmosphere increases. Some of this absorbed energy is emitted to space while some is emitted back towards the Earth.

? Review Questions 3.5.1

Explain how the greenhouse effect works.

Answer

Shortwave radiation penetrates through the atmosphere and is absorbed by the surface. The surface radiates longwave radiation toward the atmosphere. The atmosphere absorbs this energy and radiates it back down toward the surface. Increasing "greenhouse gasses" though human activities traps more radiation causing an increase in near-surface temperatures.

Briefly describe how temperature changes from the surface up to the mesosphere.

Answer

Troposphere: temperature decreases with an increase in elevation. Tropopause: no change in temperature with an increase in elevation. Stratosphere: temperature increases with an increase in elevation. Stratopause: no change in temperature with an increase in elevation.

What impact do particulates have on the atmosphere?

Answer

Particulates can reflect incoming shortwave and cause atmospheric cooling. They are also good absorbers of terrestrial earth radiation which would cause atmospheric warming. Particulates serve as condensation nuclei.

What is an inversion?

Answer

An inversion occurs when air temperatures increase with an increase in elevation. Inversions can occur under the right conditions in the troposphere. The stratosphere is noted for its inversion.

What is the environmental lapse rate of temperature?

Answer

The environmental lapse rate of temperature is the decrease in temperature with an increase in elevation through the troposphere. The temperature decreases with elevation because the earth is the immediate source of energy to heat the air.

How do humans contribute to global warming?

Answer

Fossil fuel burning (e.g., emissions from transportation and energy generation), deforestation, cattle farming and rice production to name a few.

What impact does ozone at the surface have on humans?

Answer

Ozone is an eye irritant and causes shortness of breath due to constricting air ways in the throat and lungs.

Explain why temperatures increase with height through the stratosphere.

Answer

Because ozone absorbs incoming solar radiation. The top of the stratosphere is hotter because its closer to the source of shortwave radiation. An ever diminishing amount of shortwave radiation as it passes through the stratosphere causes the temperature to decrease toward the bottom.

Describe how clouds impact climate.

Answer

Clouds can reflect solar radiation off the top of the cloud causing atmospheric cooling. They are good absorbers of terrestrial earth radiation which would cause atmospheric warming. The role of clouds in climate change is one of the most vexing problems to climate scientists.

Where does methane came from and what role does it play in the atmosphere?

Answer

Methane is a product of the decomposition of organic matter, with major natural sources being that which occurs in wetlands, melting permafrost and as a by-product termite actvities. Methane is a greenhouse gas.

? Self-assessment Quiz 3.5.1

1. Free _____ is a product of plant photosynthesis.
   A. methane
   B. carbon dioxide
   C. oxygen
   D. nitrogen
2. The concentration of carbon dioxide in the atmosphere
   A. is generally higher during the winter.
   B. has increased in the last 100 years
   C. is a greenhouse gas
   D. all the above
3. Greenhouse gases
   A. are good absorbers of solar (shortwave) radiation.
   B. are good absorbers of longwave radiation emitted by the Earth.
   C. absorb shortwave and longwave radiation equally well.
   D. absorb neither shortwave or longwave radiation.
4. Temperatures tend to _______ through much of the stratosphere.
   A. increase with an increase in elevation
   B. decrease with and increase in elevation
   C. stay the same with an increase in elevation
   D. None of the above
5. Clouds are good absorbers of
   A. insolation
   B. longwave radiation emitted by the earth
   C. UV light
   D. none of the above
6. Termites are thought to be a source of
   A. carbon dioxide.
   B. ozone.
   C. methane.
   D. none of the above.
7. Which of the following is considered a "permanent gas"?
   A. Carbon dioxide
   B. Methane
   C. Ozone
   D. None of the above
8. Particulates
   A. serve as condensation nuclei.
   B. can cause atmospheric cooling.
   C. can cause atmospheric warming
   D. can do all the above.
9. Most of the ozone found in the atmosphere is found in the
   A. troposphere.
   B. stratosphere.
   C. mesosphere.
   D. thermosphere.
10. An inversion
   A. is where temperatures increase with increasing altitude.

B. is where temperatures decrease with increasing altitude.
C. is where temperatures stay the same with increasing altitude.
D. is where temperatures increase with decreasing altitude.

Answer

1. C
2. D
3. B
4. A
5. B
6. C
7. D
8. D
9. B
10. A

Additional Resources

Use these resources to further explore the world of geography

- **Focus on The Physical Environment:** "The Carbon Cycle. NASA Earth Observatory" Elizabeth Kolbert, staff writer, The New Yorker WGBH Forum
- **Physical Geography Today:** AIRNow - real time air quality data (US EPA)
- **World of Change:** Antarctic Ozone Hole

Multimedia

"The Precious Envelope" (Annenberg/CPB) *The World of Chemistry video series* "The Earth's atmosphere is examined through theories of chemical evolution; ozone depletion and the greenhouse effect are explained. (Material is somewhat dated but still useful.)

Go to the The World of Chemistry site and scroll to "The Precious Envelope". One-time free registration may be required.

The Ozone Layer: Closing the Gap (NASA, 2019) "In the 1980s, scientists began to realize that ozone-depleting chemicals, such as chlorofluorocarbon (CFCs), were creating a thin spot—a hole—in the ozone layer over Antarctica. Through an international effort to decrease the use of CFCs, the ozone layer is starting to mend, and scientists believe it should mostly recover by the middle of the 21st century. This series of satellite images shows the ozone hole on the day of its maximum depth from 1979 through 2018."

Readings

"The Ozone We Breathe" NASA Earth Observatory

Why monitor air quality? (NASA)

3.6: Getting Ready for Chapter 3

Chapter 2 set the stage for a comprehensive survey of the earth system. We'll begin with the atmosphere, the subject of chapter 3. The structure and composition of our present day atmosphere has been relatively stable for millions of years. During the depths of the ice ages, the carbon dioxide content of the atmosphere especially decreased which helped keep air temperatures cool. But levels of oxygen have remained fairly constant, even through the ice ages for the last 50 million years or so. But, the composition of the atmosphere especially greenhouse gases like carbon dioxide and methane are changing at rates much greater than they did in the past. These changes are in part due to natural forces, but increasingly are due to the activities of humans.

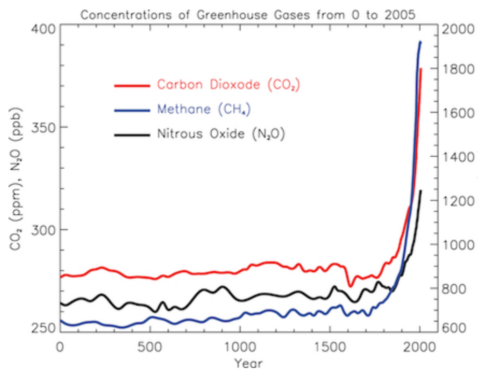


Figure 3.6.1: Concentrations of Greenhouse Gases from 0 to 2005 (Courtesy IPCC)

Concentrations of Greenhouse Gases from 0 to 2005
(Courtesy IPCC)

In Chapter 3 we'll examine the composition of the atmosphere and the importance of particular gases to the functioning of the earth system. We'll look out the structure of the atmosphere and how scientists have subdivided it based on vertical temperature patterns and the function of the different atmospheric layers. We'll also peek into the future to see what changes we can expect in our atmosphere as it changes in response to the activities of an ever-increasing population and an evolving world economy.

What you should already know ...

Chapter 3 explores the the composition and structure of the atmosphere. The atmosphere interacts with the other subsystems of the earth system. Have a good understanding of the atmosphere as a system. Biogeochemical cycles are the means whereby substances are transformed and transported through the earth system. The composition of the atmosphere is directly influenced by these cycles.

Exercise 3.6.1

1. The atmosphere is considered
   A. an open system
   B. a closed system
   C. an isolated system
   D. None of the above
2. The early atmosphere was a product of _____.
   A. accretion
   B. tectonic plate movement
   C. outgassing
   D. none of the above
3. A change in a system property that encourages further system change is called
   A. a positive feedback
   B. a negative feedback
   C. a threshold
   D. an equilibrium trigger
4. Evaporation transfers _____ from the hydrosphere to the atmosphere.
   A. heat

B. mass
C. heat and mass
D. none of the above

5. ______ is a feature of systems where no additional forcing is required for a large climate change and impact to occur.

A. A positive feedback
B. A tipping point
C. A negative feedback
D. None of the above

6. Which of the following would act to keep a system in a state of equilibrium?

A. a positive feedback
B. a negative feedback
C. a threshold
D. an equilibrium trigger

7. _______ is responsible for most of the oxygen found in the atmosphere.

A. Transpiration
B. Photosynthesizing vegetation
C. Rock weathering
D. Animal respiration

8. ______ is responsible for most of the water vapor entering the atmosphere.

A. Plant transpiration
B. Precipitation
C. Evaporation of water from land
D. Evaporation of water from the oceans

9. Though the atmosphere's temperature has varied throughout geologic history, much of the time it has been considered to be

A. in a state of dynamic equilibrium
B. in steady-state equilibrium
C. in a non-equilibrium state
D. in a geo-equilibrium state

10. The heat to raise the temperature of the air ultimately comes from ______ sources of energy.

A. endogenic
B. exogenic
C. both endogenic and exogenic
D. none of the above

Answer

1. A
2. C
3. A
4. C
5. B
6. B
7. B
8. D
9. A
10. B

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous chapter.

If you scored less than 70% you should consider reviewing the previous chapter and seeking help from your instructor.

CHAPTER OVERVIEW

4: Energy and Radiation

Figure 4.1: Sunrise over South America (Courtesy NASA)

Solar radiation is the source of energy that drives most environmental processes acting at the surface of the Earth. The spatial variation of energy affects the spatial variation of temperature, wind, and moisture which determine the geography of soils, vegetation, climate and landforms. The awesome power of hurricanes is driven by the heating of water and subsequent heat release during condensation. Unequal heating of the Earth's surface creates wind that heaps sand into great dunes.

The animation of net radiation below shows the amount of energy absorbed or lost by the earth. Orange to red areas are those where the earth is gaining energy, and the blue regions where energy is being lost. Examine the animation by clicking the play button and describe what you see. Use the slider to control the timing yourself. What patterns do you see?

The most noticeable pattern revealed is the seasonal change in where regions of positive and negative net radiation occurs. Regions of positive net radiation and energy gain occur during the summer months, and thus shifts from northern to southern hemisphere. Large positive net radiation appear in the tropics, large negative at the poles. Why does this spatial and temporal pattern in net radiation occur and what are the implications? Will this pattern change in the future?

Learning Objectives

By the end of the chapter you should be able to:

- Compare and contrast energy, heat and temperature.
- Define sun angle, solar declination, day length, and describe their geographical variation through the seasons.
- Calculate the noon sun angle for any latitude on the solstices and equinoxes.
- Explain the global pattern of insolation, net radiation, sensible heat and latent heat.

See if you are prepared for this chapter by "Getting Ready for Chapter 4: Energy and Radiation".

4.1: Energy and Heat
- 4.1.1: The Nature of Electromagnetic Radiation
- 4.1.2: Radiation as Particles
- 4.1.3: Selective Absorption by the Atmosphere

4.2: Insolation

4.3: Radiation and Energy Balance of the Earth System
- 4.3.1: The Radiation Balance
- 4.3.2: The Energy Balance

4.4: Global Patterns of Insolation, Net radiation, and Heat

4.5: Getting Ready for Chapter 4

4.6: Global Patterns of Sensible and Latent Heat Transfer

4.7: Future Geographies - Radiative Forcing and the Earth's Heat Balance

4.8: Review and Additional Online Resources

SECTION OVERVIEW

4.1: Energy and Heat

Energy is the ability to do work on matter. The work done is manifested in a variety of ways. Matter can be pushed, pulled, or lifted over distance when energy is applied. In other words, work done on matter implies a change of position or movement. ***Potential energy*** is the energy of position. A block of rock attached to a high cliff face has substantial potential energy due to its position above the ground. When it breaks away from the cliff and falls to the surface potential energy is converted into ***kinetic energy*** of motion. When the rock hits the ground, kinetic energy is converted into work when it dislodges surface material.

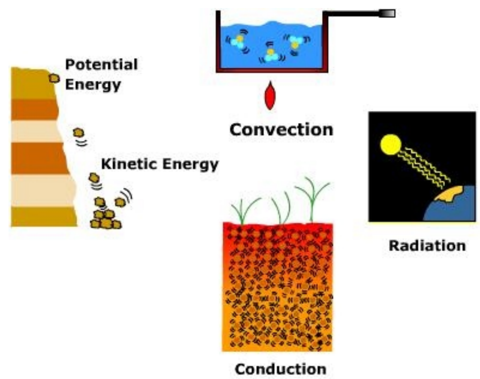


Figure 4.1.1: Forms of Energy

Heat or, *thermal energy* is the total energy associated with random atomic and molecular motions of a substance. Heat is transferred in three ways. **Radiation** is the transfer of energy via electromagnetic waves. Radiation does not need an intervening medium to pass heat energy from the emitter to the absorber. When radiation from the Sun is absorbed by the Earth it does work by setting molecules in motion and raising their kinetic energy level. In a solid, the molecules may vibrate more rapidly and collide with one another and transfer heat from warmer to colder portions of the mass by **conduction**. Though conduction is typically thought of occurring within a solid, it can occur between a solid and a fluid. When air, a fluid, comes in contact with the ground, a solid, heat can be transferred through molecular collisions. In fluids like air and water, heat is transferred by the circulation of molecules via the process of **convection**. Convection implies a vertical transfer of heat, like that which is occurs in a heated pot of water. As water warms it circulates to the surface. The same is true for air. When air is heated by the earth's surface it too circulates upward. While convection is applied to vertical transfer of heat, **advection** is a term that is applied to the horizontal transfer of heat by the wind.

Don't confuse temperature and heat, they are not the same thing. **Temperature** is a measure of the average kinetic energy level of a substance, in other words, the degree of hotness or coldness. Heat is the *total energy* associated with the motion of molecules while temperature is the *average energy* level. A boiling pan of water has a higher temperature than a tepid bathtub of water, but the tub contains more heat because there is more mass.

The **calorie** is a unit of measurement for heat. A calorie is the amount of heat required to raise the temperature of one gram of water through $1^{o}C$. Energy is expressed in terms of **joules**. One joule is the equivalent of one watt of power radiated or dissipated for one second. **Specific heat** is the heat required to raise the temperature of one unit substance (e.g., gram) through a particular temperature interval ($1^{o}C$, for example). The specific heat of water is 1 calorie/gram °C = 4.186 joule/gram °C which is higher than any other common substance on Earth. This is one reason why large bodies of water play such an important role in the heat budget of the Earth system. Radiation is often measured in watts per meter^2 or langleys per minute.

4.1.1: The Nature of Electromagnetic Radiation

4.1.2: Radiation as Particles

4.1.3: Selective Absorption by the Atmosphere

4.1.1: The Nature of Electromagnetic Radiation

Unlike convection or conduction, heat transfer by electromagnetic radiation requires no intervening medium to transmit it. Electromagnetic radiation travels through space in the form of waves. It's hard to imagine radiation moving as waves through empty space without a medium to transfer the wave form. The waves created when you drop a rock into a pool require molecules of water to propagate them, but not so for radiation.

Energy as electromagnetic waves

The quantity of energy carried in a wave is associated with the height or **amplitude** of the wave. Everything else being equal, the amount of energy carried in a wave is directly proportional to the amplitude of the wave. The type or "quality" of radiation depends on the ***wavelength***, the distance between successive crests. The greater the distance between wave crests, the longer the wavelength.

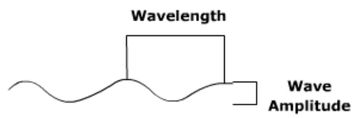


Figure 4.1.1.1: Wave properties

Any body that has a temperature is emitting electromagnetic radiation. There are an infinite number of wavelengths that make up the electromagnetic spectrum though we group them into a number of bands (Figure 4.1.1.2). The shortest wavelengths fall into the gamma rays, the electromagnetic radiation we can see with our eyes and processed by our brains falls into the visible band, and radio waves are comprised of the longest wavelengths.

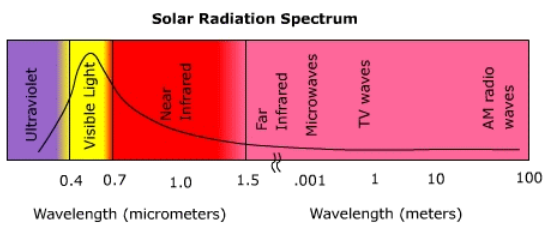


Figure 4.1.1.2: Copy and Paste Caption here. (Copyright; author via source)

The maximum wavelength at which a body emits radiation depends on its temperature. Wein's (pronounced "weens") Law states that the peak wavelength of radiation emission is inversely related to the temperature of the emitting body. That is, the hotter the body, the shorter the wavelength of peak emission. Figure 4.1.1.3 shows the wavelengths over which the Sun and Earth emit most of their radiation. The Sun being a much hotter body emits most of its radiation in the shortwave end and the Earth in the longwave end of the spectrum. The division between shortwave and longwave radiation occurs at about 3 micrometers.

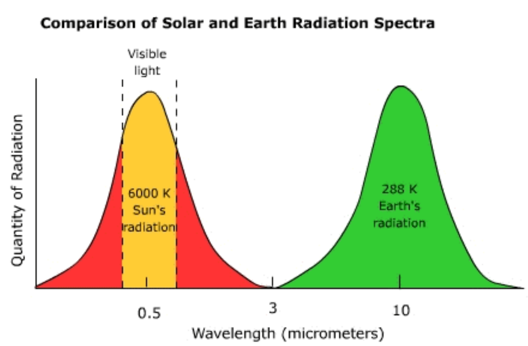


Figure 4.1.1.3: Comparison of solar and earth radiation spectra

4.1.2: Radiation as Particles

Radiation as particles

It's hard to imagine radiation moving as waves through empty space without a medium to transfer the wave form. For instance, the waves created when you drop a rock into a pool of water require molecules of H_2O to propagate them. Though we describe electromagnetic radiation as invisible waves of energy, at the smallest scale it behaves as a particle, like when light is emitted by a single atom or molecule. When energy is given off there is a change in the orbital pattern of the electrons that surround the nucleus of an atom. As the orbit changes, a bundle of energy called a "**photon**" is released. However, particles of light differ from particles of matter: they have no mass, occupy no space, and travel at the speed of light, 2.9998 X 10^8 m s^{-1}. The amount of energy carried by a photon varies inversely with wavelength, the shorter the wavelength, the more energetic the photon.

Learn more about the nature of radiation by "Digging Deeper into the Nature of Radiation: Radiation Laws" or skip and continue reading.

Digging Deeper into the Nature of Radiation: Radiation Laws

In order to understand the processes and explain patterns of weather and climate, it is helpful to dig a bit deeper into a few laws related to energy and radiation.

Stefan-Boltzmann's Law: *The total energy emitted by a black body is proportional the 4th power of its absolute temperature.* Substances that emit the maximum amount of radiation for their temperature in all wavelengths are called black bodies. Also known as Stefan's law, it can be expressed as

$$E = \sigma T^4 \tag{4.1.2.1}$$

where E is energy emitted per second from a unit are of a black body with a temperature of T(in Kelvin) and σ is the Stefan-Bloltzmann constant of 5.670 X 10^{-8}J K^{-4} m^{-2} s^{-1}

Wein's Law: *The hotter the substance, the shorter the wavelength of emission.* Wein's Law, introduced earlier in this chapter can be expressed as

$$\lambda_{(max)} = \frac{a}{T} \tag{4.1.2.2}$$

where a is the constant = 2897 μm K and T is temperature (in Kelvin). Using Wein's law reveals why the Sun emits most of its radiation as shortwave and the earth as longwave. Using average surface temperatures for the Sun and Earth

Sun: $\lambda_{(max)} = \frac{2897 \mu m\ K}{5778\ K} = 0.50\ \mu m$

Earth: $\lambda_{(max)} = \frac{2897 \mu m\ K}{287\ K} = 10\ \mu m$

Hence, the Sun emits most of its energy in the shortwave end of the electromagnetic spectrum while the Earth emits most of its energy in the longwave end.

Inverse Square Law: *The intensity of light emanating from a point source is inversely proportional to the square of the distance from the source.* The inverse square law explains why the intensity of radiation received diminishes as one moves away from the source. Notice how light (radiation) spreads as you move away from point S. Imagine a light sensor placed in the path of the light at distance d and measuring the intensity of light on one unit of area (A). As we move further away from the source, the light continues to spread, though our sensor still measures the light hitting one unit of area. When we reach a distance of 2d, the light now has spread to 4 units of area, but only 1/4 of the light falls on the sensor. If we move to 3 times the distance (3d) the light spreads further and now 1/9 of the light falls on the sensor.

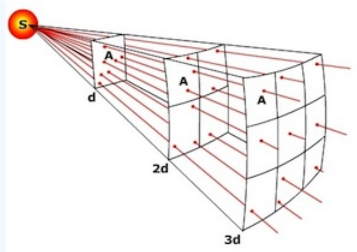


Figure 4.1.2.1: The Inverse Square Law illustrated.

The diminishing intensity of light as one moves away from the source is expressed mathematically as,

$$S_d = S_0 \left(\frac{d_0}{d}\right)^2 \tag{4.1.2.3}$$

where S is the solar intensity at some distance d, and S_0 is the intensity at some reference distance d_0.

Kirchoff's Law: *Good absorbers are good emitters at a particular wavelength, and poor absorbers are poor emitters at the same wavelengths.* In other words, some things, like the gases of Earth's atmosphere, are selective absorbers and emitters. Kirchoff's law helps explain phenomena like the greenhouse effect and why the warmest evening occur when it is cloudy. Carbon dioxide is a good absorber and emitter of of infrared radiation and thus plays an important role in the greenhouse effect. Clouds are also good absorbers and emitters of infrared radiation, creating warmer conditions than cloudless conditions during the night.

4.1.3: Selective Absorption by the Atmosphere

The gasses that comprise our atmosphere are **selective absorbers** of radiation because each gas absorbs only particular wavelengths of light. Selective absorption by particular gasses and the atmosphere as a whole is shown in Figure 4.1.3.2 The graph shows very little absorption for the atmosphere as a whole in the shortwave end of the spectrum, especially in the visible light band (the band of maximum emission for the Sun). The atmosphere absorbs far better in the longwave end of the electromagnetic spectrum which is the region of maximum emission ($10\mu m$) for the Earth.

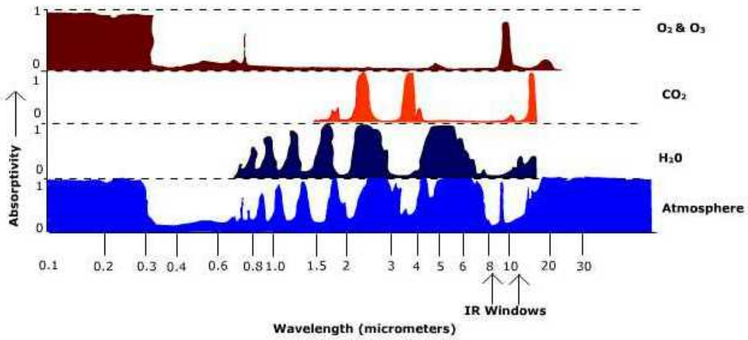


Figure 4.1.3.1: Absorption of the atmosphere and selected gasses.

The IR windows are found at about 8 - 14 μm. It is through this portion of the electromagnetic spectrum that infrared radiation is transferred through the atmosphere and into outer space. These windows can be "closed" by clouds which absorb infrared radiation.

To understand why the atmosphere behaves as a selective absorber, see "Digging Deeper: Selective Absorption by the Atmosphere" or continue reading.

Digging Deeper into Radiation and Selective Absorption

So why is the atmosphere a selective absorber? The answer is found at the atomic level where electrons orbiting the nucleus of an atom are excited when struck by a bundle of energy. Though we describe electromagnetic radiation as invisible waves of energy, at the smallest scale it behaves as a particle, like when light is emitted by a single atom or molecule. When energy is given off, there is a change in the orbital pattern of the electrons that surround the nucleus of an atom. As the orbit changes, a bundle of energy called a "**photon**" is released. Particles of light differ from particles of matter: they have no mass, occupy no space, and travel at the speed of light, 2.9998 X 10^8 m s^{-1}. The amount of energy carried by a photon varies inversely with wavelength, the shorter the wavelength, the more energetic the photon.

Electrons orbit the nucleus of an atom at fixed orbital distances called ***orbital shells***. The orbital shell for each atom is different and discrete. That is, for a given atom like hydrogen, its electrons can only orbit at particular distances and are different than those for atoms of neon.

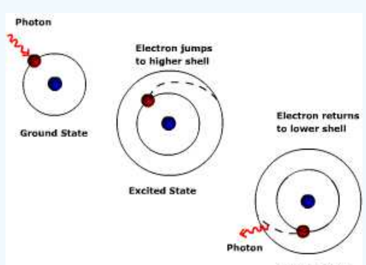


Figure 4.1.3.2: Effect of photon absorption on electron orbit.

Each orbital shell is associated with a given energy level; the greater the distance from the nucleus the greater the energy level. Electrons jump to a higher shell when excited by the absorption of energy. The photon must have the exact amount of energy to move the electron from, say, shell one to shell two. If the photon doesn't have enough energy to move the electron to shell two, it cannot move the electron half way between shell one and two. The atom does not stay in this excited, unstable state for very long. Energy is given off and the electron returns to a stable state or its "ground state" (lowest energy level or orbital distance).

Recall that the amount of energy carried by a photon depends on the wavelength. Thus the atoms that comprise a gas can only absorb, or emit, particular wavelengths of energy (i.e. photons of energy).

4.2: Insolation

The Earth is "constantly" bathed in solar radiation. On average, the Earth receives 1368 W/m^2 (1.96 ly/min) of solar radiation at the outer edge of the atmosphere, called the "**solar constant**". However, the actual amount received at the edge of the atmosphere and the Earth's surface varies from place to place and day to day on account of the orientation of the Earth to the Sun. The solar radiation that makes its way through the atmosphere and to the surface is called **insolation**. The amount of insolation received at the surface depends on 1) the sun angle, 2) day length, 3) ground slope, 4) path length, and 5) the state of the atmosphere.

Sun Angle and Insolation

The amount and intensity of solar radiation reaching the Earth is affected by the tilt of the Earth's axis and its orientation as it revolves around the Sun. The sun angle at a place varies over the course of the year as a result of the constant tilt and parallelism of the earth's axis. As the sun angle decreases, light is spread over a larger area and decreases in intensity (energy input per unit area).

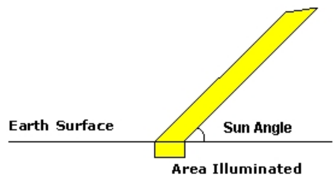


Figure $4.2.1$: Sun angle and area illuminated

Figure $4.2.2$ illustrates the effect of changing sun angle on the area illuminated and intensity of heating at different sun angles. Beam A and B have the same amount of energy as they pass through the atmosphere as shown by having the same width. Beam A strikes the surface at a 90 degree angle, the highest angle a beam of light can have. It illuminates the area outlined by the solid square. Beam B strikes the surface at a lower angle than A. Its energy is spread over a larger area, the same area as A's plus the area enclosed by the dashed lines. The result of spreading the same energy out over a larger area is to reduce the intensity . Lower intensity input results in less heating.

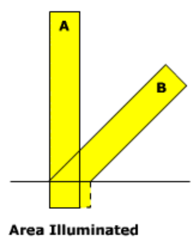


Figure $4.2.2$: Sun angle determines the intensity of energy.

Think of the sun angle as how high the Sun appears above your horizon. The Sun's **zenith angle** is the angle that a beam of light makes with a line drawn perpendicular to the surface. Think of the zenith angle as how far the Sun is from being directly overhead. The most intense incoming solar radiation occurs where the Sun's rays strike the Earth at the highest angle. For any particular location this occurs at noon. This angle is referred to as the "*noon sun angle*". Those living in the mid to high latitudes have probably noticed that the Sun never appears directly overhead at noon on any given day. This is due to the seasonal changes in the Sun's **declination**, the angular distance north or south of the equator where the Sun is directly overhead. The latitude where the Sun is directly overhead at noon is the **subsolar point**.

Daylength and Insolation

In Chapter 2: *The Earth System* we discovered that the tilt of the earth's axis and constant parallelism of the earth as it revolves around the sun causes day length to change throughout the year, except for the equator. The circle of illumination always bisects the equator resulting in equal day length, but cuts all other latitude unequally, yielding unequal periods of day and night except for the equinoxes. Simply put, the longer the daylight period, the more insolation received at a given location.

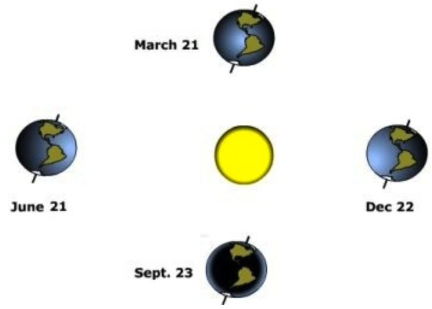


Figure 4.2.3: Orientation of the Earth to the Sun

Ground Slope and Insolation

The slope of the surface that a beam of light strikes affects the intensity of energy it receives. Slope affects insolation intensity in two ways, 1) the degree of slope inclination, and 2) the orientation of the slope to incoming light.

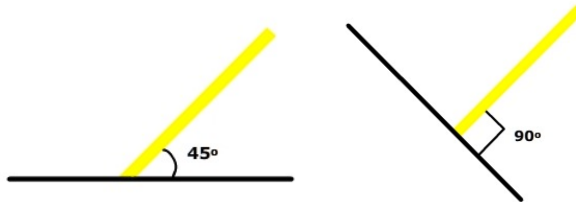


Figure 4.2.4: Effect of changing slope on sun angle

The effect of ground slope is to change the angle that a beam of light strikes the earth (i.e. the sun angle). Figure 4.2.4 shows a beam of light striking horizontal slope at a 45º angle on the left. On the right, the slope is tilted to a 45º angle while keeping the beam coming to the earth as it was before. By tilting the surface into the Sun, you effectively increase the sun angle. Increasing the sun angle increases the intensity of energy received at the surface.

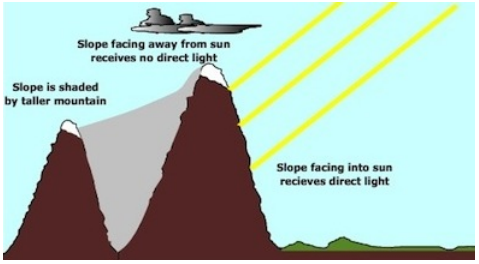


Figure 4.2.5: Effect of orientation on insolation.

Orientation, or direction the slope is facing also affects the amount of insolation received. Slopes facing into the Sun receive more while those that face away receive less. Some surfaces can be shaded during a portion of the day by obstructions reducing the amount of insolation received by them.

The video below illustrates the effect of orientation on insolation in the mountains of the Cascade Range. Start the movie and watch how slope orientation affects shading. North is at the top of the video. As the sun rises east facing slopes are receiving sunlight while the western slopes are in the shade. As the Sun travels toward the south, the range is aligned parallel to incoming light and both slopes are bathed in sunlight. As the Sun sets in the west in the late afternoon, west-facing slopes are receiving light and eastern slope are in the shade.

ulation in Wenatchee National Forest, Washington

Path length and Insolation

The distance a beam of light travels affects the amount of solar energy that ultimately reaches the Earth. Light spreads outward in all directions when it is emitted from the Sun. As the light spreads, its intensity upon reaching distant locations decreases. The intensity of light decreases as the square of the distance between the Sun and receptor increases, a relationship known as the inverse square law. The Earth receives about one-half of one billionth of the Sun's total output of energy.

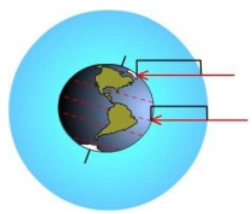


Figure 4.2.6: Influence of atmospheric path length on insolation

The Earth-Sun distance only varies by about 3 million miles compared to an average distance of 93 million miles over the year. Thus path length doesn't change much as the Earth revolves around the Sun. But once sunlight reaches the outer edge of the atmosphere, the thickness of the atmosphere has a significant impact on insolation. Due to the curvature of the Earth, a beam of light striking the Equator passes through less atmosphere than one at a higher latitude. As the amount of atmosphere through which the beam passes increases, the greater the chance for reflection and scattering of light to occur, thus reducing insolation at the surface.

State of the Atmosphere and Insolation

Clouds, particulates, and aerosols suspended in the air have a dramatic effect on the transmission of insolation. These components of the atmosphere absorb radiation emitted by the earth, reflect incoming solar radiation back to space and scatter light into many weaker beams. Scattering of light by particles in the atmosphere is responsible for the color of the sky. Clouds are particularly important in determining the amount of insolation. Clouds can reflect much light back to space or scatter and diffuse light.

Figure 4.2.7: The brilliant blue sky over the Amargosa Desert, Nevada is caused by the scattering of all but blue wavelengths. (Courtesy USGS. Source)

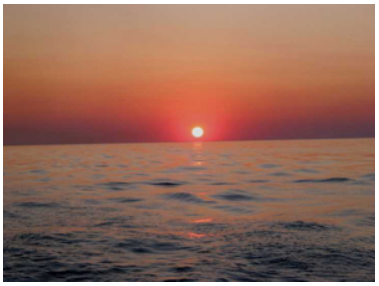


Figure 4.2.8: Scattering of red wavelengths creates this gorgeous sunset over the ocean. Being on the horizon, the pathlength is longer creating a greater chance for scattering light. (Courtesy of the NOAA ESRL Chemical Sciences Division, Boulder, Colorado, USA. Source)

Learn more with "Digging Deeper: Global Dimming" or skip and continue reading.

Digging Deeper: Global Dimming

Human activities from agriculture to industry release particulates into the air. Studies in many parts of the world indicate that insolation has been decreasing as particulate concentrations have been increasing, a phenomenon called **global dimming**. Research conducted in the Maldives demonstrated that dirty air descending from India produced a three kilometers thick pollutant layer that hung over the northern islands. The pollutant layer cut down the sunlight reaching the ocean by more than 10 percent. Climate scientists fear that the reduction of insolation by atmospheric particulates are masking the true magnitude of global warming. A reduction of particulate pollution to protect human health may cause an increase in insolation and thus accelerate global warming.

Figure 4.2.9: Contrails from passenger jets are thought to impact the daily range of temperature. (Courtesy NWS NOAA Source)

Contrails are clouds produced from jet exhaust and have been a subject of research for some time. They are difficult to study because they develop and dissipate quite rapidly, or so many of them in the sky they merge. This makes it difficult to perform baseline studies on individual clouds. When first formed they are thick and rounded blocking light like low stratus clouds causing the air to cool. Over time they morph into thinner clouds like high cirrus better at absorbing radiation thus warming the air. When air transportation was suspended over the United States shortly after the events of September 11, 2001, atmospheric scientists had an opportunity to study the effect of contrails on weather. What they found was daily temperature ranges increased by as much a two degrees fahrenheit in the absence of contrails over the contiguous United States.

Video: Climate Change and Global Dimming (Courtesy The MetOffice)

Jim Haywood, climate expert at the Met Office Hadley Centre, explains the phenomenon of global dimming and the impacts on global warming.

4.3: Radiation and Energy Balance of the Earth System

Most of the environmental processes acting near the surface of the Earth derive their energy from exchanges of heat between the Earth and the atmosphere above. Much of this heat comes from radiant energy initially provided by the absorption of solar radiation. The absorbed energy is used to warm the atmosphere, evaporate water, warm the subsurface along with a host of other processes.

4.3.1: The Radiation Balance

4.3.2: The Energy Balance

4.3.1: The Radiation Balance

The radiation balance of the Earth system is an accounting of the incoming and outgoing components of radiation. These components are balanced over long time periods and over the Earth as whole. If they weren't the Earth would be continually cooling or warming. However, over a short period of time, radiant energy is unequally distributed over the Earth.

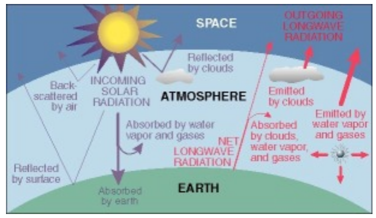


Figure 4.3.1.1: Radiation Balance of the Earth (Source: USGS geochange.er.usgs.gov/pub/carbon/fs97137/)

Shortwave radiation

The radiation balance of the Earth system is depicted in the Figure 4.18. (Shortwave radiation is colored purple and longwave radiation is in red.) Shortwave radiation from the Sun penetrates through space to the outer edge of the atmosphere unimpeded by the vacuum of outer space. Once solar radiation begins to penetrate through the atmosphere this amount begins to decrease due to absorption and reflection.

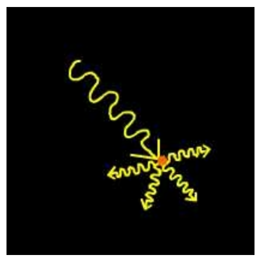


Figure 4.3.1.2: Scattering by particles in the atmosphere causes a beam of light to be broken into several weaker beams of light.

About 30% of the available solar radiation at the top of the atmosphere is reflected or scattered back to space by particulates and clouds before it reaches the ground. The gases of the atmosphere are relatively poor absorbers of solar radiation, absorbing only about 20% of what is available at the outer edge of the atmosphere. The remaining solar radiation makes its way to surface as direct and diffuse solar radiation. ***Direct solar radiation*** (S) is shortwave radiation able to penetrate through the atmosphere without having been affected by constituents of the atmosphere in any way. ***Diffuse radiation*** (D) is shortwave radiation that has been scattered by gases in the atmosphere. Scattering is a process whereby a beam of radiation is broken down into many weaker rays redirected in other directions. Together, direct and diffuse shortwave radiation accounts for the total incoming solar radiation or ***insolation*** ($K\downarrow$). In equation form:

$$K\downarrow = S+D$$

A portion of the incoming solar radiation is absorbed by the surface and a portion is also reflected away. The proportion of light reflected from a surface is the **albedo** (a). Albedo values range from 0 for no reflection to 1 for complete reflection of light striking the surface. Albedo can be expressed as a percentage (albedo multiplied by 100) that for some is easier to understand. For instance, grass has an albedo of about .23. This means that of the incoming solar radiation that strikes the grass, 23% of it is reflected away. On the other hand, highly reflective surfaces like snow have an albedo upwards of .87, or 87% of sunlight is reflected away.

Table 4.3.1.1: Sample Albedos

Surface	**Typical Albedo**
Fresh asphalt	0.04
Worn Asphalt	0.12
Bare Soil	0.17
Conifer forest (Summer)	0.08

Green Grass	0.25
New Concrete	0.55
Fresh Snow	0.80 - 0.90

The amount of reflection (K↑) is given by the following equation:

$$K\uparrow = (S+D)a$$

The amount of reflection basically depends on the color of the surface, darker surfaces reflect less than lighter colored ones. For some surfaces, like water, the sun angle affects albedo. If you have been out on a lake during the day you might have noticed that the sun reflects off the surface more when the sun is lower in the sky than it does when it is more directly overhead.

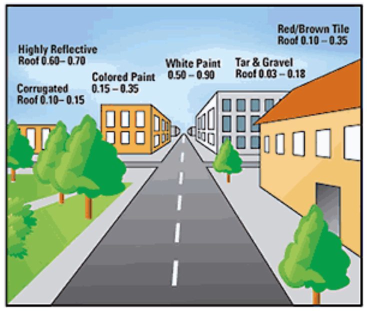


Figure 4.3.1.3: Darker urban surface absorb more heat during the day causing the urban heat island effect.

Net shortwave radiation is the difference between incoming and outgoing shortwave radiation expressed as:

$$K^* = (S+D) - (S+D)a$$

During the day, K* is a positive value as incoming always exceeds outgoing shortwave radiation. At night, K* is equal to zero as the Sun is below the horizon. (No, moonlight doesn't count!)

Longwave radiation

The energy absorbed by the surface is radiated from the Earth as **terrestrial longwave radiation** (L↑). The amount of energy emitted is primarily dependent on the temperature of the surface. The hotter the surface the more radiant energy it will emit. The gases of the atmosphere are relatively good absorbers of longwave radiation and thus absorb the energy emitted by the surface. The absorbed radiation is emitted in all directions with the downward directed portion being **longwave atmospheric counter-radiation** (L↓).

The difference between incoming and outgoing longwave radiation is **net longwave radiation** expressed as:

$$L^* = L\downarrow - L\uparrow$$

Recall that under normal conditions air temperature decreases with an increase in altitude through the troposphere. This occurs because the earth is the immediate source of energy for heating the air above it. Knowing that heat is transferred from warmer to cooler bodies, this means the surface is normally hotter than the air above. So for most situations, net longwave radiation is a negative value as more longwave radiation is emitted by the Earth than it gains from the air. Some of this radiation is emitted out to space is lost from the earth system. That which is not lost to space is absorbed by the atmosphere and drives the "greenhouse" effect.

Under other circumstances net longwave can be zero or a positive number. If zero the amount of radiation emitted by the surface would be equal to that of the air. This is true when the air and surface have the same temperature. If the air is warmer than the ground a positive value exists. This could occur with heavy cloud cover (clouds are good absorbers and radiators of longwave radiation) or if a warm air mass travels over a colder surface.

Net Radiation

Net Radiation is the difference between incoming (i.e., S and L↓) and outgoing components of radiation (S+D)a and L↑.

$$Q^* = [(S+D) - (S+D)a] + L\downarrow - L\uparrow$$

Net radiation can be positive, negative, or zero. Net radiation is positive when there is more incoming radiation than outgoing radiation. This typically occurs during the day time when the sun is out and the air temperature is the warmest. At night, net radiation is usually a negative value as there is no incoming solar radiation and net longwave is dominated by the outgoing terrestrial longwave flux. Net radiation is zero when the incoming and outgoing components are in perfect balance, which doesn't occur too often.

A net radiometer measures incoming and outgoing radiation from an alpine snow pack. Measurements such as this aid in determining snow melt and the availability of water to fill community reservoirs like those near Boulder, CO.

Understanding net radiation and its distribution is fundamental to explaining many geographical patterns of the components of the earth system. Net radiation is the radiant energy that is available to do work within the earth system. This work is manifested in a variety of ways, from heating the air, to warming the surface, to causing water to evaporate.

4.3.2: The Energy Balance

Available net radiation is used to do work in the Earth system. The principal use of this energy is in the phase change of water (latent heat, *LE*), changing the temperature of the air (sensible heat, *H*), and subsurface (ground heat, *G*) or,

$$Q^* = H + LE + G$$

Though there are other uses for net radiation like photosynthesis and the weathering of rocks, it is the three previously stated uses that are most important. LE, H, and G involve non-radiative transfers of heat. That is, conduction or convection/advection are responsible for the transfer of heat, not electromagnetic radiation.

When work is done, like heating the air above the surface, there is a transfer of energy (heat) from one place to the next. To illustrate the transfer of energy we'll use arrows either pointing away from or toward the surface of the Earth to indicate the direction of heat transfer. We will also use positive and negative signs to indicate that heat is being added to, or taken away from a body. Following the conventions of Sellers (1965) and Oke (1987), non-radiative fluxes directed away from a surface are positive. Thus positive values indicates a loss of heat from the surface while negative values indicate a gain.

Sensible Heat Transfer (H)

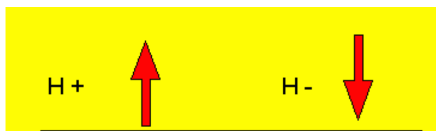


Figure 4.3.2.1: Sensible heat transfer

Sensible heat is heat energy transferred between the surface and air when there is a difference in temperature between them. A change in temperature over distance is called a "*temperature gradient*". In this case, it is a vertical temperature gradient, i.e., between the surface and the air above. We feel the transfer of sensible heat as a rise or fall in the temperature of the air. Heat is initially transferred into the air by conduction as air molecules collide with those of the surface. As the air warms it circulates upwards via convection. Thus the transfer of sensible heat is accomplished in a two-step process. Because air is such a poor conductor of heat, it is convection that is the most efficient way of transferring sensible heat into the air.

When the surface is warmer than the air above, heat will be transferred upwards into the air as a ***positive sensible heat transfer***. The transfer of heat raises the air's temperature but cools the surface. If the air is warmer than the surface, heat is transferred from the air to the surface creating a ***negative sensible heat transfer***. If heat is transferred out of the air, the air cools and the surface warms. This situation may take place at night when the sun goes down and there is no input of solar radiation. At this time, the ground cools due to longwave emission and the air directly above the surface is warmer.

Latent Heat Transfer (LE)

When energy is added to water it will change states or phase. The phase change of a liquid to a gas is called ***evaporation***. If we could see down to the molecular level we would find water being comprised of cluster of water molecules (H_2O). The clusters are bound together by bonding between the hydrogen atoms of water molecules. The heat added during evaporation breaks the bonds between the clusters creating individual molecules that escape the surface as a gas. The heat used in the phase change from a liquid to a gas is called the ***latent heat of vaporization***. We say it is "latent" because heat is being stored in the molecules. Water molecules release latent heat during the condensation process. We can't sense or feel latent heat as it does not raise the temperature of the water molecules.

When evaporation is taking place we say there is a ***positive latent heat flux*** (transfer). A positive latent heat flux (Figure 4.3.2.2) is illustrated with an arrow pointing up away from the surface of the earth. This indicates that the surface is losing energy to the air above. Evaporation is a cooling process for a surface because energy is removed from the water as molecules escape the surface. This causes the surface temperature to decrease. You've probably experienced this cooling when water or sweat evaporates from your skin.

Figure 4.3.2.2: Latent Energy Transfer

Condensation is the phase change from a gas to a liquid. During the phase change, the latent heat that was taken up during evaporation is released from the water molecule and passed into the surrounding air. During this process latent heat is converted to sensible heat causing an increase in the temperature of the air.

When radiation is absorbed by the Earth it will raise the temperature of the surface. But if the surface is water, some of that energy is used in evaporation rather than heating the water. As a result, with equal inputs of energy to land and water surfaces, land will heat up more than water. This is one of the reasons why it is cooler near large bodies of water.

Ground Heat Transfer (G)

The third major use of radiant energy is to warm the subsurface of the Earth. Heat is transferred from the surface downwards via conduction. Like in the case of sensible heat transfer, a temperature gradient must exist between the surface and the subsurface for heat transfer to occur. Heat is transferred downwards when the surface is warmer than the subsurface (positive ground heat flux). If the subsurface is warmer than the surface then heat is transferred upwards (negative ground heat flux).

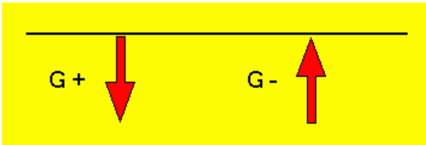


Figure 4.3.2.3: Ground Heat Transfer

The transfer of energy to and from the surface varies over the course of a day. Figure $4.3.2.4$ shows the relative amounts and direction of energy flow during the day and night for a moist surface. During the day net radiation is a positive value as incoming radiation exceeds outgoing radiation allowing the surface to gain energy. The energy is distributed over the three major categories of energy use, LE, H, and G. During the day, the available radiant energy is used to evaporate water into the air, raising the air's humidity. Sensible heat is transferred upwards to warm the air above the surface. Heat is also conducted down into the subsurface. At night the processes reverse. At night with no incoming solar radiation there is more outgoing radiation than incoming creating a negative value for net radiation. Under these circumstances the surface cools due to a loss of energy and heat is transferred from the air toward the surface. As air cools through the evening the loss of energy allow condensation to occur, so long as the air's humidity is at or near saturation. Notice that the arrow for the ground heat flux G is pointing upward toward the surface. This indicates that the energy that had been stored in the subsurface during the day is now conducted toward the surface. This occurs as the surface is cooler than the subsurface.

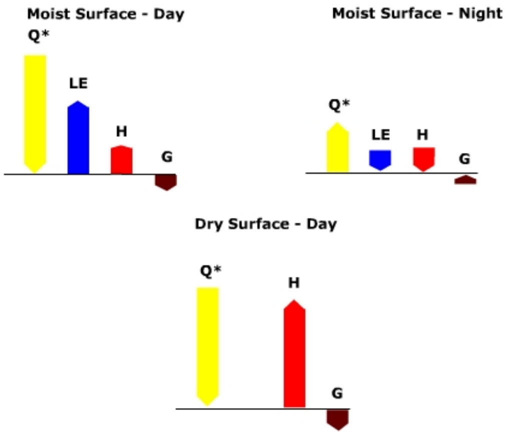


Figure 4.3.2.4: Types of energy balances. (After Rouse 1979)

Figure $4.3.2.4$ also shows the differences between how energy is used in moist and dry locations. Water is available at the surface for evaporation and latent heat transfer into the air at moist locations. Without available water, no transfer of latent energy occurs, hence the absence of an LE flux for the dry surface. Most of the available energy, Q*, is allocated to sensible heat transfer creating warm air temperatures.

Investigate more about the energy balance by "Digging Deeper: Local Energy Balances" or skip and continue reading.

Digging Deeper: Local Energy Balances

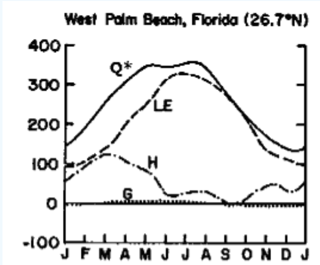


Figure 4.3.2.5: West Palm Beach, Fl energy balance (ly/day)

West Palm Beach, Florida is located in the warm and moist tropical wet and dry (savanna) climate. The annual variation of net radiation shows a typical pattern of Q* being at a maximum during the summer and minimum during the winter. Latent heat transfer (LE) is high at West Palm Beach because of the water availability near the ocean. Latent energy transfer into the air is greatest during the summer time which is the wettest period of the year, and when net radiation is the highest. Warmer summer time air can hold more moisture and hence there is a larger moisture gradient to drive latent heat transfer. The annual variation of sensible heat transfer is determined by the available net radiation and the temperature gradient between the air and surface, as well as use of energy for latent heat transfer. During the spring a larger temperature gradient exists between the surface and the air above. Ample rainfall occurs during the summer providing water for evaporation. During this time period, sensible heat transfer decreases as net radiation is allocated to evaporation and latent heat transfer.

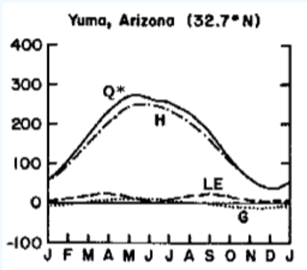


Figure 4.3.2.6: Yuma, AZ energy balance (ly/day)

At the other extreme is Yuma, Arizona, a warm and dry location typical of the midlatitude desert climate. The most noticeable characteristic of this place is the lack of latent heat transfer. Though ample radiation is available here, there is little water to evaporate. Nearly all net radiation is used for sensible heat transfer which explains the hot, dry conditions at Yuma.

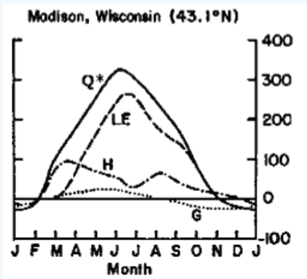


Figure 4.3.2.7: Madison, WI energy balance (ly/day)

Between these extremes is Madison, WI found in the humid continental climate of North America. Latent heat transfer dominates for most of the year in this humid climate. Sensible heat transfer is especially high when surface and air temperatures are most different. The transfer of energy in and out of the subsurface is a much greater amplitude given that large temperature swings that are experienced in this climate.

4.4: Global Patterns of Insolation, Net radiation, and Heat

Patterns of insolation and net radiation which determine the location of plants, animals, climate, soils and other elements of our physical environment can be discerned from Figures 4.4.1 through 4.4.3. Figure 4.4.1 illustrates the latitudinal distribution of incoming solar radiation and outgoing terrestrial radiation. From approximately 35^o N to 35^o S latitude (the red area of the graph) there is a surplus of energy as incoming radiation exceeds outgoing. The blue regions indicate that there is more outgoing energy than incoming, yielding a net loss of energy from the Earth's surface. One might ask then why the middle to higher latitudes aren't getting colder through time as a result of the net loss, and the subtropical to equatorial regions getting constantly hotter due to the net gain. The reason is that the energy is redistributed by circulation of the atmosphere and oceans. Heat gained in the tropics is transported poleward by the global circulation of air and warm ocean currents to heat higher latitude regions. Cooler air from the higher latitudes and cold ocean currents push equatorward to cool the lower latitudes. This process of redistributing energy in the Earth system helps maintain a long-term energy balance.

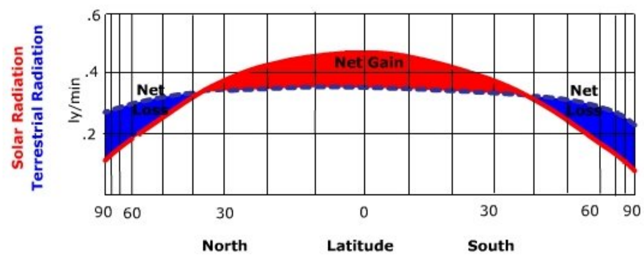


Figure 4.4.1: Latitudinal Variation of the Radiation Balance

Insolation

Figure 4.4.1 simplifies the geographic distribution of insolation. For the Earth as a whole, particular patterns can be accounted for by variation in surface features that impact insolation. Insolation maxima are found in the tropical and subtropical deserts of the earth. Here, high sun angles and a lack of cloud cover in desert regions allow much solar radiation to the surface. Insolation decreases to a minimum at the poles where low sun angles and the fact that the Sun doesn't rise above the horizon nearly half the year reduces annual insolation.

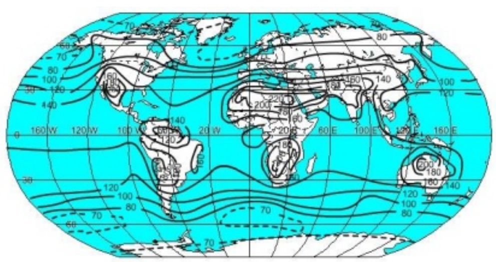


Figure 4.4.2: Annual global distribution of solar radiation (Kcal/cm^2) (after Sellers, W. D., 1965)

Net radiation

Net radiation exhibits a different pattern from that of insolation. Maximum net radiation is found over the tropical and subtropical oceans. The sun angle is always high over the tropical oceans so the surface receives intense radiation throughout the year. With an high sun angle the albedo of the surface is low and absorption is high. However, the energy received is partitioned into warming the surface as well as evaporating water. The result is a lower surface temperature than one might expect with such high sun angles. Additionally, the high specific heat of water means that it takes much more energy to heat a unit mass of water than that of land, resulting in lower ocean surface temperatures. With lower surface temperatures the water surface does not radiate as much longwave radiation out to the atmosphere as nearby land at the same latitude. With much radiation coming in and little going out, the net value is large compared to land at the same latitude. Net radiation is at a minimum over the poles as the sunlight that comes in at a low angle is reflected from the ice-covered surface. Combined with the long polar night, very little net radiation is found at these latitudes.

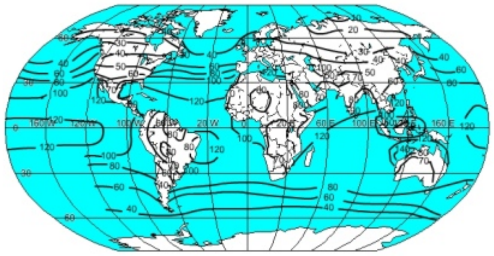


Figure 4.4.3: Annual global distribution of net radiation (Kcal/cm^2) (after Sellers, W. D., 1965)

4.5: Getting Ready for Chapter 4

Chapter 3 gave us an introduction to the structure and composition of the atmosphere, the gaseous envelope that supports life as we know it. We've found that some gases act to absorb heat released from the surface, creating a greenhouse environment and making earth habitable. But the concentration of greenhouse gases is on the rise, and human activities are responsible for much of it. Other gases shield the earth from receiving too much ultra-violet light. Their concentrations have been affected by human activities as well.

Figure 4.5.1: Sunset over the Pacific (Courtesy Image Science and Analysis Laboratory, NASA-Johnson Space Center. "The Gateway to Astronaut Photography of Earth. Source: https://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=ISS015&roll=E&frame=10469)

Ahead in Chapter 4, *Energy and Radiation*, we'll examine the sources of heat that not only warm the atmosphere, but drive most of the environmental processes acting at the surface of the earth. We'll gain insight into how exogenic sources of energy ultimately heat the air, change the state of water, and warm the surface of the earth. Using these new insights, we'll be able to explain the geographical variation of radiation and energy. A peek into future changes in the earth's heat balance as a result of human-induced climate change will conclude the chapter.

What you should already know...

The content of Chapter 4 *Energy and Radiation* is some of the most important material for understanding the functioning of the earth system. Chapter 4 delves into the nature of energy and heat. Much of the chapter discusses energy received from the Sun, the ultimate source of energy to drive most environmental processes acting at the surface of the Earth. The knowledge gained in this chapter will serves as the foundation for understanding the geography of temperature, phase changes of water, circulation of the air, and much more.

Before beginning you should be comfortable with the material covered in Chapter 2 *The Earth System*. Have a good understanding of the Earth in space, and how the orientation, rotation, and revolution of the Earth around the Sun affects sunlight reaching the earth system.

Exercise 4.5.1

1. The Earth is closest to the Sun in
   - A. January
   - B. March
   - C. September
   - D. July
2. The Earth's axis of rotation is tilted
   - A. 23.5 degrees from perpendicular to the plane of the ecliptic
   - B. 66.5 degrees from perpendicular to the plane of the ecliptic
   - C. 0 degrees from perpendicular to the plane of the ecliptic
   - D. 90 from perpendicular to the plane of the ecliptic
3. The subsolar point on June 21st is
   - A. 23.5 degrees north latitude
   - B. 0 degrees (the equator)
   - C. 23.5 degrees south latitude
   - D. 66.5 degrees north latitude.

4. There is 12 hours of day and 12 hours of night
   A. on June 21
   B. on December 22
   C. every day of the year at the equator
   D. none of the above.
5. Tangent rays
   A. strike the north and south poles on the solstices
   B. strike the equator only on the solstice.
   C. strike the north and south poles on the equinox
   D. only strike the earth on the solstice
6. 24 hours
   A. of daylight occurs at the South Pole on June 21
   B. of daylight occurs at the South Pole on March 21
   C. of darkness occurs at the South Pole on June 21
   D. of darkness does not occur anywhere
7. The subtropical latitude zone is located
   A. 10 degrees N - 10 degrees S
   B. 10 degrees - 25 degrees N and S latitude
   C. 25 degrees - 35 degrees N and S latitude
   D. 35 degrees - 55 degrees N and S latitude
8. Most greenhouse gases
   A. are good absorbers of solar radiation
   B. are good absorbers of radiation emitted by the Earth
   C. are known as "uniform absorbers"
   D. are all the above
9. The largest sources of particulates entering the atmosphere is from
   A. salt from sea spray and bursting bubbles.
   B. windblown dust
   C. volcanoes
   D. biomass burning
10. Solar radiation is considered
    A. an exogenic source of energy
    B. an endogenic source of energy
    C. an adiabatic source of energy
    D. a diabatic source of energy

Answer

1. A
2. A
3. A
4. C
5. C
6. C
7. C
8. B
9. A
10. A

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous material.

If you scored less than 70% you should consider reviewing the previous material and seeking help from your instructor.

4.6: Global Patterns of Sensible and Latent Heat Transfer

Sensible heat transfer (H) into the air is dependent on the temperature gradient between the surface and the air above. An examination of the global distribution of sensible heat transfer reveals that it is at a maximum in the tropical and subtropical deserts. Here the high surface temperature conducts much heat into the air above. Sensible heat is lowest near the poles where the surface temperatures are quite cold.

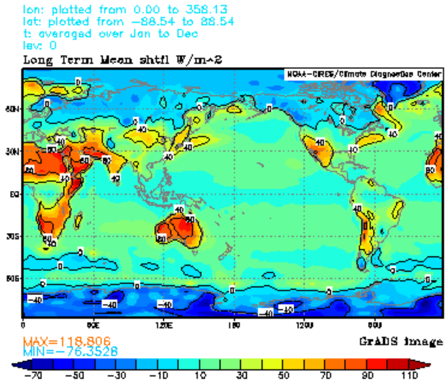


Figure 4.6.1: Global distribution of sensible heat. (Image provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at https://www.cdc.noaa.gov/.)

The maximum amount of latent heat transfer (LE) occurs over the subtropical oceans where there is a maximum of net radiation and, of course, water to evaporate. The lowest rates occur in desert locations. Even though there is ample available energy for LE, there is little water present. Off the east coast of midlatitude continents like North America, we'll find very high rates of latent energy transfer into the air. Here, dry air blows off the continent and over the warm ocean current that flows along the coast. This produces a large moisture gradient between the surface and the air above that induces evaporation and LE transfer.

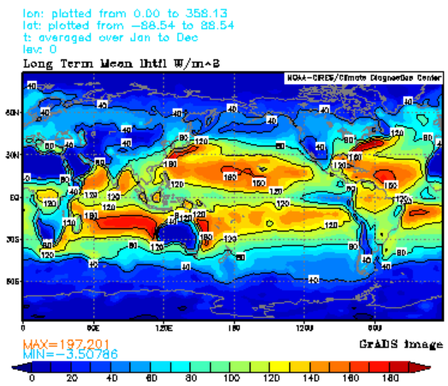


Figure 4.6.2: Global distribution of latent heat. (Image provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, from their Web site at https://www.cdc.noaa.gov/.)

4.7: Future Geographies - Radiative Forcing and the Earth's Heat Balance

The future physical geography of Earth, as affected by global warming, comes down to changes in the heat balance of the Earth system. Radiative forcing is a measure of the strength of agents, both natural and human, that cause climate change. Radiative forcing agents are factors that change the balance between incoming solar radiation and outgoing infrared radiation within the Earth's atmosphere. The radiative forcing of greenhouse gases is what will propel much of this change. Documented changes with relatively high level of scientific understanding from 1750 to 2005 has been presented by the Intergovernmental Panel on Climate Change.

The Present Picture

Two long-lived greenhouse gases produced from human activities, carbon dioxide and methane, are the most potent, contributing 1.66 and 0.48 (W/m^2) respectively at the global scale. Shorter-lived troposphere ozone contributes an average of 0.35 (W/m^2), though we have only a medium level of scientific understanding of its contribution.

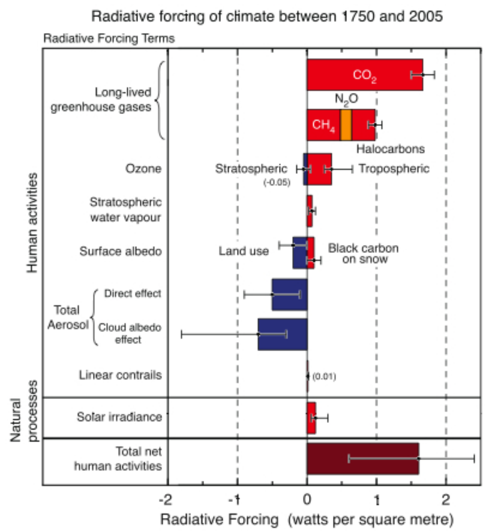


Figure 4.7.1: Principal agents of the radiative forcing of climate change 1750 - 2005. (Courtesy IPCC Source)

Though human activities affect agents that increase radiative forcing, they also negatively impact radiative forcing. A notable impact, is that of the aerosol content of the atmosphere. Aerosols themselves can negatively impact radiative forcing by reflecting solar radiation. But a much larger impact, and one with less scientific certainty, is their role in creating clouds which also reflect solar radiation.

In addition to changes in the gaseous composition of the atmosphere, surface albedo changes from human activities also effects radiative forcing. This is particularly true when forests are cleared for agriculture. Forests generally have a lower albedo than open land thus absorbing more incident solar radiation. These changes induce a radiative forcing by effecting the shortwave radiation balance. This is particularly true when snow is present. Open land has a more complete cover of highly reflective snow, while the lower albedo trees stand above the snow.

Natural radiative forcing largely results from changes in solar output and volcanic eruptions. As noted earlier, sunspot activity varies on an 11-year cycle. But since the dawn of the industrial age, solar output has been slowly increasing and thus the the Sun has had a positive radiative forcing effect. Volcanic eruptions produce a variety gases, though their presence in the atmosphere is relatively short lived (2 to 3 years). The most notable is sulphate aerosols injected into the stratosphere causing a negative radiative forcing. The stratosphere is presently free of appreciable amounts of volcanic aerosols. The last major eruption to affect stratospheric aerosol content was Mt. Pinatubo in 1991.

Adding the effects of other radiative forcing components like surface albedo changes, the combined net anthropogenic radiative forcing is estimated to be +1.6 (W/m^2). This, according to the IPCC, indicates that since 1750, it is extremely likely that human activities have caused a substantial effect on warming Earth's climate. Additionally, is it likely that this estimate is five times greater than that which can be attributed to natural changes in the output of the Sun.

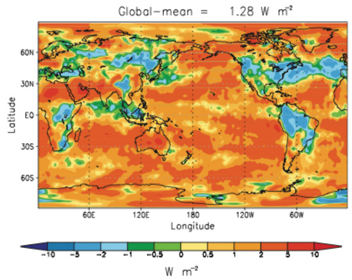


Figure 4.7.2a: Instantaneous change in the distribution of the net radiative ï¬,ux (W/m^2) due to natural plus anthropogenic radiative forcings between the years 1860 and 2000 at the tropopause. (Courtesy IPCC Source)

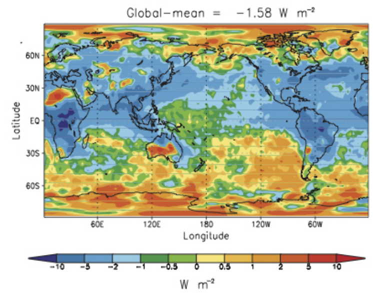


Figure 4.7.2b: Instantaneous change in the distribution of the net radiative ï¬,ux (W/m^2) due to natural plus anthropogenic radiative forcings between the years 1860 and 2000 at the surface. Courtesy IPCC. Source)

Figures $4.7.2a$ and b show estimates of the spatial pattern of the net radiative flux due to both natural and human factors for one particular model that incorporates the aerosol cloud albedo effect. The radiative forcing is positive for most of the earth and principally associated with long-lived greenhouse gases like carbon dioxide. This is especially true for the southern hemisphere due to the higher levels of aerosols in the source-rich continental regions of the northern hemisphere midlatitudes. Wherever high concentrations of aerosols are found, especially in the northern hemisphere, surface forcing is negative. This is due to the influence of aerosols in reducing the shortwave radiation that reaches the ground. As aerosol concentrations are lower over much of the southern hemisphere oceans and at high latitudes. With less aerosols more shortwave radiation reaches the earth thus surface forcing becomes positive.

Future Forcings

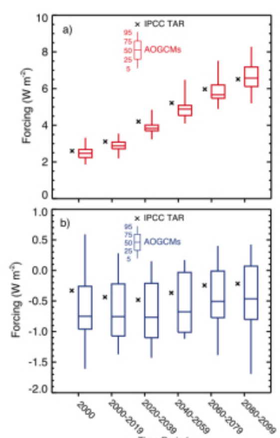


Figure $4.7.3$: Radiative forcings for the period 2000 to 2100 for the SRES A1B scenario diagnosed from atmosphere/ocean general climate circulation (AOGCMs) and from the Third Assessment Report (IPCC, 2001) forcing formulas (Top) Longwave forcing; (Bottom) shortwave forcing. (Courtesy IPCC, Source)

Future heat balance conditions from the forcings is tricky and predictions from various AOGCMs do not precisely agree with one another, largely due to the radiatively active gases used, solar variability, land use change, and how radiation transfer is formulated. Figure $4.7.3$ shows the range of forcing using "box and whisker" diagrams estimated by these models using a scenario where economic growth is rapid, world population peaks at 9 billion in 2050 and then declines, there is a quick and efficient spread of technologies, extensive social and cultural interaction occurs worldwide, and world-income and way of life converges between regions. Longwave forcing continues to increase fueling continued warming of the earth system.

Global warming will continue unabated without changes in how human activities impact radiative forcing agents. In future chapters, we'll investigate how changes in these agents will impact patterns of temperature, pressure and wind, weather, biotic systems, the hydrosphere and earth surface processes.

4.8: Review and Additional Online Resources

Review

Aurora Australis, the Southern Lights are seen during strong geomagnetic events in the Southern Hemisphere. Courtesy NOAA

Figure 4.8.1

Assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts 4.8.1

- **Energy**
  the ability to do work on matter
- **Potential Energy**
  the energy of position
- **Kinetic Energy**
  the energy of motion
- **Heat**
  aka thermal energy; the total energy associated with random atomic and molecular motions of a substance
- **Calorie**
  a unit of measurement for heat. A calorie is the amount of heat required to raise the temperature of one gram of water through 1^{o}C.
- **Specific Heat**
  the heat required to raise the temperature of one unit substance (e.g., gram) through a particular temperature interval.
- **Joule**
  unit of measurement for energy. One joule is the equivalent of one watt of power radiated or dissipated for one second.
- **Conduction**
  the transfer of heat from warmer to colder portions of the mass in a solid
- **Convection**
  heat is transferred by the circulation of molecules in fluids
- **Radiation**
  the transfer of energy via electromagnetic waves.
- **Advection**
  a term that is applied to the horizontal transfer of heat by the wind

- **Temperature**
  a measure of the average kinetic energy level of a substance, the degree of hotness or coldness
- **Amplitude**
  the height of the wave
- **Wavelength**
  the distance between successive crests
- **Photon**
  a bundle of energy
- **selective absorber**
  absorbs only particular wavelengths of light
- **Shortwave radiation**
  ultraviolet, visible, and a portion of infrared energy
- **Longwave radiation**
  infrared, (like microwave, TV, radio waves)
- **Direct shortwave radiation**
  shortwave radiation able to penetrate through the atmosphere without having been affected by constituents of the atmosphere in any way.
- **Diffuse Shortwave radiation**
  shortwave radiation that has been scattered by gases in the atmosphere
- **Insolation**
  the total incoming solar radiation
- **Albedo**
  The proportion of light reflected from a surface
- **Net shortwave radiation**
  the difference between incoming and outgoing shortwave radiation. K= (S+D) - (S+D)a
- **Terrestrial longwave radiation**
  The energy absorbed by the surface is radiated from the Earth
- **Atmospheric counter-radiation**
  long-wave radiation emitted from the earth to the atmosphere after it has absorbed the shorter-wave radiation of the sun.
  - **Net radiation**
    the difference between incoming (i.e., S and L↓) and outgoing components of radiation (S+D)a and L↑: Q*= [(S+D) - (S+D)a] + L↓ - L↑
- **Sensible heat transfer**
  heat energy transferred between the surface and air when there is a difference in temperature between them
- **Latent heat transfer**
  transfer of energy where temperature does not change/cannot be sensed

- **Ground heat transfer**

    The transfer of energy to and from the surface

Review Questions 4.8.1

Generally speaking, where is the highest and lowest amounts of insolation and net radiation on a global basis?

Answer

Insolation: highest amount in the tropical/subtropical deserts; minimum at the poles. **Net radiation**: maximum in the tropical/subtropical oceans; minimum at the poles.

What is albedo and what determines the albedo of a surface?

Answer

Albedo is the proportion of light reflected from the surface. It is mostly determined by the color of the surface though sun angle influences albedo for some surfaces like water.

What determines the amount of radiation emitted by a body?

Answer

The amount of radiation emitted by a body depends on the temperature of the emitting body.

What determines sun angle at a place?

Answer

Sun angle is a largely determined by the tilt of Earth's axis. The sun angle varies by latitude, time of day. time of year, and slope of the surface.

Why do physical geographers refer to the gasses of the atmosphere as a "selective absorber" of radiation?

Answer

A gas that is a selective absorber is one that absorbs only particular wavelengths of light. The gasses of Earth's atmosphere are considered selective absorbers as they tend to allow shortwave solar radiation through but absorbs longwave radiation emitted by the surface.

Compare and contrast conduction, convection, and radiation.

Answer

Conduction is the heat transfer via molecular collisions. **Convection** is heat transfer by circulation. **Radiation** is heat transfer via electromagnetic radiation.

Explain why the maximum wavelength of emission for the Sun is different than that of the Earth.

Answer

The maximum wavelength of emission depends on the temperature of the emitting body, the hotter the body the shorter the maximum wavelength of emission. The Sun being much warmer than the Earth emits most of its energy in the shortwave end of the electromagnetic spectrum while the Earth emits its energy in the longwave end of the electromagnetic spectrum.

Briefly describe how the vertical rays of the sun at noon change throughout the year.

Answer

- March 21 and Sept 23: 0^{o} latitude
- June 22: 23.5^{o} North latitude
- Dec 22: 23.5^{o} degrees South latitude

How do clouds affect solar radiation?

Answer

They block incoming solar radiation reflecting it of their top and back out to space. They diffuse incoming solar radiation as well.

What is net radiation?

Answer

Net radiation is an accounting of incoming and outgoing components of radiation. It also is the amount of energy used to do work in the earth system.

Briefly describe the latitudinal variation of the radiation balance.

Answer

There is a net gain of radiation between about 38^{o} North and South latitude. Poleward of these latitudes there is a net loss of radiation.

Compare and contrast latent heat transfer in humid and arid regions.

Answer

There is more latent heat flux in a humid region because there is more water available than in a desert region.

Exercise 4.8.1

1. The earth is closest to the sun on about
   A. January 4th
   B. March 21st
   C. July 4th
   D. June 21st
2. Latent heat is transferred into the air by
   A. conduction
   B. convection
   C. radiation
   D. none of the above
3. Which place likely receives the most insolation at noon (barring any effect of clouds)?
   A. 90 N on June 22nd
   B. 45 N on June 22nd
   C. 23.5 N on June 22nd
   D. 0 on June 22nd
4. The highest amount of net radiation is found
   A. over polar seas
   B. over midlatitude continents
   C. over subtropical deserts
   D. over tropical oceans
5. The earth's maximum wavelength of emission is about
   A. .5 micrometers
   B. 1.0 micrometers
   C. 10 micrometers
   D. 100 micrometers
6. The sun is directly overhead of 23.5 S at noon on

A. March 21st
B. June 22nd
C. Sept. 23rd
D. Dec. 22

7. The hotter the emitting body
   A. the shorter the wavelength of maximum emission
   B. the longer the wavelength of maximum emission
   C. the less energy it will emit
   D. the more latent heat it will store
8. Clouds are good absorbers of radiation at a wavelength of about
   A. .5 micrometers
   B. 1 micrometers
   C. 10 micrometers
   D. at all the above wavelengths
9. ________ is the total energy associated with random atomic and molecular motions of a substance.
   A. radiation
   B. temperature
   C. potential energy
   D. heat
10. Where would I expect to find the largest amount of latent heat transfer into the air?
   A. The west coast of the United States near Los Angeles
   B. The east coast of the United States near New York
   C. In the middle of the Sonoran Desert of Mexico
   D. In the tropical rain forest of Brazil

Answer

1. A
2. B
3. C
4. D
5. C
6. D
7. A
8. C
9. D
10. B

Additional Resources

Focus on The Physical Environment: "Arbiters of Energy" (NASA Earth Observatory)

World of Change: Solar Activity

Multimedia

Particles and Waves (Annenberg/CPB:) The Mechanical Universe "Evidence that light can sometimes act like a particle leads to quantum mechanics, the new physics." Go to The Mechanical Universe site and scroll to "Particles and Waves". One-time free registration may be required.

CHAPTER OVERVIEW

5: Air Temperature

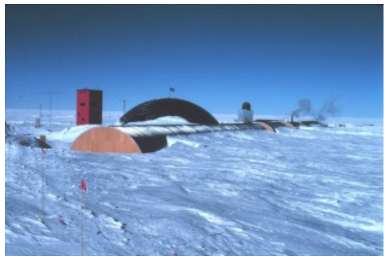


Figure 5.1: South Pole Station, Antarctica, one of the coldest places on Earth (Credit NOAA)

The temperature of our atmosphere is controlled by a complex set of interactions between the biosphere, lithosphere, hydrosphere, and atmosphere. Energy is constantly exchanged between the surface and the air above, as well as circulating around the globe. Here we'll look at what controls the air temperature at a particular place by examining radiation and energy exchanges between the earth and air above. Then we'll examine how the global circulation of air and water affects air temperature.

Learning Objectives

By the end of the chapter you should be able to:

- Define temperature and describe how air temperature is measured.
- Explain what controls daily and seasonal temperature variations.
- Determine the temperature gradient using isotherms.
- Calculate average daily and annual temperature, daily and annual temperature range, determine seasonal temperature lag.
- Explain the global pattern of air temperature.
- Summarize the effects of global warming on temperature patterns.

See if you are ready for this chapter by Getting Ready for Chapter 5: Air Temperature.

5.1: Temperature
5.2: Controls over Air Temperature
5.3: Explaining Patterns of Air Temperature
5.4: Getting Ready for Chapter 5
5.5: Future Geographies - Global Warming and Regional Temperature Patterns
5.6: Review and Additional Resources

5.1: Temperature

Temperature is a measure of the average speed of the random motion of molecules that comprise a substance. Basically, it is a measure of how hot or cold something is. In Chapter 4 we made an important distinction between temperature and heat. Heat is the total molecular motion associated with a substance while temperature is the average motion of molecular that make up a substance.

There are two ways that the temperature of the air can change. There can be a physical exchange of heat between the air and the earth surface in the presence of a temperature gradient. For example, if the surface is warmer than the air above, heat will be transferred into the air to warm it up. This is a case of **diabatic temperature change**. The temperature of the air can also change without a physical exchange of heat. This is called an **adiabatic temperature change** that occurs with rising parcels of air. As a parcel of air rises it expands. In the process of expansion requires the expenditure of its internal energy and as a result the parcel cools. We'll look at this process in more detail in Chapter 7.

Measuring Temperature

Surface temperature is the temperature of the earth surface, not the temperature of the air above it. *Air temperature* is measured at a height of 4 to 6 feet above the surface. For accurate results, instruments should be shielded from the Sun and away from buildings and other structures that could affect temperature measurements. A Stevenson screen, like that shown in Figure 5.1.1 is ventilated to allow air through it.

Figure 5.1.1: Stevenson screen for measuring weather conditions like air temperature.

One of two scales of measurement are common to most of us, the **Fahrenheit scale** in the United States and Celsius in most other countries. The **Celsius scale** is an accepted international system of measurement because it is based on a decimal scale having 100 units between the freezing and boiling points of water. The Fahrenheit scale sets the freezing point of water at 32^{o}F and 212^{o}F for boiling. In much scientific research the **Kelvin scale** is used. It is based on the "kelvin", a unit increment of temperature. Unlike the Fahrenheit and Celsius scales, the kelvin is not referred to as a "degree". It is an absolute scale given that at absolute zero all molecular movement ceases. It too has 100 units between the freezing and boiling points of water. Absolute zero is -273^{o} on the Celsius scale.

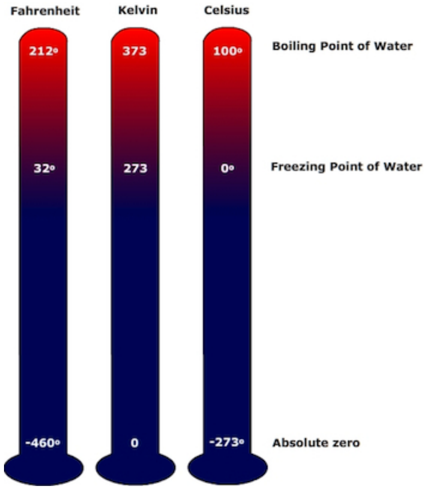


Figure 5.1.2: Temperature Scales

Temperature Statisics

A variety of statistics are available to easily communicate the volumes of temperature data available. The **daily temperature range** for a place is the difference between the highest and lowest temperatures over a 24 hour period. The average daily temperature is the sum of highest and lowest temperature of the day divided 2. This the sum of the average daily temperature divided by the number of days in the month. The annual temperature range is the difference between the highest and lowest monthly temperature for a place. The average annual temperature is the sum of the mean monthly temperature divide by 12.

Video: Taking Earth's Temperature (Courtesy NASA)
This short video describes how researchers use models to understand the Earth's changing temperature.

Located in the interior, Wichita, KS has the largest temperature range.

5.2: Controls over Air Temperature

Temperature is a measure of the heat content of a body. It is a measure of the average speed of the random motion of molecules that comprise a substance. The air temperature at any place is determined by (1) radiation and heat transfers between the surface and the air above, (2) the location relative to a large body of water, and (3) the movement of vast pools of air called air masses.

Radiation, sensible heat and temperature

The air temperature at a place is determined by the exchange of radiant energy between the Sun, Earth, and its atmosphere. Solar radiation is the *principle source of energy to heat the surface*. Shortwave solar radiation easily penetrates to the surface without much absorption by the gases that comprise the atmosphere. As the sun heats the surface during the day, the earth warms and increases its output of infra red, or longwave radiation. The gases of the atmosphere, being relatively good absorbers of longwave radiation, are warmed and experience a rise in temperature. Thus, the *immediate source of energy to heat the air* is the surface of the earth. The daily cycle of radiation and air temperature is shown in Figure 5.2.1.

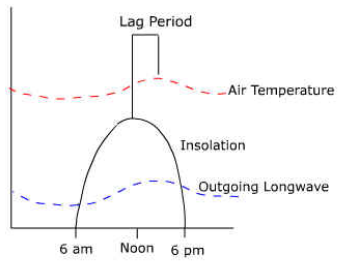


Figure 5.2.1: Daily Cycle of Radiation and Temperature

Solar radiation increases after sunrise to a maximum at noon and then decreases to a minimum at sunset. Outgoing radiation increases after sunrise but lags somewhat behind the insolation curve. The graph for air temperature follows the same pattern as that of outgoing radiation. This should seem reasonable as it is the absorption of outgoing energy from the surface that determines air temperature. The amount of time between maximum incoming energy and maximum temperature over the day is known as the ***daily temperature lag.***

A similar type of lag occurs on an annual basis. The ***seasonal lag of temperature*** is the amount of time between the highest incoming insolation and highest temperature on an annual basis. For instance, in the midlatitudes the highest angle that the sun makes with the surface, and thus the most intense heating, occurs around June 22nd. It isn't until about a month later that the highest temperatures occur. The lag is often longer near a large body of water like the Great Lakes or the ocean. A temperature lag of two months is not uncommon for places located near large bodies of water.

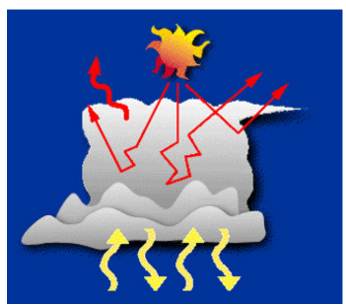


Figure 5.2.2: Cloud effects on radiation (Courtesy NASA Earth Observatory, Source)

Clouds have an impact on the radiation balance and air temperature of a place. Clouds can block incoming solar radiation by reflection of their tops. Clouds also act to diffuse light as it penetrates towards the surface. Both of these would act to cool the atmosphere. Clouds and water vapor are good absorbers of longwave radiation emitted by the earth's surface too. You've probably noticed that the warmest evenings tend to be when we have a heavy cover of clouds. These clouds absorb the radiation emitted by the earth and radiate it back down toward the earth's surface, warming the air. The coldest evenings occur during cloudless conditions. The lack of clouds in the desert creates large daily temperature ranges. During the day, sunlight streams to the earth's surface heating it to very high temperatures. Near surface air temperatures are very high as a result. At night, the absence of clouds allows emitted longwave radiation to escape to space causing the surface to cool and the air above to do so as well.

The atmosphere is also heated by the exchange of sensible heat between the surface and the air above. Sensible heat is transferred into the air by conduction and convection. Heat is most efficiently moved by turbulent eddies, or swirls of vertically moving air. The initial transfer is due to the presence of a temperature gradient between the surface and the air. If the surface of the earth is warmer than the air above, heat will be transferred upwards raising the temperature of the air. If the air is warmer than the surface, heat will be transferred towards the surface, thus cooling the air. The lag of temperature behind incoming radiation is also a result of the time it takes for sensible heat to transferred upwards.

Air Temperature, Water Bodies and Continentality

Air temperature is greatly affected by the location of a place relative to a large body of water. The impact of continental location on weather and climate characteristics of a place is called "***continentality***". Air temperature near or over bodies of water is much different from that over land due to differences in the way water and land heat and cool. Properties that affect water temperature are:

- Transparency
- Allocation of Q*
- Ability to circulate
- Specific heat

Explore how each of these properties affect the temperature of air by clicking on the buttons below.

Norfolk, VA on the east coast is influenced by air msases from the continent and the nearby ocean. It location results in a moderate temperature range. Norfolk and Wichita have a one month seasonal lag period.

Transparency | Allocation of Net Radiation | Circulation | Specific Heat | Continentality

Air Temperature and Air Mass Movement

If radiation was the only cause of temperature at a place, the daily and seasonal cycle of temperature would be very regular and exhibit the temporal pattern discussed earlier. The movement of large air masses across the surface can drastically change all this. The movement of a very cold air mass into a region can drop temperatures during the day when we expect the highest temperatures. Or if a warm air mass streamed over us at night, we might experience the highest temperature of the past 24 hours during the evening hours rather than during the daytime.

An ***air mass*** is vast pool of air, covering thousands of square kilometers, having about the same humidity and temperature characteristics over its horizontal extent. Air masses are classified based on the temperature and humidity at their ***source region***. Sources for air masses may be either oceanic or continental. Those that are oceanic tend to be moist while continental air masses are typically dry. Latitudinally, air masses form near the equator, in the subtropical zones, "polar" regions, and the Arctic and Antarctic. Most people think of the polar regions as those being located at the pole. For air masses, the polar source region is approximately 60 degrees north or south latitude. Combining the type of surface and latitude we derive a classification for the different kinds of air masses. A few are listed below and their geographic origin is shown in Figure $5.2.3$. We'll deal with air masses in more detail when we investigate weather systems.

- ***Maritime Tropical*** (mT)
  - Originates over the tropical oceans
  - Warm and Moist
- ***Continental Polar*** (cP)
  - Originates over high latitude continents (about 60 degrees north)
  - Cold and dry
- ***Maritime Polar*** (mP)
  - Originates over mid to high latitude oceans.
  - Cool and moist

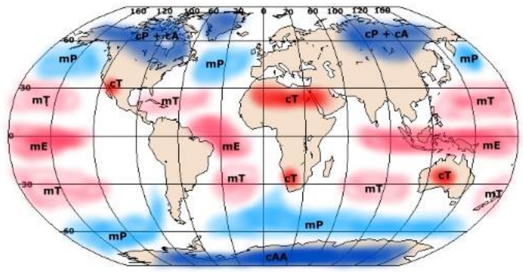


Figure 5.2.3: Global air mass source regions

Influence of air masses on temperature at a place.

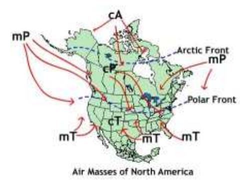


Figure 5.2.4: Air masses affecting North America.

The influence that air masses have on the temperature of a place depends the location with respect to the source of the air mass and the ***trajectory*** of the air mass as it moves from its source region. For instance, if one is located in the heart of an air mass source region, your climate will be fairly uniform throughout the year. If you lived in north central Canada you are located in the heart of the continental polar air mass (cP). You should expect temperature to be cool to cold, and the humidity relatively low throughout much of the year. However, if you live in central Illinois, you will experience a much greater variation in temperature because you are in the boundary zone between several different air masses. Two air masses in particular influence this region, cP and mT. The cP air brings cool, dry weather while mT air is responsible for humid and warm conditions. When these air masses collide, storms are generated.

Inversions

Under normal circumstances, air temperature tends to decrease with increasing elevation above the surface through the troposphere. Under particular conditions the lapse rate of temperature is reversed and temperatures increase with increasing elevation creating an **inversion** or **inverted lapse rate of temperature.**

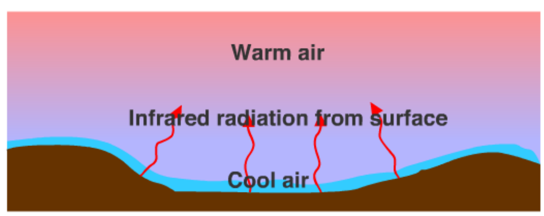


Figure 5.2.5: Radiation inversion

A **radiation inversion** commonly occurs when the evening air is still and there are no clouds to trap heat. Surface temperature drops as longwave radiation emitted by the Earth escapes to space. Air in contact with the surface cools, but that at a higher elevation and not in direct contact with the earth remains somewhat warmer creating the inversion. Cool air will collect in depressions as air density increases and gravity pulls it down slope.

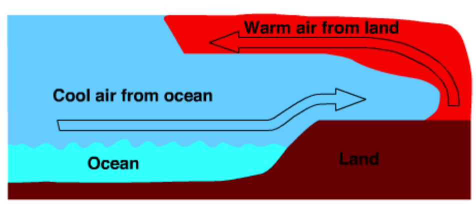


Figure 5.2.6: Sea breeze inversion

Sea breeze inversions occur along windward coasts bordered by cold ocean currents. The bottom layer of a warm maritime air mass originating over the ocean becomes cooler upon coming in contact with the cooler water bordering the coast. This creates cooler air near the surface with warmer air aloft.

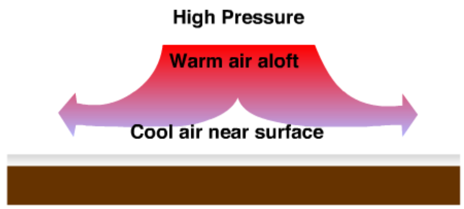


Figure 5.2.7: Subsidence inversion

Areas dominated by high pressure are also subject to inversions. **Subsidence inversions** form when subsiding air undergoes adiabatic heating aloft, while air in contact with the surface remains cooler. Subsidence and subsidence inversions in association with high pressure are discussed in Chapter 6.

5.3: Explaining Patterns of Air Temperature

Explaining Patterns of Air Temperature

Global patterns of air temperature are a reflection of the relative importance of sun angle and insolation intensity, day length, and location with respect to water bodies. We have found that low latitude locations experience less variation in sun angle and day length than do mid- and high latitude locations. Places located near large bodies of water tend to have more moderate temperatures than those further inland.

Mapping Patterns of Air Temperature

Isotherms, lines connecting points of equal air temperature are used to map the geographic pattern of temperature across the earth's surface. The spacing of isotherms depict the temperature gradient across a portion of the Earth's surface. Widely spaced isotherms (line A-B in Figure 5.3.1) indicate a small change in temperature over distance and closely spaced isotherms (line C-D in Figure 5.3.1) indicate large changes in temperature.

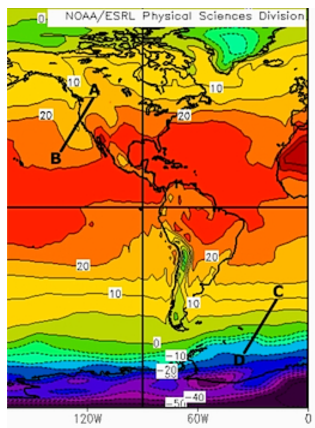


Figure 5.3.1: Isotherms and Temperature Gradient

The shape of isotherms as they appear on a map are influenced by the distribution of large land masses and water bodies and the time of the year. Follow the 10^C (50F) isotherm from left to right across the Figure 5.3.2. During January, the water stays warmer than the land causing the 10^C isotherm to shift toward the south. In July (Figure 5.3.3) the 10^C isotherm swings to the north as we move from the cool water to the warmer land. This differential heating of land and water results in a small variation in the position of the 10^C isotherm over water but a much larger variation over land.

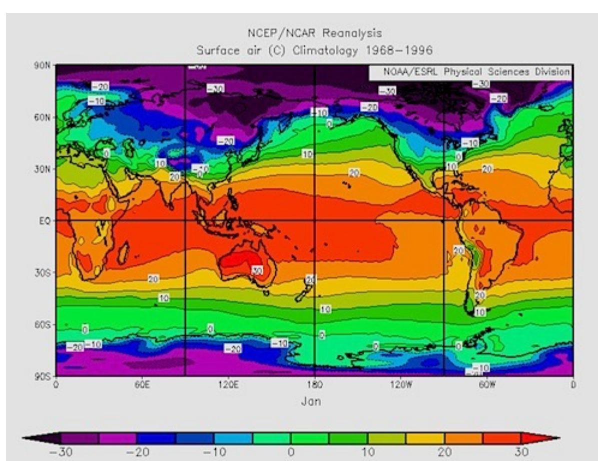


Figure 5.3.2: CAverage January Temperature

We can certainly see the effect of differential heating of oceans and continents in the average January and July temperature maps depicted in figures 5.3.2 and 5.3.3. The isotherms are more linear (straight across) in the Southern hemisphere. Isotherms bend much more between seasons in the Northern Hemisphere than in the Southern Hemisphere. The Southern hemisphere is more uniformly water than the Northern hemisphere. Large landmasses in the Northern hemisphere cause isotherms to bend toward the equator in winter and poles in summer as they change their temperature much more than the water. Air temperatures over land fluctuate more because land changes its temperature much more rapidly than ocean water does. Thus they shift north and south much more over land through the year than they do over water.

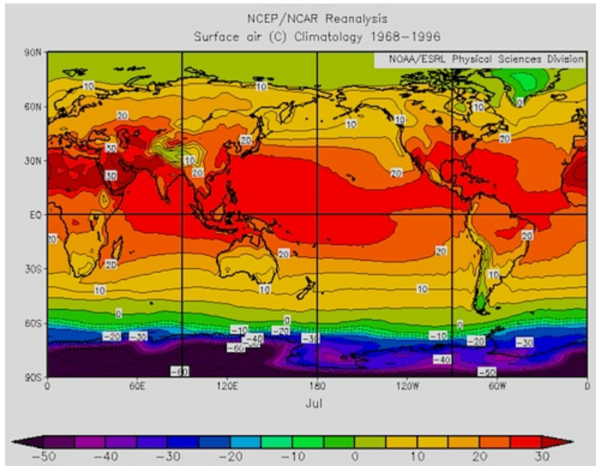


Figure 5.3.3: Average July Temperature

Comparing the difference in the values of the isotherms between seasons, the smallest temperature ranges are found near the equator while the largest are found over high latitude continental interiors, Siberia for example.

The difference in temperature across latitudes is the latitudinal temperature gradient. The winter hemisphere (January for the Northern hemisphere, July for the Southern Hemisphere) has the larger temperature gradients as shown by the closely spaced isotherms. Also note that the temperature gradient is steepest in the midlatitude to subarctic geographical zones. Here is where strongly contrasting tropical and polar type air masses clash along the polar front.

Latitudinal Patterns (north to south patterns)

The values of the isotherms validate our general conception of the distribution of world temperatures. Low latitudes that experience the highest sun angles throughout the year have the highest air temperatures. The highest temperatures occur in the tropical and subtropical deserts of North Africa, Australia, and the southwestern portion of the United States. Because the angle of the sun doesn't vary much during the year and day length is about the same, annual temperature ranges tend to be small, on the order of only a few degrees. However, daily temperature ranges can be quite large as pointed out earlier in this chapter.

High latitude locations have much lower annual temperatures as the sun never gets directly overhead and sun angles are quite a bit lower than those in low latitudes. However, the seasonal temperature range is large. Cold air masses penetrate south dropping air temperatures during the winter months. During the summer, warm tropical air masses stream toward higher latitudes raising temperatures. The movement of air masses and more varied sun angles results in larger temperature ranges than one experiences in the low latitudes.

Longitudinal Patterns (west to east patterns)

Longitudinal patterns of temperature reflect the influence of continentality and ocean circulation. Let's examine the longitudinal temperature patterns one sees in the midlatitudes of North America. In the mid-latitudes the prevailing wind direction is from west to east. Places located along the coast receive a constant influx of oceanic air throughout the year. Because oceans don't change their temperature much during the year, the air above them doesn't change much either. When the oceanic air streams on to land, temperatures tend to be rather mild.

The changes in air temperature one experiences as you travel from west to east across a midlatitude continent largely reflect the influence of continentality. The temperature range along the west coast of North America tends to be small due to the constant influx on oceanic air. Temperature extremes increase as distance from the coast increases. In the interior of the North American continent, warm air masses from the Gulf of Mexico work their way northward, especially during the summer. During the winter, cold continental polar air masses dominate. The great difference in the temperature of these two air masses results in a large temperature range. Air masses moving to the east from the interior tend to be warm, but the proximity to water keeps air temperatures mild giving east coast locations moderate ranges of temperatures.

Table 5.3.1 West - East comparison of Annual Temperature Range

City	January Temperature	July Temperature	Temperature Range
San Francisco, CA	9.6°C (49.3°F)	16.2°C (61.1°F)	6.6°C (11.8°F)
Dodge City, KS	-.4°C (31.3°F)	26.1°C (79°F)	26.5°C (47.7°F)
Atlantic City, NJ	0°C (32°F)	23.8°C (74.84°F)	23.8°C (42.8°F)

Temperature Trends

Figure 5.3.4: Geoscientist examines ice core used to study changes in atmospheric composition. (Courtesy: National Ice Core Laboratory, NOAA)

The fact that atmospheric gases contribute to the heating of the Earth is not new. A hundred years ago, Swedish scientist Svante Arrhenius became the first person to investigate the effect that doubling atmospheric carbon dioxide would have on global climate. Though all atmospheric scientists agree that there is a greenhouse effect, not all agree on the impact that human beings are having on it. In particular, many cannot agree that the present global warming that we are experiencing is a product of human activities. Analysis of ice cores has shown a significant variation in the carbon dioxide content of our atmosphere which has affected global air temperatures since the great ice sheets marched across the continents. Measurements of greenhouse gas concentrations over the last 150 years have shown a steady increase in carbon dioxide with an apparent increase in global temperatures as a result. Research has shown that there has been a 30% increase in the carbon dioxide content since the dawn of the industrial age. This increase is due to a number of activities such as fossil fuel burning, deforestation, and loss of other carbon dioxide "sinks" like wetlands and forests. The burning of fossil fuels releases stored carbon into the atmosphere raising the carbon dioxide content of the air. Forest removal leaves carbon dioxide in the air to enhance the natural greenhouse effect.

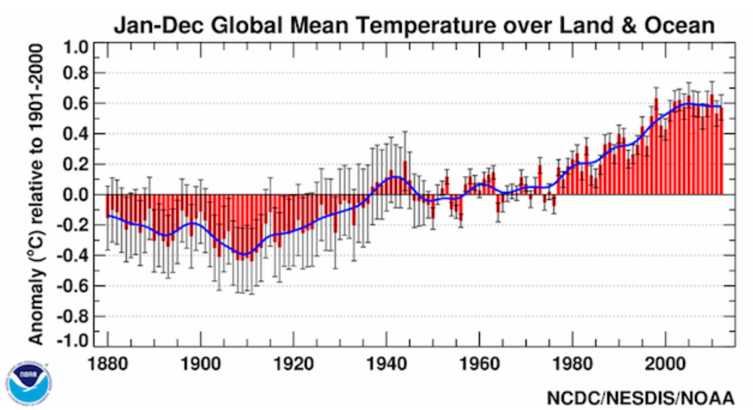


Figure 5.3.5: Global mean temperature Anomalies relative to 1901 - 2000 temperature (Courtesy NCDC/NESDIS/NOAA)

Increasing levels of greenhouse gases results in rising global air temperatures. Global mean surface temperatures have increased roughly 1.53°F (0.85°C) from 1880 to 2012. The annual trend in average global air temperature through December 2012 is shown in Figure 5.3.5. The range of measurement uncertainty is indicated by the gray vertical bars. The temperature trends over the past 100-plus years in Figure 5.3.6 clearly indicate rising temperatures on all continents and over the oceans.

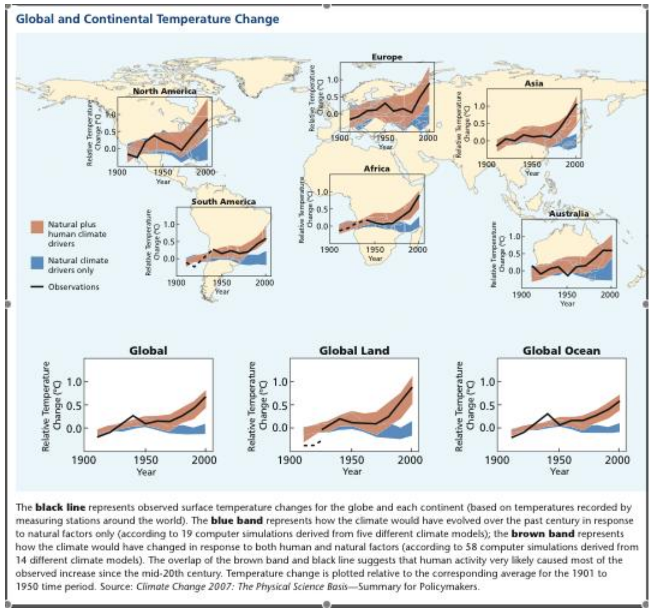


Figure 5.3.6: Global and Continental Temperature Change, 1900 - 2000. Data for the last hundred years already show clear trends in warming for the globe and continents. (Source)

The last decade, 2000-2009, ended on the second warmest year on record. The temperature anomaly map (Figure 5.3.7) shows the departure from "normal" for the reference period of 1951 through 1980. Very little of the earth showed cooling while most experienced warming. The greatest warming occurred in the Arctic, coinciding with changes in surface albedo as annual sea ice diminishes.

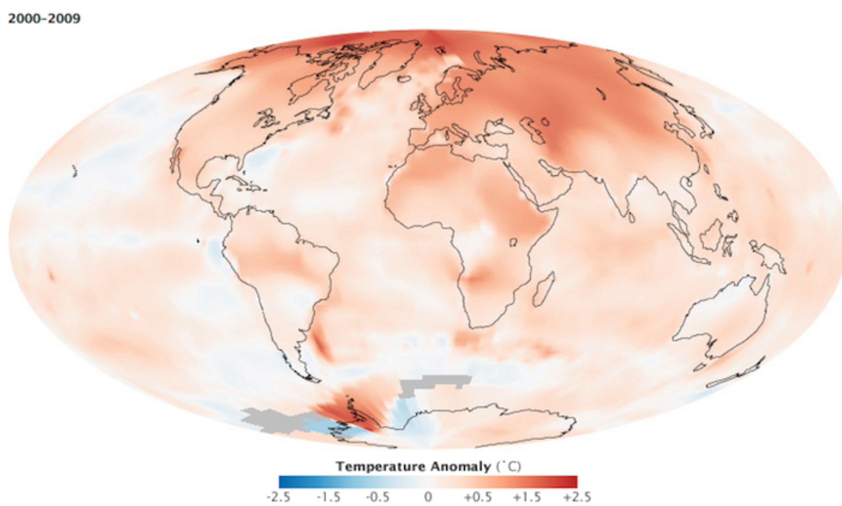


Figure 5.3.7: 2000 - 2009 Temperature Anomaly. (Courtesy NOAA EOS)

Video: "Global Warming 101" (Courtesy of National Geographic)

5.4: Getting Ready for Chapter 5

Chapter 4, "Energy and Radiation" is one of the most important chapters of this book. In it we discovered that the energy received from the Sun drives many of the environmental processes acting at the surface of the Earth. As we look ahead to chapter 5, "Air Temperature" and beyond we'll see how important this material is. The absorption of longwave radiation and and the transfer of sensible heat affect the temperature of the air. When water changes phases it gains or loses latent heat, affecting the temperature of the surrounding environment.

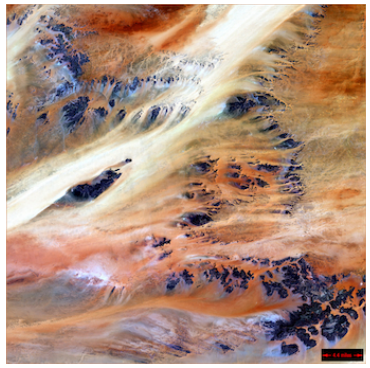


Figure 5.4.1: High sun angles and lack of clouds results in much insolation in the Sahara Desert (Landsat image). (Courtesy NASA Source)

Figure 5.4.2: Low sun angles and high albedo results in very little absorbed solar radiation in the ice-covered continent of Antarctica. (Courtesy Jim Yungel/NASA, Source)

The geography of air temperature and what controls it is the subject of chapter 5. In chapter 5 we'll examine horizontal and vertical variations in air temperature that will be important in explaining atmospheric and geomorphic processes. For instance, differences in temperature over distance affects air pressure and in turn determines how hard the wind blows. Wind erodes precious top soil, arranges sand into beautiful dunes of various shapes, and creates waves that sculpt coastlines. We'll conclude the chapter by looking at future patterns of air temperature resulting form global warming.

What you should already know ...

Before beginning you should be comfortable with the material covered in Chapter 2 The Earth System and Chapter 4 Energy and Radiation. You should have a good understanding of the controls over the distribution of insolation, longwave radiation, net radiation,sensible and latent heat transfer.

? Quiz 5.4.1

1. Which of the following does not need an intervening medium to transfer energy?

   A. conduction
   B. convection.
   C. radiation
   D. all require an intervening medium

2. The earth primarily emits ____ radiation while the sun primarily emits_ radiation.

   A. shortwave; shortwave
   B. shortwave; longwave
   C. longwave; shortwave

D. longwave; longwave

3. Clouds
   A. are good absorbers of shortwave radiation emitted by the sun.
   B. are good absorbers of longwave radiation emitted by the earth.
   C. are good absorbers of both longwave and shortwave radiation.
   D. are poor absorbers of both longwave and shortwave radiation.
4. The troposphere
   A. usually exhibits an increase in temperature with an increase in altitude.
   B. has a normal lapse rate of 1C.
   C. is primarily heated by solar radiation.
   D. is primarily heated by energy emitted by the earth.
5. The heat used to change the temperature of the air is called
   A. potential heat.
   B. sensible heat.
   C. latent heat.
   D. ground heat.
6. A positive sensitive heat transfer means
   A. heat is transfer from the surface into water.
   B. heat is transferred from the surface downward into the subsurface.
   C. heat is transfer from the surface into the air.
   D. none of the above.
7. The subsolar point on June 22 is
   A. 23.5 degrees S
   B. 0
   C. 66.5 degrees N
   D. 23.5 degrees N
8. Net radiation for the year is greatest
   A. over tropical oceans.
   B. off the west coast of the United States
   C. over the Arctic ocean
   D. in the Sahara desert
9. ____ heat is used in the evaporation process.
   A. Sensible
   B. Latent
   C. Ground
   D. Potential
10. Insolation for the year is greatest
    A. over tropical oceans.
    B. off the west coast of the United States.
    C. over the Arctic ocean.
    D. in the Sahara desert.

Answer

1. C
2. C
3. B
4. D
5. B
6. C

7. D
8. A
9. B
10. D

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous material.

If you scored less than 70% you should consider reviewing the previous material and seeking help from your instructor.

5.5: Future Geographies - Global Warming and Regional Temperature Patterns

An enhanced greenhouse effect caused by human activities is expected to upset the radiation balance of the earth system resulting in a variety of changes to the geography of our planet. The most notable change will be the spatial pattern of air temperature. The global temperature anomalies between 1880 and 2010 shown in Figure 5.5.1 show that temperature changes are occurring to a greater degree in some regions more than others. The most notable region is the Arctic where the disappearance of sea ice has made the surface less reflective causing surface and air temperatures to rise.

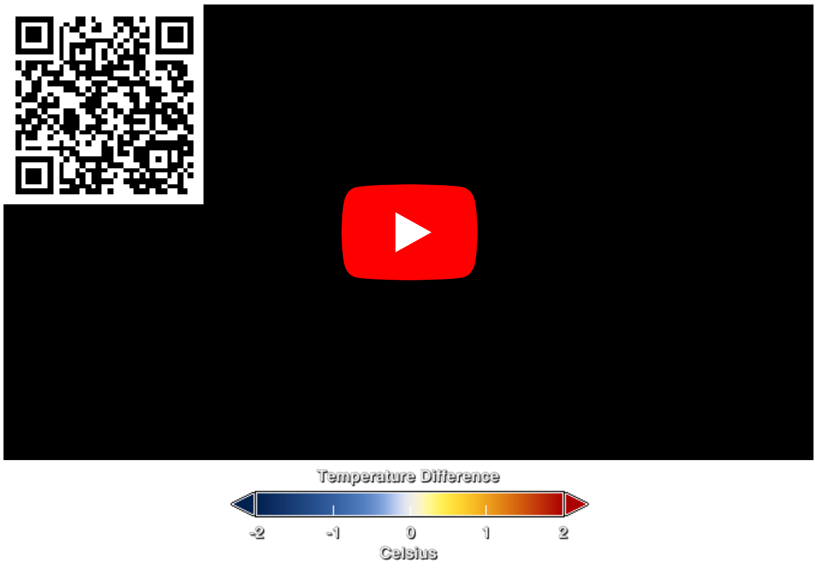


Figure 5.5.1: Five-Year Average Global Temperature Anomalies from 1880 to 2010 relative to base period of 1951 - 1980. (Courtesy NASA GSFC, source)

Predicting changes to the the global patterns of temperature is a challenging undertaking for scientists as they must rely on models for their forecasts. The models are numerical representations based on how our earth system functions. They are limited by our understanding of earth system processes and long-term data sets. Using a variety of models, geoscientists have forecast a range of possible scenarios. One thing is clear from their predictions, that the amount of temperature change varies geographically.

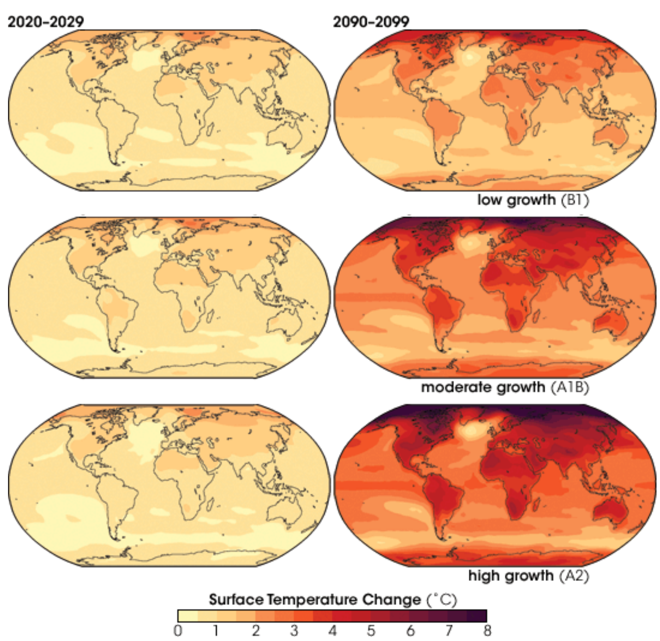


Figure 5.5.2: Projected future regional patterns of warming based on three emissions scenarios: low, medium, and high growth. (Source: NASA Earth Observatory, based on IPCC Fourth Assessment Report (2007))

Arctic regions

The arctic regions appear to be impacted the most. Observations of mean annual surface air temperature over the past 50 years has increased 2^{o}C to 3°C in Alaska and Siberia and decreased by 1°C over southern Greenland. Mean annual surface air temperature over the Arctic region (north of 60° latitude) is projected to increase 1.1°F by 2050 and 4.4°C by 2100.

The Midlatitudes

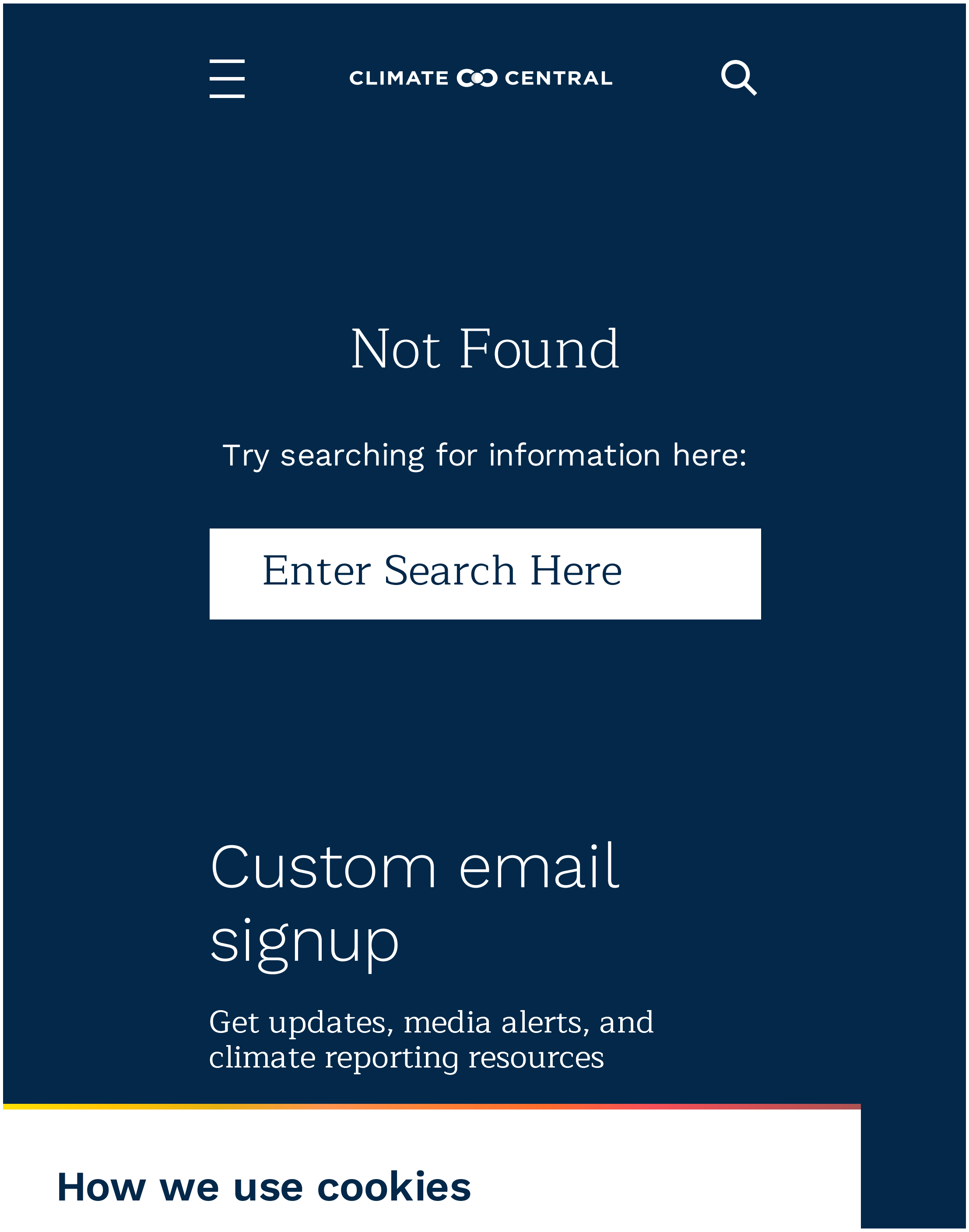
Climate change is expected to increase the frequency of extreme events in midlatitude regions like the midwest United States. A severe drought in 1988, heat waves in 1995 and 1996, flooding on the Mississippi in 1993 (100-year flood) and 2002, and numerous tornadoes and severe thunderstorms can be expected in the future. Illinois will be become warmer, especially in the summer having temperatures more like present-day Oklahoma or Arkansas. Wisconsin temperatures could rise 2.7^o-5.5^{o}C in the winter and by 4.4^o - 9.4^o C during the summer by 2100. Extreme heat will be more common than today. Southern Ontario's winter temperatures are expected to increase by 3^o - 7^{o}C and summer's to be 4^o-8^{o}C warmer. More southerly states like Illinois will experience less warmer. Winter temperatures are expected to increase by 2.7^o-3.8^{o}C during the winter in Indiana while summer temperatures are expected to increase by 4.4^o - 5.5^{o}C. Growing seasons could be 4 to 7 weeks longer in Wisconsin and 3 to 6 weeks longer to the south in Illinois. Under a medium-high emissions scenario, the IPCC predicts a 3^o- 4.9^{o}C change statewide in California.

Subtropical Regions

Though most geoscientists have felt that the Arctic will show the first true signs of a future climate, dramatic changes have been recorded in subtropical regions. Recent analysis of satellite data has found that each hemisphere's jet stream has moved poleward by about 1 degrees of latitude or 70 miles. Jet streams are found on the poleward limit of the tropics which means they are getting wider. Continued movement will mean the spread of subtropical deserts like the Sahara. Regional climate predictions for southern Africa during summer suggest a warm season increase of 2^{o}C to 4^{o}C over the subcontinent, with the doubling of carbon dioxide. Current climate models project regional temperature increases approximately 2 to 5.5^{o}C by 2100, with an 4.5^o to 8.3^{o}C increase in the average summer heat index for the southeastern United States.

Tropical Regions

Most model predictions indicate the smallest change to temperature will occur in tropical latitudes. Depending on model assumptions and location, annual changes on the order of .1^{o}C to 3^{o}C are predicted. Analysis indicates that there may be significant differences within the tropics, especially in Asia, depending on proximity to the sea. Warming is projected to be least in the islands and coastal areas throughout Indonesia, the Philippines, and coastal south Asia and Indo-China and greatest inland. Even with relatively small temperatures, they can be devastating. A 3^o Celsius rise in temperature would result in a 60 percent reduction in the arabica coffee area in Brazil, the world's largest producer.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5.6: Review and Additional Resources

Review

Assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Then, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts 5.6.1

- **Temperature**
  a measure of the heat content of a body
- **Fahrenheit scale**
  scale used for measuring temperature; mainly in the US; based on body temperature
- **Celsius scale**
  an accepted international system of measurement because it is based on a decimal scale having 100 units between the freezing and boiling points of water.
- **Kelvin scale**
  It is an absolute scale given that at absolute zero all molecular movement ceases.
- **Daily temperature range**
  the difference between the highest and lowest temperatures over a 24 hour period
- **Average daily temperature**
  the sum of highest and lowest temperature of the day divided 2
- **Average monthly temperature**
  the sum of the average daily temperature divided by the number of days in the month
- **Annual temperature range**
  the difference between the highest and lowest monthly temperature for a place
- **Average annual temperature**
  the sum of the mean monthly temperature divide by 12.
- **Daily temperature lag**
  The amount of time between maximum incoming energy and maximum temperature over the day
- **Annual or Seasonal temperature lag**
  the amount of time between the highest incoming insolation and highest temperature on an annual basis
- **Land/Sea contrasts**
  Water is a transparent medium and land is opaque. Water allows light to penetrate to depth, leaving the surface layers cooler than they would be if the surface was opaque. A cooler water surface results in cooler air temperatures above.
- **Continentality**
  The impact of continental location on weather and climate characteristics of a place
- **Specific heat**
  the amount of heat required to raise the temperature of one unit of mass of a substance by one degree celsius

- **Air mass**

  vast pool of air, covering thousands of square kilometers, having about the same humidity and temperature characteristics over its horizontal extent

- **mT air mass**

  Maritime Tropical - originates over the tropical oceans; warm and moist

- **cP air mass**

  Continental Polar - originates over high latitude continents; cold and dry

- **mP air mass**

  Maritime Polar - originates over mid to high latitude oceans; cool and moist

- **Air mass trajectory and temperature**

  The influence that air masses have on the temperature of a place depends the location with respect to the source of the air mass and the trajectory of the air mass as it moves from its source region.

- **Radiation inversion**

  commonly occurs when the evening air is still and there are no clouds to trap heat.

- **Sea breeze inversion**

  occur along windward coasts bordered by cold ocean currents

- **Subsidence inversion**

  form when subsiding air undergoes adiabatic heating aloft, while air in contact with the surface remains cooler.

- **Isotherm**

  lines connecting points of equal air temperature are used to map the geographic pattern of temperature across the earth's surface.

- **Global warming**

  Increasing levels of greenhouse gases results in rising global air temperatures

? Self-assessment Quiz 5.6.1

1. The annual temperature range is greatest
   A. in the east coast of the United States (Washington D.C. for example)
   B. in the interior of the continent (Kansas City, KS, for example)
   C. the west coast of the United States (Los Angeles, CA, for example)
   D. near the equator.
2. The air temperature of a large body of water does not change as much as nearby land because
   A. most of the net radiation is used for latent heat transfer rather than sensible heat.
   B. mixing of the water occurs
   C. the specific heat of land is lower than that of water
   D. all the above are true
3. The coldest temperature over the course of the day normally occurs
   A. at midnight
   B. at sunset
   C. just after sunrise
   D. at 8:00 pm
4. The daily range of temperature is greatest

A. when skies remain cloudless during the day and night
B. when the sky remains cloudy all day and night
C. when the sky is cloudy during the day but cloudless at night
D. when the sky is cloudless during the day but cloudy at night.

5. The seasonal lag of temperature
   A. is greater for places located on the coast
   B. is greater for places located in the interior of a continent
   C. is not any different if you are located on a coast or in the interior of the continent
   D. is nonexistent along a coast
6. Which of the following air masses is the coldest during the winter?
   A. mP
   B. cP
   C. mT
   D. they are all equally cold during the winter but not during the summer
7. Isotherms
   A. in the Northern Hemisphere bend towards the north when passing over passing over the Gulf Stream current during the winter.
   B. tend to be linear in form in the Southern Hemisphere.
   C. are more closely spaced over the North American continent in winter than summer.
   D. exhibit all the above.
8. Which of the following statements is false?
   A. Maximum outgoing radiation and maximum incoming solar radiation generally occur at the same time.
   B. Maximum outgoing radiation generally occurs at the same time as maximum daily temperature.
   C. Maximum daily temperature lags behind maximum daily incoming solar radiation.
   D. Maximum outgoing radiation generally lags behind maximum incoming solar radiation.
9. Which of the following energy balance components has the most significant impact on the temperature of the air above the surface?
   A. sensible heat transfer
   B. latent heat transfer
   C. ground heat transfer
   D. none of the above affect the temperature of the air.
10. Heat transfer into the air is most efficient
    A. when there is turbulent mixing\
    B. when the air is still
    C. when there is no difference in the temperature between the air and the surface
    D. none of the above

Answer

1. B
2. D
3. C
4. A
5. A
6. B
7. D
8. A
9. A
10. A

Additional Resources

Connections: "Warming Oceans". (NPR) *All Things Considered*

CHAPTER OVERVIEW

6: Atmospheric and Ocean Circulation

Figure 6.1: Hurricane-generated waves break on sea wall (Courtesy NOAA)

The atmosphere around us is in constant motion, even if we don't feel the wind across our face. Molecules of air dart about transferring heat and moisture from one place to the next at a variety of geographic scales. The animation below shows the wind pattern over North America during 1988 when this region experience a severe drought. Winds are show at three heights, the blues arrows at 9,300 meters (30,000 feet), white arrows at 5,500 meters, and black (18,000 feet) and 1,500 meters (5,000 feet). Watch the animation by clicking the play button and describe what you see.

One feature that stands out is a zone of winds making broad loops along the boundary between the United States and Canada. One can see the arrow moving much faster through this zone from the west than other regions. Why does this region of high velocity winds occur here and what are the implications of its meandering path? Is this a typical wind pattern or could it change in the future?

In this chapter you will learn how winds at a variety of spatial scales form and what controls their behavior. You'll look at how atmospheric pressure and wind patterns influence weather and climate. Finally you will delve into what causes oceanic circulation and how it relates to atmospheric motion.

Learning Objectives

By the end of the chapter you should be able to:

- Define air pressure and what determines air pressure at a place.
- Describe the forces acting on wind and how they affect wind direction and speed.
- Interpret the strength of a pressure gradient from a weather map.
- Determine wind speed and direction from a weather map.
- Draw a diagram of the air flow around highs and lows in the Northern and Southern hemispheres.
- Explain the relationship between upper-air circulation and surface pressure systems.
- Explain how land/sea breeze, mountain/valley, and Santa Ana winds form.
- Explain how the monsoon circulation operates.
- Describe how El Nino/La Nina conditions form and their effects.
- Construct a diagram and label the global pattern of pressure and wind.
- Describe the potential impact of global warming on atmospheric circulation.

See if you are prepared for this chapter by Getting Ready for Chapter 6: Atmospheric and Oceanic Circulation.

6.1: Getting Ready for Chapter 6

6.2: Air Pressure

6.3: Controls over wind direction and speed

6.4: Cyclones and Anticyclones

6.5: Local Scale Wind

6.6: Regional Scale Winds - The Monsoon

6.7: Global Scale Circulation

6.8: Wind and Pressure Aloft
6.9: Ocean Circulation and Atmospheric Circulation
6.10: Future Geographies - Atmospheric Pressure and Winds
6.11: Review and Additional Resources

6.1: Getting Ready for Chapter 6

In Chapter 5 we learned that the temperature at any place is a function radiant energy (e.g., solar and terrestrial longwave radiation) and heat (e.g., sensible heat). The amount of energy and heat may be controlled by local factors such as cloudiness, proximity to large bodies of water, and the presence of different air masses. The change in temperature from one location to another, the temperature gradient, is a function of the variation in the energy/heat content of the air from one location to the next. In other words, an energy gradient creates a temperature gradient.

Temperature affects many of the other elements weather and climate, like air pressure and humidity. Warm air has a tendency to rise and thus can promote lower pressure at the surface. Cold and dense air has a tendency to sink and promote higher pressure at the surface. Warm air is more likely to evaporate more water than cold air. Humid air rising from the surface may ultimately condense to form clouds which promote precipitation formation.

As we venture further, the role of temperature in determining the patterns in the earth system will become increasingly apparent and important. Plants and animals have particular temperature and moisture requirements for them to live, and thus the biogeography of Earth is closely correlated with patterns of temperature. Chemical reactions are controlled by temperature (and moisture), and thus the weathering and shaping of earth materials is affected. Temperature is important because if our climate continues to warm, the changing pattern of global temperatures will directly impact the future physical geography of Earth.

What you should already know...

Chapter 6 examines air pressure, wind and the circulation of the atmosphere and ocean. As you come to find out, air pressure, wind and atmospheric circulation is strangly influenced by the heating and cooling of the earth. Be sure you have a good understanding of the heating and cooling of the earth's surface discussed in Chapter 4 and Chapter 5. A quick review of Chapter 3, and "Isolines" from Chapter 1 will prove helpful.

? Review Questions 6.1.1

1. Latitudinal temperature gradients
   A. are steeper in the winter
   B. are generally steeper in summer
   C. show little difference between seasons
2. Heat transfer by circulation of a fluid is called
   A. radiation
   B. convection
   C. latent heat
   D. conduction
3. Closely spaced isolines indicate
   A. a gentle gradient
   B. a steep gradient
4. The layer of the atmosphere closest to the surface is the
   A. troposphere
   B. stratosphere
   C. mesosphere
   D. thermosphere
5. The earth rotates in a ___ direction when viewed from above the North Pole
   A. clockwise
   B. counterclockwise
6. When comparing the temperature of nearby land and water
   A. water temperature tend to rise more quickly than land during the day
   B. land temperature tends to rise more quickly than water during the day
   C. water and land temperature tends to rise and fall at the same rate
7. Subsidence inversions

A. only occur at night
B. are associated with low pressure
C. form along coastlines
D. none of the above

8. A change in temperature without a physical exchange of heat is called
   A. adiabatic temperature change
   B. diabatic temperature change
9. _____ heat is released from water molecules and converted to ____ heat during condensation.
   A. sensible; latent
   B. latent; sensible
10. Latitudinal temperature gradients are steepest in which one of the following?
   A. The equatorial zone
   B. The tropical zone
   C. The subtropical zone
   D. The midlatitude zone

Answer

1. A
2. B
3. B
4. A
5. B
6. B
7. D
8. A
9. B
10. D

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous chapter.

If you scored less than 70% you should consider reviewing the previous chapter and seeking help from your instructor.

6.2: Air Pressure

Pressure variations across the Earth

Air pressure is the force exerted by the weight of a column of air above a particular location. To conceptualize the notion of air pressure, imagine a sealed container full of air as shown in Figure 6.2.1. When the molecules of air collide with the inside surfaces of the container they exert a pressure. The amount of pressure they exert depends on the number of collisions that occur between the molecules and the inside surface of the container. We can change the pressure in two ways. First, we can increase the density of the air by either putting more air molecules into the container or reducing the volume of the container. Secondly, we can increase the temperature of the air to make the molecules move faster and thus collide with the sides more often. Therefore, changes in air pressure can come about by changes in air density or temperature.

In nature, pressure variations across the surface of the Earth are created by mechanical or thermal means. Mechanical changes in pressure occur when air flow is impeded causing a mass of air to build up over a particular location thus increasing air pressure. Heating and cooling the air (thermal mechanisms) also create variations in air pressure. When air is heated it rises, and if pushed away aloft, surface air pressure decreases. Conversely if air is cooled, it subsides toward the surface causing air pressure to increase.

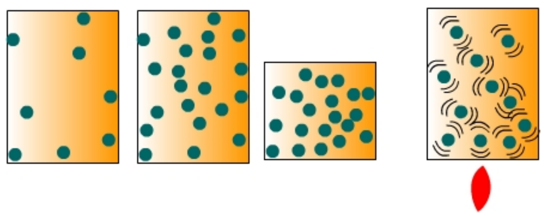


Figure 6.2.1: Air pressure within a sealed container.

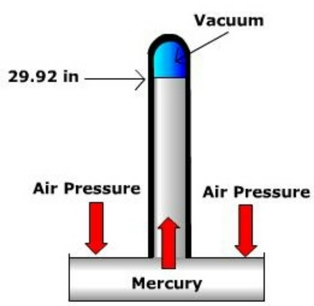


Figure 6.2.2: A mercury barometer.

Air pressure is measured using a ***barometer***. Several different barometers exist, two of the most common are the mercury barometer and the aneroid barometer. The mercury barometer is a tube with a reservoir of mercury at one end. Under average sea level conditions, the atmosphere exerts enough pressure to push a column of mercury up to the height of 29.92 inches. The aneroid barometer uses an *aneroid* or *sylphon* cell to measure pressure. The aneroid cell is a metal chamber that expands and contracts with changing air pressure. Though inches of mercury are often reported on your daily weather forecast (especially in the United States), meteorologists use millibars as the units of measurement for air pressure. Under average sea level conditions the atmospheric pressure is 1013.2 millibars (29.92 inches of mercury). Average sea level pressure serves as the division between what we call "high pressure" and "low pressure" at the surface. **High pressure** is defined as values greater than 1013.2 mb and **low pressure** is below 1013.2 mb.

Air pressure decreases as one moves upward through the atmosphere because the length of the column of air shortens and hence there is less mass above a given location. However, the rate of decrease is not the same between two elevations (Figure 6.2.3). Because air is highly compressible, the air is closely packed together near the surface (high density) and less densely packed aloft. In fact, over 90% of the atmosphere is found below 10 miles. As a result, the air pressure decreases more rapidly between two elevations close to the surface than between two points separated by the same distance aloft.

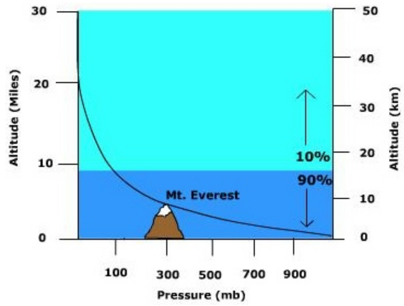


Figure 6.2.3: Vertical variation in atmospheric pressure.

As explained previously, we use an average value of sea level pressure to differentiate between high pressure and low pressure. Because air pressure decreases aloft, the average pressure at any point above the surface is less. At 5600 meters the average pressure is 500 mb. If on any given day the pressure is larger than 500 mb we consider it high pressure at this elevation. If we measure a smaller amount then it is low pressure *at this elevation*. Do not confuse high pressure with *higher* pressure and low pressure with *lower* pressure. Adding the "*er*" to the end of the word indicates a change relative to a previous state. For instance, lets say you measure the air pressure to be 1015 mb at the surface and 516 mb at 5600 meters. Both cases are under the influence of high pressure at their respective locations. However, the pressure is *higher* at the surface than at 5600 meters.

Analyzing air pressure patterns

Meteorologists have a variety of ways to visualize weather data, a map being the most common. To analyze pressure patterns, a constant height map is often used. A **constant height map** (also known as a "constant height chart") shows the distribution of pressure at sea level. **Isobars**, lines connecting points of equal air pressure are used to show pressure patterns on constant height maps. Most of the maps of air pressure in this book are constant height maps.

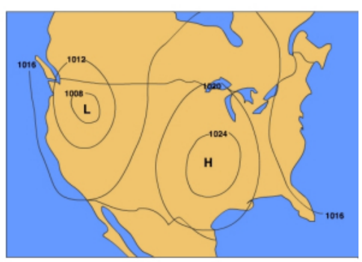


Figure 6.2.4: Constant height map with isobars

Another map that is used to analyze pressure patterns is called a **constant pressure map** (also known as a "constant pressure chart"). A constant pressure map shows the change in elevation of an **isobaric surface** which is a surface upon which the pressure is the same at all locations. By examining the height of an isobaric surface relative to it's normal elevation, one can discern where areas of high and low pressure are.

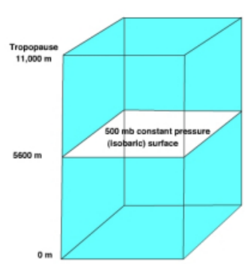


Figure 6.2.5: 500 mb constant pressure (isobaric) surface

The 500 mb surface is commonly used to by meteorologists in weather forecasting. The normal height of 500 mb surface is 5600 meters. Recall, that at the surface we consider high pressure to be greater than normal sea level pressure and low pressure to be less than normal sea level pressure. In a similar way we can use the normal height of the 500 mb surface to identify where high and low pressure areas are located.

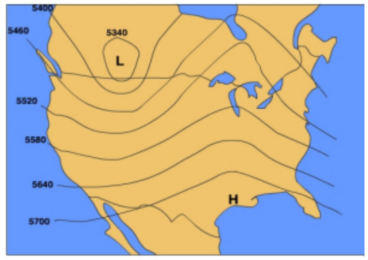


Figure 6.2.6: Constant pressure map with contour lines

Let's consider a simple situation to understand how the height of an isobaric surface relates to air pressure. Recall that air pressure is related to force exerted by the weight of a column of air above a given point. If air temperature varies through any part of an air column, the density and pressure will also vary. Figure 6.2.7 shows a column with warm air to the left and cool air to the right. The 500 mb surface is shown as the white surface dipping from left to right. Let's assume that the surface pressure remains constant. When air is heated it becomes bouyant causing it to rise and when cooled it sinks. As the warm air rises more air molecules will be found *above 5600 meters* than normal and thus the 500 mb surface is found at a higher elevation. To the right where cold air has sunk to the surface fewer air molecules than normal are found above 5600 meter and thus the 500 mb surface is found at a lower elevation. If there are more molecules above 5600 meter in the warm region, then high pressure is *located at 5600 meters*. If fewer air molecules are above 5600 meters in the cold region, then low pressure is *located at 5600 meters*.

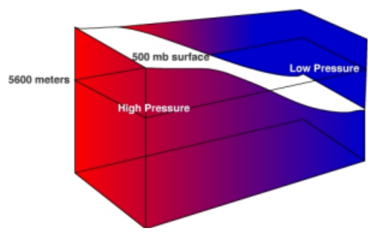


Figure 6.2.7: Air pressure - isobaric surface height relationship

6.3: Controls over wind direction and speed

Air is constantly moving to seek an equilibrium between areas of more air molecules (higher pressure) and those with less (lower pressure). You have probably experienced this by opening a container that has been vacuum packed. Because the container is vacuum packed, there is less air inside the can (lower pressure) than outside the can (higher pressure). When you open the container you here a "whoosh" as air rushes into it. The air rushing from outside the container into it is a wind, albeit at the microscale. ***Wind*** is nothing more than the movement of air molecules from one place to the next. The direction and speed of the wind represents the balance between three basic forces acting on it: the pressure gradient, the Coriolis force, and surface friction.

Pressure Gradient

The spacing of isobars indicates the change in pressure over distance otherwise known as a ***pressure gradient***. We can induce a change in pressure over distance by the unequal heating of the Earth's surface. This can be done when one location receives more incoming energy than another, possibly because one place has a higher sun angle than another. Heating the air in one place causes it to rise off the surface promoting low pressure with the pressure increasing away from that location. The creation of a pressure gradient initially causes the air to flow from higher toward lower pressure creating a wind. So in terms of a cause-and-effect relationship:

Energy gradient -> temperature gradient -> pressure gradient -> wind

The orientation or direction of a pressure gradient is always described as being from higher toward lower pressure. The speed of the wind is controlled by the strength of the pressure gradient, the stronger the pressure gradient the higher the wind speed. The strength of the pressure gradient can be discerned from the spacing of isobars on a weather map. Figure PC.4 shows two different pressure gradients. The distance between points A and B and C and D are the same but the amount of pressure change is quite different. You can tell that the pressure gradient is greater between A and B because the spacing of the isobars is much closer than between C and D. As a result, the wind blows much faster between A and B.

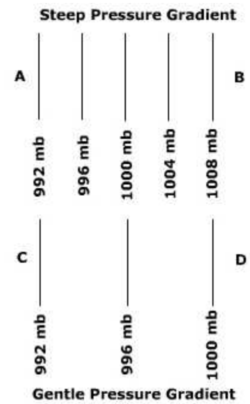


Figure 6.3.1: Isobar spacing and pressure gradient.

Coriolis Force

The Coriolis force is the effect of earth rotation on the direction of the wind. The Coriolis force arises for two reasons, first our directional system of latitude and longitude has been fixed to a rotating earth. Thus, our frame of reference for monitoring the direction of a free-moving object above the Earth is constantly changing. The second reason is the amount of turning about a vertical axis varies from a maximum at the poles and minimum at the equator. Demonstrate this by standing a pencil on end at the north pole and turn the globe. The pencil completes one full rotation. But standing the pencil on end at the equator and rotating the earth yields no rotation about a vertical axis. Figure 6.3.1 shows the deflection that a missile experiences when shot from the North Pole towards the Equator. Because the Earth, and the target, has rotated underneath the free-moving missile, it appears that the missile has veered off course (changed direction). Such is the case for winds blowing above the surface. The deflection works the same way for an east-west wind, the path will curve to the right as it moves across the surface. Go to Coriolis Force animation

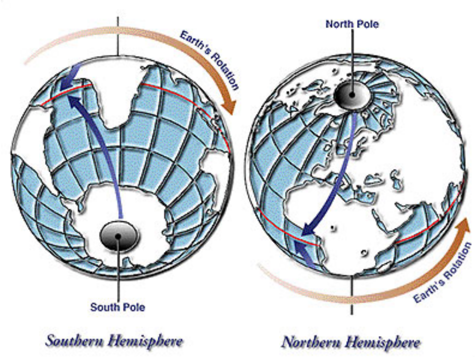


Figure 6.3.2: The influence of the Coriolis force on wind. (Courtesy NASA JPL, Source)

Though the air is deflected to the right of its path in the Northern hemisphere, in the Southern Hemisphere wind is deflected to the left of its path. Why the difference? It all has to do with perspective. Pick up a globe and spin it in a west to east direction. Now look down on it from above the North Pole. It appears to by spinning in counterclockwise direction. Now keep it spinning from west to east, lift the globe over your head and look at it from above the South Pole. It appears to be going in a clockwise direction. (Kind of weird, huh?)

Friction

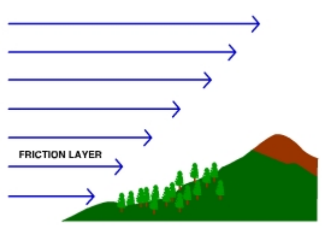


Figure 6.3.3: Friction Layer

Generally speaking wind speed increases with height above the surface as the frictional force of surface diminishes with height. The friction imposed on air mechanically slows the wind and diverts its direction. The ***friction layer*** is the layer of air that is influenced by friction caused by the surface. The friction layer varies in height across the Earth, but for the most part lies within about a kilometer of the surface.

Investigate how geoscientist measure and analyze wind by "Digging Deeper: Measuring, Visualizing, and Analyzing Wind Direction and Speed" or skip and continue reading.

✔ Digging Deeper: Measuring, Visualizing, and Analyzing Wind Direction and Speed

There are two basic measurements taken of wind conditions, speed and direction. As noted in this chapter, wind speed is simply how fast the wind is blowing. Wind direction is described as where the wind comes from, not where it's going to. Let's dig deeper into how scientists measure and visualize wind speed and direction when analyzing weather.

Instrumentation

Wind speed is measured using an anemometer. A typical anemometer consists of 3 or 4 spinning "cups" mounted at equal angles to one another and then attached to a rod. The cups rotate proportional to the air flow past them. The number of revolutions in a unit of time is converted into a wind speed and recorded on a data logging device or read from dial. The speed is reported in miles per hour, kilometers per hour, or knots.

Figure 6.3.4: Anemometer (right) and Wind Vane (left) (Courtesy NOAA, Source)

The Beaufort Scale was created in 1805 by Sir Francis Beaufort as a qualitative measure of wind condition effects on the sails of his ship. Thirteen classes, from 0 to 12, determined the number of sails to hoist. At 0 all sails would be raised with just enough wind to give steerage. At 6 half his sails would be up, and at 12 all sails would be down as conditions were to severe for canvas sails to withstand them. In 1906, the descriptions were changed to how seas behaved under different wind conditions. The Beaufort scale continues to be used by citizen weather spotters to estimate of conditions in the absence of instrumentation during severe weather.

Table 6.3.1 Beaufort Scale (Courtesy NOAA: Source)

Beaufort*	Avg Miles per Hour	Knots	Surroundings
0 calm		0-1	Smoke rises vertically and the sea is mirror smooth
1 light air	1.2 - 3.0	1 - 3	Smoke moves slightly with breeze and shows direction of wind
2 light breeze	3.7 - 7.5	4 - 6	You can feel the breeze on your face and hear the leaves start to rustle
3 gentle breeze	8.0 - 12.5	7 - 10	Smoke will move horizontally and small branches start to sway. Wind extends a light flag
4 moderate	13.0 - 18.6	11 - 16	Loose dust or sand on the ground will move and larger branches will sway, loose paper blows
5 fresh breeze	19.3 - 25.0	17 - 21	Surface waves form of water and small trees sway
6 strong breeze	25.5 - 31.0	22 - 27	Trees begin to bend with the force of the wind and causes whistling in telephone wires. Some spray on the sea surface
7 moderate gale	32.0 - 38.0	28 - 33	Large trees sway. Moderate sea spray
8 fresh gale	39.0 - 46.0	34 - 40	Twigs break from trees, and long streaks of foam appear on the ocean
9 strong gale	47.0 - 55.0	41 - 47	Branches break from trees
10 whole gale	56.0 - 64.0	48 - 55	Trees are uprooted and the sea takes on a white appearance
11 storm	65.0 - 74.0	56 - 63	Widespread damage
12 hurricane	75+	64 +	Structural damage on land, and storm waves at sea

A wind vane is a instrument to measure wind direction (on left in Table 6.3.1 above). At its most simple configuration it is a pointed rod with a vane mounted perpendicular to the rod and attached to a vertical pole on which it rotates. The vane acts to orient the pointed end into the wind and hence points to the direction the wind comes from.

An aerovane is an instrument that can measure both wind direction and speed simultaneously.Â The aerovane sits atop a pole and rotates as the wind direction changes. The propeller spins faster as the wind speed increases. The spin of the propeller at the front spins faster as the wind speed increases. A signal is sent to a data logger where the orientation of the aerovane and spin of the propeller is converted into units of wind direction and speed. A vane on the tail orients the instrument into the wind.

Figure 6.3.5: Aerovane. (Courtesy NOAA Source)

Visualization and Analysis

Once wind data has been recorded it can be archived in print, or more likely digital form and symbolized on maps for further analysis.

Wind direction

Wind direction can be reported as a direction or in degrees. Wind direction is symbolized on a weather map with a line radiating out from a point in the direction of the wind. The direction of the wind as symbolized in figure 6.3.6 is northeast.

Figure 6.3.6: Wind direction weather symbol

The prevailing wind the the direction that the wind comes from the most often. It can be determined by measuring the wind direction at many different times for a particular location and the calculating the percentage of times the wind comes from different directions. A wind rose is used to visualize the prevailing wind wind. The "rose" is constructed with bars or lines placed around a circle and drawn to a length proportional to the amount of time the wind blows from different directions. The prevailing wind shown in figure 6-D is from the south. Wind barbsor a color code can be added to show the average speed from a given direction.

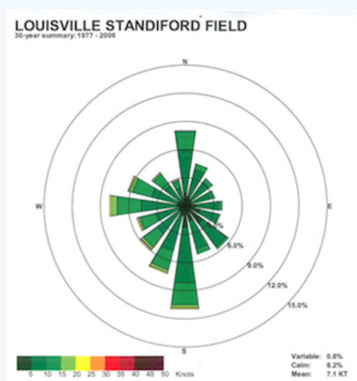


Figure 6.3.7: A wind rose. (Courtesy NOAA NWS (Source))

Wind speed

Wind speed is recorded in either miles per hour, kilometers per hour or knots. Small barbs or triangles attached to weather direction symbols are used to visualize wind speed on weather maps. Given that wind speed fluctuates so much over a short period of time, the symbols represent ranges of wind speed.

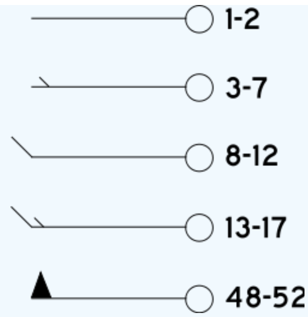


Figure 6.3.8: Wind speed. (Courtesy Wikimedia)

A "rule of thumb" for remembering the symbols is, half barb=5 knots, full barb=10 knots, flag=50 knots.

The patterns of wind speed and direction can be shown on weather maps, like the one in Figure 6-F. As described earlier in the chapter, the pressure gradient determines the speed of the wind. Note how the wind speed is greater where the isobars are closer together. The wind direction symbols show the typical clockwise movement around highs, and counterclockwise around lows. Local conditions at the time the data was collected may show some deviation from this generalization.

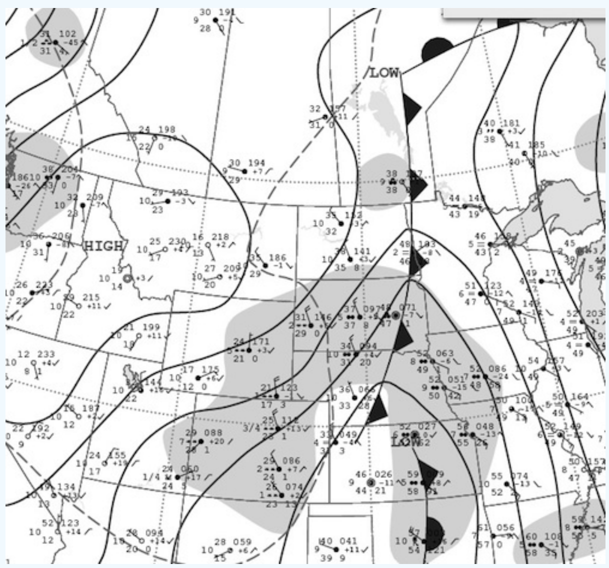


Figure 6.3.9: Surface Weather Map. (Courtesy NWS NOAA)

Surface circulation around highs and lows.

The combined effects of the pressure gradient, Coriolis effect, surface friction is shown in Figure 6.3.10. Recall that air always flows from higher towards lower pressure. Around high pressure systems (H), air is directed outward from the center. Around low pressure systems (L) air is directed inward toward the center. If pressure gradient was the only force acting on the air, wind would move directly across isobars at a perpedicular angle. Wind instead moves across the isobars at an angle of anywhere from 10^o to 45^o. Because the Coriolis Effect bends the air to the right of of it's path (i.e. the direction of the pressure gradient) in the Northern hemisphere, air takes on a clockwise flow around highs and counterclockwise around lows. In the Southern hemisphere, air circulates in a counterclockwise fashion around highs and clockwise around lows.

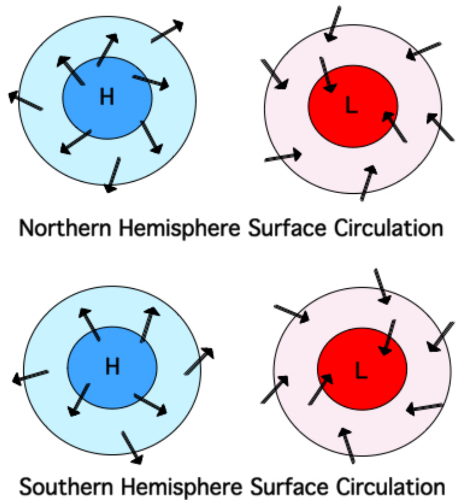


Figure 6.3.10: Surface Circulation Around High and Low Pressure Systems

Above the "friction layer", only the pressure gradient and Coriolis effect operate on wind. At particular latitudes, the opposing pressure gradient and Coriolis forces can balance one another high in the troposphere above the friction layer. When this occurs, winds tend to blow parallel to isobars. Winds that blow roughly parallel to isobars are called "geostrophic winds". The fast-moving jet streams are type of geostrophic wind.

6.4: Cyclones and Anticyclones

Cyclones are areas of low pressure. Cyclones usually exhibit nearly circular isobars. If isobars are oblong or elongate with the lowest pressure near the center we call them ***troughs***. As air enters an area of low pressure from all directions, the Coriolis effect bends the direction of the wind to the right of its path. This creates a counterclockwise rotation around the low and ***convergence*** near the center of the system. As the air collides near the center it is forced aloft where ***divergence*** takes air away from the center of the system. The upper-level divergence is necessary for the system to be maintained as an area of low pressure. Without the divergence, the system would fill with air and the horizontal pressure differences would be equalized causing the system to dissipate. ***Anticyclones*** are areas of high pressure that exhibit nearly circular isobars. If isobars are oblong or elongate with the highest pressure near the center we call them ***ridges***. For high pressure areas, air descends toward the surface due to convergence aloft. As the air nears the surface it is forced outward (divergence) from the center. The Coriolis effect bends the air to the right of its path creating a clockwise rotation around the high.

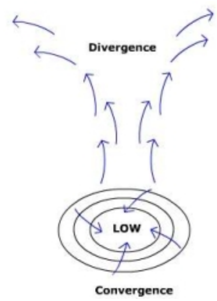


Figure 6.4.1: Circulation within a low pressure system in the Northern Hemisphere

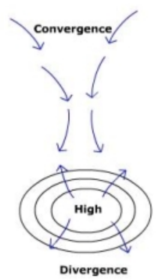


Figure 6.4.2: Circulation within a high pressure system in the Northern Hemisphere

Figure 6.4.3: Cyclone in the Southern Hemisphere

Because the Coriolis effect works in the opposite direction in the Southern Hemisphere, circulation around lows are clockwise and inward toward the center at the surface and highs exhibit a diverging, counterclockwise rotation. You can see this effect in the cloud pattern created by a cyclone in the Southern Hemisphere.

6.5: Local Scale Wind

Land - Sea Breeze

Local scale circulation generally operates over a distance of 10 to 100 kilometers. Many local scale winds are created by unequal heating of the earth. For instance, ***a land - sea breeze*** is created along coasts where land and water create variations in pressure due to differences in the way these two bodies heat and cool.

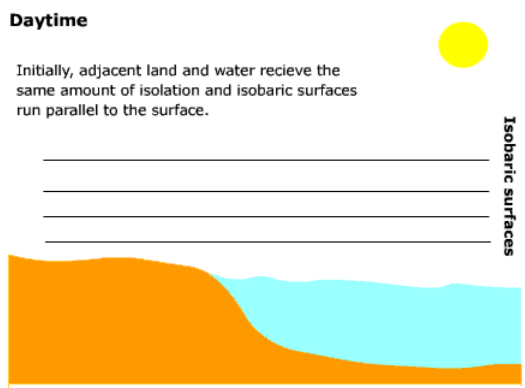


Figure 6.5.1: Land-sea breeze conditions.

During the day, land heats more rapidly than water resulting in low pressure forming over land and higher pressure over water. Air moves from over the water toward land in response to the pressure gradient creating a ***sea breeze***. During the evening, the land cools more rapidly than water promoting higher pressure over the land and lower pressure over water. The pressure gradient induces the air to flow from the land toward the water as a ***land breeze***.

Mountain-Valley Winds

During the daytime, mountain slopes warm causing the air over the slope to be warmer than the air over the valley at the same elevation. Warming the air causes it to rise upwards creating a ***valley wind***. During the evening, the air chills due to a loss of surface energy to space. The cool dense air moves down slope as a ***mountain wind***.

Chinook

The term "Chinook" is a old Native American word that means "snow eater". A ***chinook*** is a warm dry wind on the leeward side of a mountain. As air descends the leeward side of a mountain it is compressed and adiabatically heated. Warming the air causes the saturation point to increase resulting in a decrease in its relative humidity (assuming the water vapor content remains the same). The newly created warm and dry wind moves down slope quite rapidly, and during the Spring causes substantial melting of mountain snow packs.

Santa Ana Winds

Santa Ana winds are another warm and dry wind. Over plateau regions in the desert region of the United States, high pressure pushes air off the plateaus forcing the air into narrow mountain valleys. As the air is forced through the valley it is compressed and warms. As the air warms the saturation point rises and its relative humidity drops. Santa Ana winds have been responsible for fueling wildfires in southern California. The dry wind desiccates the surface and whips wildfires into raging fire storms.

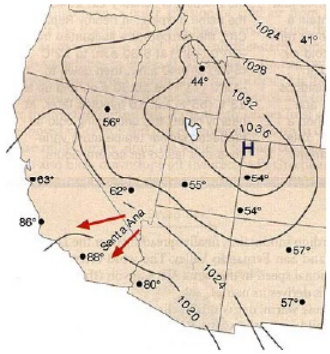


Figure 6.5.2: Weather conditions for Santa Ana winds (Courtesy NOAA NWS (Source))

6.6: Regional Scale Winds - The Monsoon

Monsoon means wind that changes direction with season. Monsoon conditions are found in a variety of regions around the world, the most noted is the monsoon of Asia. During the summer, the continent of Asia heats up more than the surrounding ocean due to the differences in the way land and water heat. The warm surface creates a large area of low pressure over north-central Asia and a smaller one over India. This creates an onshore wind bringing the moisture laden maritime air from the Pacific and Indian oceans onto land. As the air streams across the land, convection induced by the warm surface, convergence into the areas of low pressure, and uplift along major mountain systems like the Himalayas force the air to rise creating the abundant rainfall of the *wet monsoon season*. During the winter, the flow of air reverses. The continent cools rapidly forming a large area of high pressure over north central Asia, known as the Siberian High, and a smaller area over India. Now the drier, colder air of the continent blows offshore creating the *dry monsoon season*.

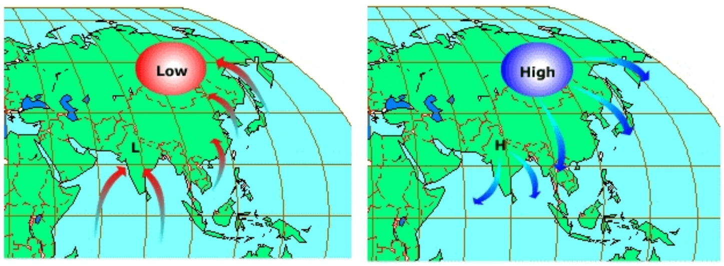


Figure 6.6.1: Monsoon Circulation (Summer - left, Winter - right)

Monsoon conditions are also found in east-central Africa. This region experiences a seasonality of precipitation induced by alternating influence of global pressure belts. During the high sun season, the ITCZ moves in bringing warm, moist unstable air that induces precipitation. During the low sun season the ITCZ shifts out and the influence of the descending motions of the subtropical high dominate the region. During this period the subtropical high inhibits the development of precipitation.

The southwest desert of the United States experiences a pseudo-monsoon during the summer. The intense heating of the surface creates a thermal low over the desert at this time of year. The low induces moist Gulf air to move into the region where it is uplift by convergence or orographic uplift to produce precipitation. During the winter the desert surface cools, the low dissipates, and dry conditions prevail.

6.7: Global Scale Circulation

The circulation of air over the earth is largely due to the unequal heating of the surface. The global circulation of pressure and wind plays an integral role in the heat balance of the earth, as well as creating global ocean currents. The global circulation of the atmosphere transfers warm air from low latitudes towards high latitudes, and cold air from high latitudes towards low latitudes. This exchange keeps low latitude regions where there is a net gain of energy through the year from continually heating up and high latitudes from continual cooling due to a net loss of energy (see latitudinal variation in the radiation balance).

Geographers often use a *three-cell model* to describe the basic features of Earth's global patterns of wind and pressure. The basic assumptions of the model are:

- an Earth of uniform surface composition; and
- the unequal receipt of insolation yields a temperature gradient between the equator and the poles

With these conditions on a rotating Earth, three circulation cells between the equator and the poles are predicted, the **Hadley Cell** between the equator and latitude 30^{o}, the **mid-latitude** or **Ferrel Cell** between latitudes 30^{o} and 60^{o}, and the **polar cell** between latitude 60^{o} and 90^{o}.

Idealized surface pressure and wind

The equatorial region of the Earth experiences a net gain of energy over the course of a year. The intense heating found in low latitudes is due to high sun angles and nearly equal day length throughout the year. The heat gained by the earth surface is transferred into the air via radiation and sensible heat transfer. Condensing water vapor adds heat to the surrounding air as well. The heated air gains buoyancy and easily rises into the wet tropical atmosphere. The convective rise of air promotes a broad area of low pressure that straddles the equator called the ***equatorial trough***. The Equatorial trough is also known as the ***Intertropical Convergence Zone***.

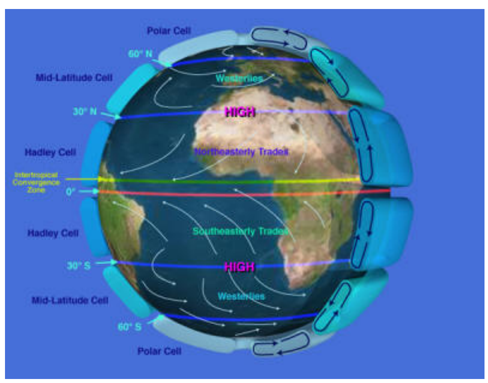


Figure 6.7.1: Global pattern of wind and pressure ((Courtesy NASA JPL) (Source))

As air rises above the surface it diverges near the top of the troposphere and moves poleward. Advancing toward the pole the air begins to converge at between about 25 and 35 degrees north and south latitude. You can easily demonstrate why this occurs by placing your fingers on the lines of longitude printed on a globe. Move your hand poleward keeping your fingers on the longitude lines. Notice how your fingers converge as your hand moves poleward. A similar thing happens to the air. Upper air convergence and radiational cooling cause the air to subside in the subtropics. As the air reaches the surface, atmospheric pressure increases forming the ***subtropical highs***. The subtropical highs have a significant impact on the climate of the earth as well as a being a force behind the major ocean currents. Subsidence towards the surface prevents the uplift of air needed to produce large scale condensation, cloud formation and precipitation. In addition, compressional heating of the air as it descends causes a drop in the relative humidity of the air. The location of majors deserts like the Sahara Desert, coincides with the presence of the subtropical highs.

As the air subsides toward the surface it diverges outward from the center of the subtropical highs. Equatorward of the subtropical highs the winds are generally light and variable. The "horse latitudes" as called by Spanish sailors was a region where ships where often calmed for days on end. To conserve water, the Spanish conquistadors would throw horses into the sea. In the Northern hemisphere the air is turned to the right of its path as it moves outward. Equatorward of the subtropical high, the pressure gradient between the high at 30^{o} N and the low over the equator creates the ***northeast trade winds***. In the southern hemisphere, the air is turned to the left of its path as it diverges from the subtropical high creating the southeast trades.

At the equator, convergence occurs between the northeast tradewinds of the northern hemisphere and the southeast trade winds of the southern hemisphere creating the Intertropical Convergence Zone. The converging tradewinds form a zone of calms and weak winds with no prevailing wind direction called the "doldrums" between about 5^{o} north and south latitude. Old sailing ships often remained calmed for days on end awaiting the winds to pick up.

On the poleward side of the subtropical highs the air heads poleward but is turned to create a westerly wind pattern between 30º N and 60º N in the Northern hemisphere. This wind belt is known as the ***westerlies***. A similar westerly belt of winds can be found between the 30º and 60º S in the southern hemisphere.

The loss of energy at the poles creates very cold air that subsides towards the surface. This creates a dome of high pressure called the ***polar high***. Air moving equatorward is turned in an easterly direction creating the ***polar easterlies***. The polar easterlies collide with the westerly wind belt at about 60 N and S creating a broad belt of low pressure called the ***subpolar low***. This is a zone of storms and migrating high and low pressure systems, the topic of the "Weather Systems" module.

The global wind and pressure belts are extremely important elements of the Earth's climate system. To a great extent, they determine the geographical pattern of precipitation. Low pressure systems promote moist conditions while high pressure tends to suppress precipitation. Global air masses ride within the global winds belts to bring moisture needed for precipitation or scorching hot temperature. The relationships between the global wind and pressure belts and the geographical distribution of precipitation is taken up in the "Atmospheric Moisture" and "Climate Systems" chapters.

Global Pressure Patterns, Precipitation, and Climate

Global pressure systems play a direct role in the geographic distribution of precipitation. This influence is especially apparent in the relationship between pressure patterns and the distribution of precipitation and climate in Africa. For the most part, there is a horizontal pattern of climates stretching from the equator to poleward of 30^{o} N related to the location of the Intertropical Convergence Zone (ITCZ), the semi-permanent Subtropical High (STH), and cyclones of the midlatitudes.

Starting at the equator are the rainiest climates on earth, the tropical rain forest (Af) and tropical monsoon (Am). The tropical rain forest is noted to for its high, year-round rain fall that often exceeds 100 inches in a year. The copious rainfall is a product of the warm moist air masses that converge into the low pressure belt that straddles the equator and uplifted by convection. The monsoon climate in Africa, like the Asian monsoon, has a notable dry period during the low sun season. The dry period is due to the presence of the subsiding air of the subtropical high, while the wet season is due to the presence of the ITCZ and moisture-bearing trade winds along the coast.

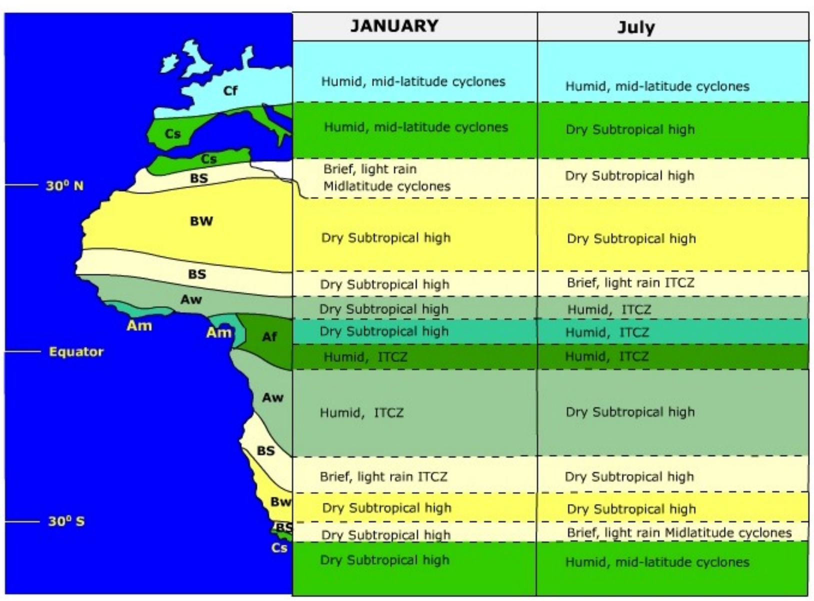


Figure 6.7.2: Relationship of climate to global pressure patterns in Africa (Modified from Trewartha, Robinson, Hammond, and Horn, 1977, p. 100)

Poleward of the monsoon and rain forest climates is the Tropical Wet/Dry climate (Aw) often called the "Savanna" climate. Like the monsoon climate, precipitation is seasonal though the Tropical Wet/Dry climate receives much less on an annual basis. During the low sun season, it is dominated by the STH producing extremely dry conditions. The savanna climate is considered a transitional climate between the rainy tropical and dry tropical climates.

The Tropical Steppe climate (BS) is dominated by the STH for much of the year, though it does receive brief high-sun season rains as the ITCZ migrates into this region. The Tropical Steppe climate is considered a semi-arid climate with enough precipitation to support drought resistant grasses but not for trees. Poleward of the steppe is the Tropical Desert Climate (BW). The tropical desert climate is the driest on Earth that in some locations has virtually no measurable precipitation on an annual basis. The extreme aridity is due in part to the year-round dominance of the subtropical high.

At about 30^{o} north latitude we encounter another zone of tropical steppe climate. Though the climatic conditions are the same, the seasonal dominance of pressure systems has reversed. During the high sun season the STH moves into this region to create dry conditions. During the winter, cyclones spawned in the midlatitudes slip into the steppe climate to bring sporadic and brief rain showers.

Finally, we reach the Mediterranean Sea where we find the Dry Summer Subtropical Climate (Cs), or sometimes called the "Mediterranean Climate". Like the steppe climate on its equatorward border, it has a dry summer/wet winter precipitation regime. However, the region receives more precipitation on an annual basis than its neighboring steppe climate.

To learn more about the effects of atmospheric circulation on our environment, proceed by: "Digging Deeper: Air Quality and Pressure Systems" or continue to the next topic.

Digging Deeper: Air Quality and Pressure System

Regions susceptible to air pollution problems result from the interaction of climatic and topographic conditions in the presence of pollution sources. Air pollution is especially prominent where high pressure dominates. Subsiding motions within an anticyclone suppress air trying to rise off the surface. Adiabatic warming of subsiding air creates a *subsidence inversion* which acts as a cap to upwardly moving air. Pollution problems dissipate when a low pressure system replaces a retreating anticyclone.

Los Angeles, CA is a perfect case study for the effect of climate and topography on air pollution. Topographically, Los Angeles sits in a basin with the San Gabriel Mountains to the east of the city. During the summer the subtropical high pressure cell over the eastern Pacific has migrated to its northern most limit and expanded in size. The subsiding air of the subtropical high is compressed as it descends through the atmosphere, creating a warm layer of air aloft. In addition, adiabatic heating lowers the relative humidity, preventing the development of clouds. The cloudless skies enable much insolation to reach the surface.

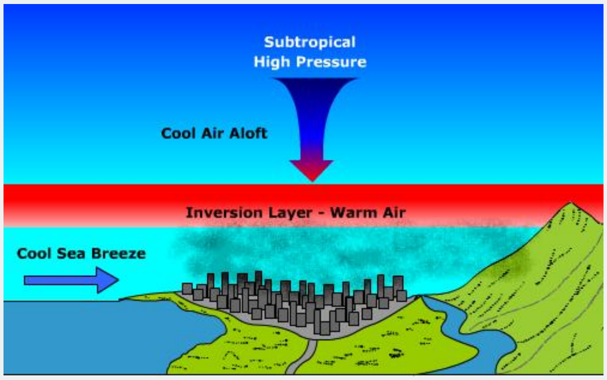


Figure 6.7.3: Factors contributing to air pollution in Los Angeles, CA (Redrawn after Gabler et. al., 1999)

At the surface, air cooled by the cold California current comes ashore on cool sea breezes. The dense cool air sinks into the basin as it comes onto land. The mountains to the east prevent air from moving out of the vicinity of the basin. With cool air at the surface and the warm layer aloft, inversion conditions take hold. The inversion limits the height to which pollutants generated by industrial activities and motor vehicles are moved. Under cloudless skies, insolation initiates photochemical reactions in the urban atmosphere to create the infamous smog problem that Los Angeles has.

6.8: Wind and Pressure Aloft

In the preceding section we examined the global circulation of air near the surface. At the top of the troposphere the circulation is much different. Between 15^o - 20^o north and south latitude are the ***upper air easterlies***, which are considered to be an extension of the trade winds. For most of the upper troposphere poleward of 15^o to 20^o latitude there is an average westerly flow, called the ***upper air westerlies***. Being above the frictional resistance of the earth, the winds aloft move at a much more rapid pace. Embedded in the upper air westerlies are the jet streams, very strong currents of air encircling the globe.

Recall that the steepness of a pressure gradient is due to a gradient of temperature. The latitudinal temperature gradient across the Earth's surface, and hence latitudinal pressure gradient, achieves a maximum in the mid-latitudes. This coincides with the ***polar front***, the boundary between polar and tropical types of air. Here then lies the region of the ***polar front jet stream***, a high speed corridor of air responsible for creating and moving large pressure systems through the midlatitudes. Additionally, a subtropical jet stream forms at approximately 30^o of latitude due to convergence of air aloft at that latitude as discussed earlier. You'll learn more about jet streams in "Weather Systems".

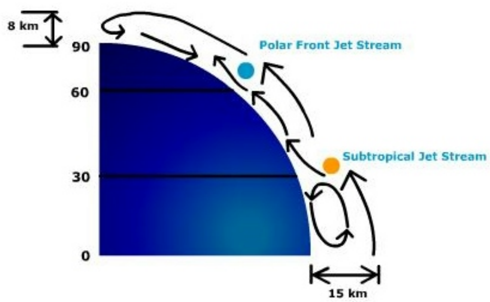


Figure 6.8.1: Profile of jet streams

Over the poles the air is very cold and subsides creating high pressure at the surface. The subsidence, however, creates a vast area of low pressure aloft called the ***circumpolar vortex***. At the equatorward boundary of the vortex lies the polar front jet stream. The polar vortex expands and contracts through the year as a result of the shifting of surface energy receipt. The equatorward edge, along with the jet stream, takes on a wave-like form with cold air invading into the middle latitudes and warm air pushing poleward. When this occurs, there is a transfer of cold air toward the south and warm air toward the north. Under this situation we say that the polar vortex exhibits a ***meridonal flow*** pattern. At times the edge is flatter, running more west to east in direction called ***zonal flow*** pattern. Under this scenario there is little latitudinal exchange of air and energy. This brings relatively mild, maritime polar air masses across the continents, lacking any strong temperature contrast. Maritime tropical air is usually kept from spilling northward.

6.9: Ocean Circulation and Atmospheric Circulation

Like the circulation of air, the circulation of the world's oceans is important in the latitudinal redistribution of energy. ***Warm ocean currents*** are corridors of warm water moving from the tropics poleward where they release energy to the air. ***Cold ocean currents*** are corridors of cold water moving from higher latitudes toward the equator. They absorb energy received in the tropics thus cooling the air above. A distinct correlation between the pattern of ocean currents and the air circulation above them can be made.

Ocean currents

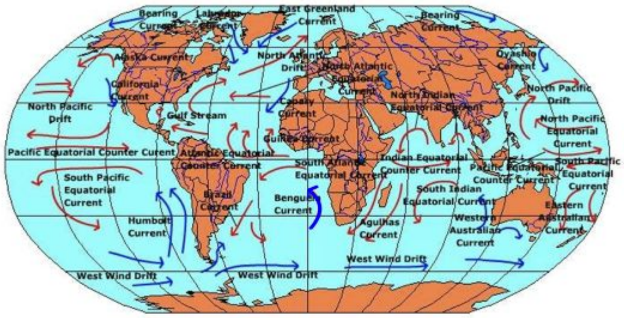


Figure 6.9.1: Major ocean currents

The major ocean currents are wind-driven currents, though some ocean currents result from density and salinity variations of water. The subtropical high pressure cells are responsible for many of the Earth's great ocean currents. Examine the location of the subtropical highs and then place their position on the map of world ocean currents. See any correlation? Notice how the position of the subtropical highs and the circulation around them coincide with the circulation of many of the world's ocean currents. Take the Gulf Stream for example. As air blows out of the western side of the subtropical high it flows over a warm pool of subtropical water dragging it northward creating a warm ocean current. Approaching the eastern seaboard of the United States it is deflected toward the northeast flowing towards the north Atlantic and Europe. After crossing the Atlantic it turns into the North Atlantic Current (Drift). The Gulf Stream enhances instability and the likelihood for precipitation as air passes over it. The warmth of the North Atlantic Drift moderates the climate of The British Isles.

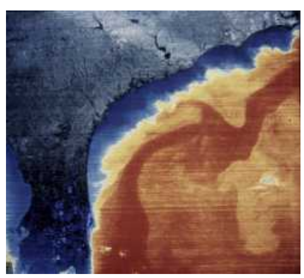


Figure 6.9.2: The Gulf Stream appears in this historical satellite image. (Image courtesy of NOAA.)

As air circulates around the eastern sides of the subtropical highs it blows over cold pools of water dragging them equatorward creating cold ocean currents. The Peru Current is a wind-driven cold current that flows along the coast of South America. Air moving over the cold current is stabilized, inhibiting uplift, the development of clouds and precipitation. Cool coastal deserts form along some coasts that are bordered by cold ocean currents, for example, the Atacama Desert. These deserts derive their meager moisture from fogs that form when warm, moist air masses from further out in the ocean travel over the cold current causing condensation.

Examine the map of ocean currents. The circulation of air around the subtropical highs and the currents it creates creates a general pattern to the distribution of cold and warm ocean currents. Generally speaking, warm currents are found along the east coasts of most continents and cold ocean currents along west coasts. We'll see how this pattern affects the distribution of climates in Chapter 9.

El Niño and La Niña

For centuries, we have recognized a seasonal change in Pacific ocean circulation. Peruvian fisherman in the late 1800's named the seasonal swing of ocean water "El Niño" (Spanish for the "Christ Child") as it usually occurred around Christmas. A periodic weakening of the trade winds in the central and western Pacific allows warm water to invade the eastern Pacific. Along the Peruvian coast, the encroaching warm water displaces the nutrient-rich north-flowing cold ocean current causing a decline in fisheries. Today, the phenomenon is known as the " El Niño/Southern Oscillation" and we are coming to understand how this change in the seasonal wind and ocean circulation impacts global weather patterns (See December - February conditions; June - August conditions). Cooler than normal ocean temperature in this region is called "La Niña". It too has significant impacts on worldwide weather.

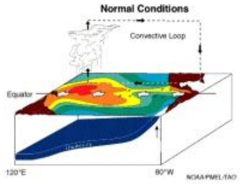


Figure 6.9.3a: Normal Conditions (Courtesy NOAA)

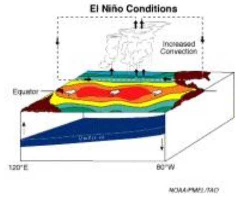


Figure 6.9.3b: El Niño Conditions (Courtesy NOAA)

6.10: Future Geographies - Atmospheric Pressure and Winds

As we have seen in this chapter, the circulation of the atmosphere is largely a result of the unequal heating of the earth's surface. We should then expect changes in the patterns of air and ocean circulation as a result of changing temperature patterns due to future global warming.

Global Scale Pressure and Wind

According to the Intergovernmental Panel on Climate Change, air pressure is to increase over the subtropics and midlatitudes, and decrease in the high-latitude regions of Earth. These changes will result from the poleward expansion and weakening of the Hadley Cell circulation and poleward migration of storm tracks causing an increase in cyclonic circulation patterns in the arctic and antarctic regions. The increase in high pressure will likely be accompanied by drier conditions in many parts of the subtropics and midlatudes. During the 1960s to the mid-1990s midlatitude westerly winds generally increased in both hemispheres which was accompanied by the poleward displacement of the Atlantic and southern polar front jet streams and enhanced storm tracks.

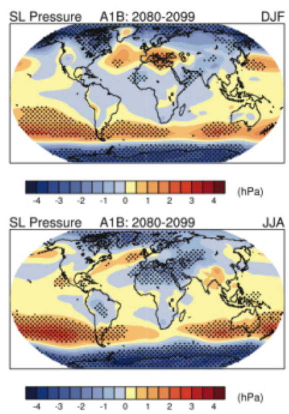


Figure 6.10.1: Forecasted Changes in winter (top) and summer (bottom) air pressure. Courtesy IPCC (Source)

The location of jet streams are strongly tied to horizontal temperature gradients. If these temperature gradients change as a result of global warming, we should expect jet streams and the storms that track along them to shift as well. Recent research seems to indicate that this is occurring. A 2008 research report from the Carnegie Institution's Department of Global Ecology examined jet stream conditions in both northern and southern hemispheres over a 23-year period from 1979 to 2001. They found that jet streams in both hemispheres have risen in altitude and shifted toward the poles. The jet stream in the northern hemisphere has also weakened. These changes fit predictions from global warming climate models and have drastic implications for the frequency and intensity of storms systems and patterns of precipitation that will reverberate through the earth system.

El Niño/La Niña

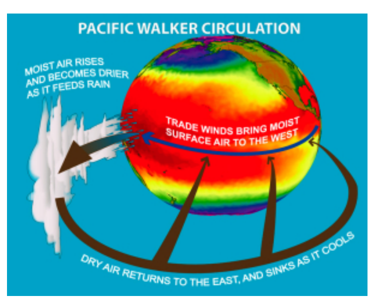


Figure 6.10.2: Walker Circulation Loop (Courtesy NOAA (Source))

The future impact of global warming on El Niño/La Niña is less certain. Recent research by the National Atmospheric and Oceanic Administration has found a 3.5% weakening in the Walker Circulation and hence tradewinds since the mid-1800s. The slowing trend appears to have intensified since the 1940s and larger than what is expected from natural climate variability. The only way to account for the observed changes was through the impact of human activity, primarily the effects of greenhouse gases from fossil fuel burning. A further 10% weakening is expected over the next 100 years. These changes point to a future climate more like that associated with El Niño.

The Monsoon

Global warming projections indicate a more rapid increase in temperature over land than over the oceans. Continental-scale land/sea temperature gradients will be larger during summer and smaller during the winter suggesting a weaker winter and stronger summer monsoon. Model predictions indicate a more complex pattern of potential effects. Some show a weakening of the Asian summer monsoon circulations as the temperature contrast between the continent and ocean decreases. The changing pressure patterns will impact the amount and intensity of precipitation during the summer and winter monsoon. This is taken up in "Future Geographies: Global Precipitation Patterns".

Local winds

Global warming is likely to have an impact on local scale winds as well. Using regional climate models, geoscientists have shown that as land/sea temperature contrasts increase in the future, strengthening of land/sea breezes is expected to occur. Results show an increase of 2 meters per second increase, a substantial impact given the current 5 meter per second average wind speed along the west coast of the United States. Strengthening onshore winds could enhance upwelling of nutrient-rich coastal waters, but the risk of wind-whipped wild fires increases as well.

Figure 6.10.3: Smoke from 2007 Malibu, CA fire is blown out to sea by strong Santa Ana winds. (Courtesy NASA EOS (Source))

Global warming may decrease the risk of severe Santa Ana conditions. The most severe conditions occur when a large dome of high pressure builds over the high desert of the Great Basin. Winds are whipped into a frenzy when cold air is adiabatically warmed as it spills down and through mountain passes. The air is then drawn into low-pressure areas off the coast near Los Angeles, CA. With global warming, the land heats more quickly during the fall and early winter, thus the dampening the temperature forcing of the Santa Ana winds.

6.11: Review and Additional Resources

Review

Assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts 6.11.1

- **Air pressure**
  the force exerted by the weight of a column of air above a particular location
- **Average sea-level pressure**
  serves as the division between what we call "high pressure" and "low pressure" at the surface
- **High pressure**
  values greater than 1013.2 mb
- **Low pressure**
  below 1013.2 mb
- **Wind**
  nothing more than the movement of air molecules from one place to the next
- **Pressure gradient**
  The spacing of isobars indicates the change in pressure over distance
- **Coriolis effect**
  a mass moving in a rotating system experiences a force acting perpendicular to the direction of motion and to the axis of rotation
- **Friction**
  The friction imposed on air mechanically slows the wind and diverts its direction.
- **Cyclone**
  areas of low pressure
- **Anticyclone**
  areas of high pressure that exhibit nearly circular isobars
- **Convergence**
  moving towards a point/area
- **Divergence**
  moving away from a point/area
- **Intertropical convergence zone**
  The Equatorial trough
- **Subtropical high pressure**
  Upper air convergence and radiational cooling cause the air to subside in the subtropics. As the air reaches the surface, atmospheric pressure increases forming the subtropical highs

- **Subpolar low pressure**
  The polar easterlies collide with the westerly wind belt at about 60 N and S creating a broad belt of low pressure
- **Polar high**
  dome of high pressure created by loss of energy at the poles
- **Northeast tradewinds**
  the pressure gradient between the high at 30^{o} N and the low over the equator
- **Westerlies**
  wind belt
- **Polar easterlies**
  Air moving equatorward is turned in an easterly direction
- **Monsoon**
  wind that changes direction with season
- **Land/Sea breeze**
  created along coasts where land and water create variations in pressure due to differences in the way these two bodies heat and cool.
- **Chinook**
  a warm dry wind on the leeward side of a mountain
- **Mountain/Valley wind**
  During the daytime, mountain slopes warm causing the air over the slope to be warmer than the air over the valley at the same elevation. Warming the air causes it to rise upwards creating a valley wind. During the evening, the air chills due to a loss of surface energy to space. The cool dense air moves down slope as a mountain wind.
- **Santa Ana wind**
  warm and dry wind.
- **Upper-level westerlies**
  the upper troposphere poleward of 15^{o} to 20^{o} latitude there is an average westerly flow
- **Upper-level easterlies**
  Between 15^{o} - 20^{o} north and south latitude; considered to be an extension of the trade winds
- **Jet Stream**
  a high speed corridor of air responsible for creating and moving large pressure systems through the midlatitudes
- **Circumpolar vortex**
  The subsidence creates a vast area of low pressure aloft
- **Meridonal flow**
  transfer of cold air toward the south and warm air toward the north
- **Zonal Flow**
  edge is flatter, running more west to east in direction
- **Warm ocean current**
  corridors of warm water moving from the tropics poleward where they release energy to the air.

- **Cold ocean current**

  corridors of cold water moving from higher latitudes toward the equator

- **El Niño**

  weakening of the trade winds in the central and western Pacific allows warm water to invade the eastern Pacific. Along the Peruvian coast, the encroaching warm water displaces the nutrient-rich north-flowing cold ocean current causing a decline in fisheries. Today, the phenomenon is known as the " El Niño/Southern Oscillation"

- **La Niña**

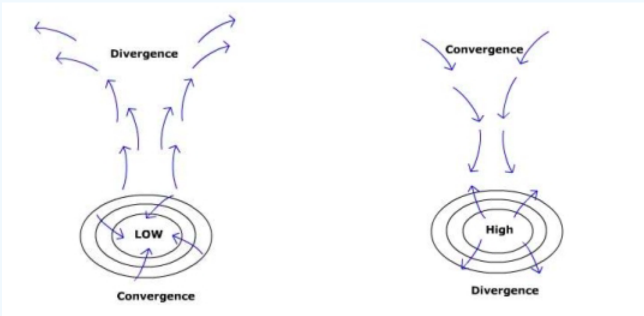
  Cooler than normal ocean temperature in the eastern pacific/Peruvian Coaast region is called "La Niña"

Review Questions 6.11.1

Compare and contrast the movement of air around cyclones and anticyclones.

Answer

Cyclones: Air moves inward toward the center of a cyclone (converges) at the surface, then rises up and diverges from the top. In the Northern Hemisphere air moves in a counterclockwise direction at the surface while in the Southern Hemisphere the air moves in a clockwise direction. **Anticyclones**: Air converges at the top, subsides toward the surface, then diverges outward. In the Northern Hemisphere air moves in a clockwise direction outward from the center at the surface. In the Southern Hemisphere the air moves in a counterclockwise direction at the surface.



Why does air pressure vary across Earth's surface?

Answer

Variations in air pressure across the surface can occur in two ways, by thermal and mechanical means. Thermal means require the heating or cooling of air. When air is heated it becomes buoyant and rises off the surface and lowers surface pressure as it circulates away. If air is chilled it can sink, building pressure at the surface. Surfeace features like mountains can slow air allowing it to build up and increase pressure.

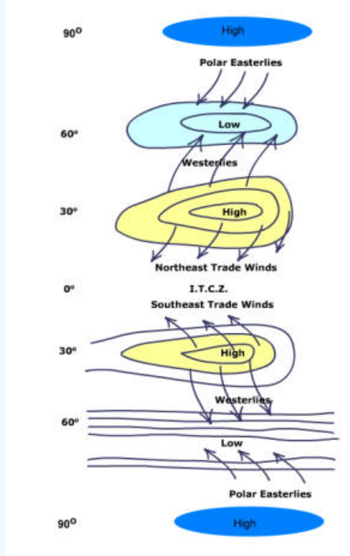
What controls wind velocity?

Answer

Wind velocity is primarily a function of the pressure gradient force and surface friction. The greater the pressure greater the faster the wind. Rough surfaces impart friction to air and slow it down.

Draw a diagram of the global pattern of wind and pressure from the equator to the poles.

Answer



Define Monsoon. Explain how the monsoon circulation over Asia develops.

Answer

Monsoon means wind that changes direction with season. During the summer, the Asian continent warms more than the ocean creating lower pressure over land and higher pressure over water. The resulting pressure gradient causes wind to blow from over the ocean toward land. This is the wet monsoon period. During winter, the pattern reverses with higher pressure over land and lower pressure over water. Air now travels from over the land toward the ocean. This is the dry monsoon period.

Explain how cold and warm ocean currents function.

Answer

The major ocean currents are wind-driven currents. Cold currents form in response to air blowing out of a subtropical high that passes over a cool pool of water dragging it equatorward. Warm ocean currents form in response to air blowing out of a subtropical high that passes over a warm pool of water dragging it poleward.

Describe the effect of ocean currents on weather and climate.

Answer

Ocean currents help redistribute heat across the Earth's surface. Warm ocean currents move heat gained in low latitudes toward high latitudes. Cold ocean currents moving equatorward help conduct heat out of the tropical atmosphere thus lowering low latitude temperatures. Ocean currents also affect precipitation. Cold ocean currents tend to make air stable thus inhibit precipitation formation. Warm ocean currents help to promote unstable conditions which enhance the likelihood for precipitation.

Explain how land - sea breezes form.

Answer

Land/sea breezes form along coast of major bodies of water. A sea breeze occurs during the day as land warms more than nearby water. The differential temperature pattern creates a pressure gradient directed from over water (higher pressure) to land (lower pressure). Air travels from over the water toward land. A land breeze typically occurs at night when land cools more than nearby water. This creates a pressure gradient oriented from over the land (higher pressure) toward water (lower pressure).

Describe the effect of the global pattern of pressure on global precipitation patterns.

Answer

Generally speaking, low pressure is associated with moist conditions while high pressure is associated with dry conditions. The ITCZ creates moist conditions in the low latitudes by promoting converging air masses. The subtropical high creates dry conditions in the subtropics like those found in the great deserts of the Earth (e.g. Sahara). In the midlatitudes the presence of the subpolar low and polar front jet stream creates humid conditions. Over the poles, the subsiding air of the polar high inhibits the creation of precipitation promoting dry conditions there.

Compare and contrast the two basic flow patterns in the upper troposphere.

Answer

Meridonal flow occurs when the jet stream and circumpolar vortex takes a North-South wave-like form transferring cold air equatorward and warm air poleward. When the edge of the circumpolar vortex and jet stream is flatter and exhibits an west to east flow it is called zonal flow.

How does jet stream affect surface pressure systems?

Answer

The jet stream provides support for the formation and life-cycle of surface pressure systems. Regions of convergence and divergence are found in the jet stream. Some surface cyclones form beneath zones of diverging air aloft while surface anticyclone can form beneath zoned of converging air aloft.

? Self-Assessment Quiz 6.11.1

1. Wind blows ___________In the Northern Hemisphere
   A. in a counterclockwise direction into the center of a low pressure system.
   B. in a counterclockwise direction into the center of a high pressure system
   C. in a clockwise direction into the center of a low pressure system
   D. in a clockwise direction into the center of a high pressure system.
2. Air _____ at the surface and ______ above a low pressure system
   A. converges; diverges
   B. converges; converges
   C. diverges; converges
   D. diverges; diverges
3. If my latitude was 20 N I will be under the influence of
   A. the polar easterlies
   B. the westerlies
   C. the northeast trade winds
   D. none of the above.
4. A warm, dry wind that descends the lee side of mountains is called
   A. a monsoon
   B. a chinook
   C. a valley wind
   D. a land breeze
5. A valley breeze
   A. occurs when wind is blowing in the down slope direction
   B. occurs when higher pressure is found near the top of the mountain
   C. occurs at night
   D. occurs when none of the above are true
6. During the summer over monsoon Asia
   A. winds blow from land toward water creating a dry season

B. winds blow from land toward water creating a wet season
C. winds blow from water toward land creating a dry season
D. winds blow from water toward land creating a wet season

7. Which of the following patterns of pressure will you experience traveling from the equator to the north pole?
   A. low - high - low - high
   B. high -low - high - low
   C. low - low - high - high
   D. high - high -low - low
8. Which of the following patterns of wind belts will you experience traveling from the equator to the north pole?
   A. Easterlies, Westerlies, Tradewinds
   B. Tradewinds, Easterlies, Westerlies
   C. Westerlies, Easterlies, Tradewinds
   D. Tradewinds, Westerlies, Easterlies
9. Given equal energy input to both surfaces, I would expect to find
   A. higher pressure over land and lower pressure over water during the day
   B. air flowing from land toward water during the day
   C. lower pressure over water and higher pressure over land during the day
   D. none of the above
10. According to the weather station model below, the wind direction is
    A. northeast
    B. southwest
    C. northwest
    D. southwest

Answer

1. A
2. A
3. C
4. B
5. D
6. D
7. A
8. D
9. D
10. A

Additional Resources

Use these resources to further explore the world of geography.

- **Focus on The Physical Environment**: "El Nino's Extended Family" (*NASA Earth Observatory*)
- **Connections**: "When the Dust Settles" (*NASA Earth Observatory*); "The Effects of Globally Transported African and Asian Dust on Coral Reef and Human Health" (USGS)

Multimedia

USGS Public Lecture Series: "Out of Africa--Dust in the Wind" (October, 2009) Description from the site: "Every year, billions of tons of fine desert dust from the Saharan Desert are transported thousands of miles through the atmosphere to the Americas, Europe and the Near East. Living microorganisms and chemical contaminants such as pesticides and metals are carried along with the dust. What biological and chemical contaminants are hitchhiking with the dust and how might downwind ecosystems such as coral reefs and human health be affected?"

"The Blue Planet" (Annenberg/CPB) *Planet Earth* Series. Scientists aboard the space shuttle study the oceans from above while researchers dive to the depths of the "middle ocean" to view rare life forms. (58:00) Go to the Planet Earth site and scroll to "The Blue Planet". One-time free registration may be rquired.

Web Sites

Ocean (NOAA) National Oceanic and Atmospheric Administration main web site about the ocean.

CHAPTER OVERVIEW

7: Atmospheric Moisture

Learning Objectives

By the end of the chapter you should be able to:

- Explain the phase changes of water.
- Determine the stability of air and its likelihood for cloud development
- Identify common cloud types.
- Describe how precipitation forms.
- Explain the global pattern of precipitation.

"It is better to read the weather forecast before we pray for rain." - *Notebook; More Maxims of Mark*, Johnson, 1927

Water in its various forms sustains life, transports energy and erodes the surface beneath our feet. Water is needed for cell growth, photosynthesis, the formation of soil, and to absorb and transport nutrients in plants and animals. Without water, living things could not survive. Energy is transported between the various spheres of the Earth system via phase changes of water. Nearly every portion of the Earth has been sculpted by the movement of water across the surface at some point in geologic history. Here we'll look at water in its various forms, as a gas, liquid, and solid. We'll investigate how it moves through and the vital role it plays in the Earth system. You will become familiar with the geographic distribution of precipitation and its impact on the environment.

The animation below shows the global pattern of cloud cover measured as the fraction of sky covered by clouds from January 2005 to April 2011. Cloud fraction ranges from 0 for cloudless skies (dark blue) to 1 for total cloud cover (white). Watch the animation by clicking the play button and describe what you see.

Seasonal changes in cloud fraction (Courtesy NASA Earth Observatory (Source))

Tropical regions appear to uniformly cloudy through out the year. The noticeable band of clouds circling the tropics shifts slightly to the north and south through the year. Much of subtropical Africa and Antarctica have relatively low cloud cover throughout the year. The midlatitudes have more variable cloud conditions. Why does this spatial and temporal pattern in cloud cover occur and what are the implications? Will this pattern change in the future?

Assess if you are ready for this chapter by "Getting Ready for Chapter 7".

7.1: Getting Ready for Chapter 7

7.2: Phases of Water
7.2.1: Evaporation
7.2.2: Transpiration
7.2.3: Humidity
7.2.4: Condensation
7.3: Adiabatic Temperature Change and Stability
7.4: Clouds and Precipitation
7.4.1: Fog
7.4.2: Clouds
7.4.3: Precipitation Process
7.5: Global Patterns of Precipitation
7.5.1: The Equator to the Subtropics
7.5.2: Midlatitudes to the Poles
7.6: Future Geographies - Global Precipitation Patterns
7.7: Looking Ahead
7.8: Review and Additional Resources

7.1: Getting Ready for Chapter 7

In Chapter 6 we learned how the atmosphere and oceans circulate air and water redistribute heat from regions of excess energy to those that are deficient. The energy that drives atmospheric circulation is largely that provided by the Sun. The unequal heating of the Earth creates temperature and pressure gradients that result in large scale circulation of the atmosphere. To a great extent, the major ocean currents are controlled by the circulation of the atmosphere. Atmospheric and oceanic circulation are the means of transport that enables the hydrologic cycle to function. As water is evaporated from the oceans or land, the circulation of the atmosphere moves it to another location where it can condense and precipitate out.

Figure 7.1.1: Heat transport. Red arrows are the jet streams
(Courtesy UNEP, Radiation. (2009). In UNEP/GRID-Arendal Maps and Graphics Library. Retrieved 19:17, December 21, 2009 from maps.grida.no/go/graphic/radiation.)

In Chapter 7, *Atmospheric Moisture*, we'll examine the processes that cause evaporation, condensation and the formation of precipitation. Using these new insights, we'll be able to explain the geographical distribution of atmospheric moisture. A look at how precipitation patterns may change as a result of human-induced climate change will conclude the chapter.

What you should already know ...

Understanding the processes that cause phase changes of water and control the distribution of pressure depends on knowledge gained in Chapter 2, Chapter 3, Chapter 4, and Chapter 6. In particular, you should have a handle on the basic terminology of heat and energy, how the radiation and energy balance relates to the water vapor content of the air, and how pressure systems influence air flow.

Use the quiz below to assess your understanding of a few key topics from these chapters.

Quiz 7.1.1

1. The heat used in the phase change of water is
   A. ground heat.
   B. latent heat.
   C. sensible heat.
   D. potential phase change heat.
2. The average rate of decrease in temperature with an increase in elevation is
   A. the normal lapse rate of temperature.
   B. the environmental lapse rate of temperature.
   C. the latitudinal temperature gradient.
   D. none of the above.
3. The greatest amount of latent heat transfer into the air for a year
   A. occurs over the midlatitude deserts.
   B. occurs near the Arctic ocean.
   C. occurs off the west coast of midlatitude continents.
   D. tropical oceans.
4. The amount of energy required to raise the temperature of one gram of substance through 1^{o}C is
   A. latent heat.
   B. potential heat.

C. specific heat.
D. sensible heat.

5. A line that connects points of equal precipitation is called an
   A. isotach.
   B. isohyet.
   C. isobar.
   D. isobath.
6. A cyclone exhibits
   A. converging surface air and subsidence.
   B. converging surface air and uplift.
   C. diverging surface air and uplift.
   D. diverging surface air and subsidence.
7. The amount of heat required to raise the temperature of one gram of water through 1^oC is called
   A. latent heat.
   B. specific heat.
   C. a calorie.
   D. a joule.
8. Net radiation for the year is greatest
   A. over tropical oceans.
   B. off the west coast of the United States.
   C. over the Arctic ocean.
   D. in the Sahara desert.
9. A change in air temperature without the physical exchange of heat is called
   A. a diabatic temperature change.
   B. an adiabatic temperature change.
   C. an environmental lapse rate.
   D. none of the above.
10. A negative latent heat transfer
    A. means heat is removed from water molecules.
    B. means heat is added to water molecules.
    C. means the air temperature is high.
    D. none of the above.

Answer

1. B
2. A
3. D
4. C
5. B
6. B
7. C
8. A
9. B
10. A

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous material.

If you scored less than 70% you should consider reviewing the previous material and seeking help from your instructor.

SECTION OVERVIEW

7.2: Phases of Water

A water molecule is composed of two atoms of hydrogen and one atom of oxygen. The molecule looks kind of like Mickey Mouse, with the oxygen forming the head and the two hydrogen forming the ears. Water exists in one of three phases, solid, liquid, or gas. Water molecules cluster together by bonding to the hydrogen atoms of neighboring water molecules. The molecules that comprise a solid, like ice, are arranged in a particular order. The molecules do not circulate but they do move. That is, the molecules vibrate in place around an average location. Solids represent the lowest level of kinetic energy. The molecules of a liquid, like water, have a higher kinetic energy level than solids and thus are free to circulate as "clumps" of molecules but constrained by a surface. Molecules of a gas are free to circulate as well, but are unconfined and move about with the highest kinetic energy level.

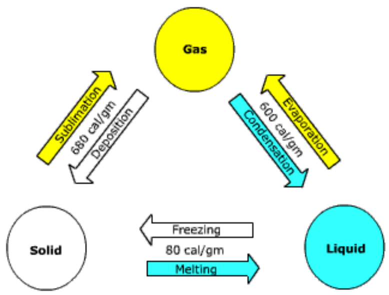


Figure 7.2.1: Phase changes of water.

In order for water to change from a solid to liquid and finally to a gas, the water molecule must gain energy. The energy absorbed by water is used to break the hydrogen bonds between groups of molecules. When the bonds are broken between the molecules of ice, it melts and they can circulate as a fluid. The energy required to convert ice into water is called the ***latent heat of fusion***. It takes about 80 calories of heat to convert one gram of ice into water.

7.2.1: Evaporation

7.2.2: Transpiration

7.2.3: Humidity

7.2.4: Condensation

7.2.1: Evaporation

Evaporation is the phase change of a liquid to a gas. There are three very important requirements for evaporation to take place, 1) available energy, 2) available water, and 3) a vertical moisture gradient. Approximately 600 calories of heat must be added to a gram of water for it to evaporate into the air. This energy is called "***the latent heat of vaporization***". Latent heat is used to break the hydrogen bonds that bind water molecules together. In doing so, the energy is "locked up" in the water molecules. The energy remains "latent" in the molecules until they combine during the condensation process to form a liquid. When this happens latent energy is released into the surrounding environment as sensible heat. Sensible heat warms the surrounding air, and thus is an important source of energy to heat the atmosphere.

Even if you have all the energy required for evaporation it will not occur unless there is water present. Desert regions are noted for their lack of precipitation. One reason is that they have little available water to evaporate to later condense and form precipitation. Eighty-eight percent of the water that is evaporated into the air comes from oceans that lie between 60^{o} north and south latitude. Most of the evaporation occurs in the tropical and subtropical oceans where the highest amounts of net radiation occur.

The third requirement for evaporation is the presence of a vertical moisture gradient. That is, there is a difference in moisture content with increasing height above the surface. All this means is that the humidity is high at the evaporating surface (liquid water), and the air above has a lower humidity. Evaporation will be the predominate phase change until the air is saturated with moisture. Though not required, wind aids in the evaporation process. Wind transfers water molecules away from the evaporating surface and hence maintains a vertical moisture gradient.

7.2.2: Transpiration

The principal way in which water enters the air is through evaporation. Plants are another important source of atmospheric moisture. Plants contribute water to the atmosphere by transpiration. **Transpiration** is the transfer of water into the air via leaf pores or *stomata*. Interestingly, the same three requirements for evaporation apply to transpiration. Approximately 600 cal/gm of energy is required to transpire water from leaves. The transfer of water into the air removes heat from the plant and so transpiration, like evaporation, is a cooling process. Thus transpiration is an important means of transporting heat between the surface and air above.

Water for transpiration comes from that which is stored in the soil and then extracted by plant roots. The amount of water that is held in the soil moisture zone is dependent on the texture and structure of the soil. Coarse textured soil dominated by sand-size particles holds less moisture than a finer textured soil.

Figure 7.2.2.1: Irrigating germinating crops, Yuma, AZ (Courtesy NRCS)

How important is plant transpiration? Consider this, one mature oak tree can transpire as much as 100 gallons of water in a day. An acre of corn can transpire as much as 4000 gallons of water per day (EPA). The problem that many countries face is an ever dwindling resource of groundwater to promote agriculture in regions too dry to do so. Far too often, groundwater resources are extracted faster than they can naturally replenish themselves. Over pumping depletes groundwater reserves in aquifers and ultimately leads to their collapse. This is happening in the semiarid and arid regions of the United States. One aquifer in particular, the Ogallala Aquifer, is at risk of being depleted. The recharge area where water enters the aquifer is in the Rocky Mountains. The aquifer extends underground for hundreds of miles into the Great Plains. The aquifer is used to support agriculture and municipal water supplies on the Great Plains. Unfortunately, water is being pumped out of the aquifer much faster than the rate of replenishment. The fear is that over pumping will lead to the aquifer running dry causing severe stress on the Great Plains agricultural economy.

7.2.3: Humidity

Humidity is a measure of the water vapor content of the air. The amount of water vapor in the air depends on the controls over evaporation discussed earlier. There are several ways in which a meteorologist can express the humidity of the air. Each humidity measure is controlled to some degree by air temperature.

Absolute humidity is the weight of water vapor per unit volume of air, usually measured in units of grams of water vapor per cubic meter of air. Absolute humidity is not often used to express the moisture content of air because it is sensitive to changes in both the temperature of the air and atmospheric pressure. For instance, let's say that a 1 cubic meter parcel of air at the surface has 2 grams of water in it. Now lift the parcel of air upwards into the atmosphere. As the air rises upward the decrease in atmospheric pressure on the parcel allows it to expand outward occupying more space. Let's say that the parcel doubles in size as a result of uplift. Before rising, the absolute humidity was 2 gm/m^3. As the air doubles in volume the new absolute humidity is 1 gm/m^3. In actuality the parcel still has the same weight of water in it, 2 grams. But given the way absolute humidity is calculated it appears the amount of water in the air has decreased.

Instead of absolute humidity, we use a measure that is not sensitive to volume changes in the air. ***Specific humidity*** is measured as the weight of water vapor in the air per unit weight of air, which includes the weight of water vapor. The units of measurement are grams of water vapor per kilogram of air. Given that weight is not significantly influenced by temperature or atmospheric pressure, specific humidity is much more useful as a measure of humidity. Another measure very similar to specific humidity is the mixing ratio. The ***mixing ratio*** is the weight of water vapor per unit weight of dry air. Because the atmosphere is made up of so little moisture by volume, the mixing ratio is virtually the same as the specific humidity.

Humidity is not only measured as a weight, but also by the pressure it creates. ***Vapor pressure*** is the partial pressure created by water vapor. Vapor pressure, like atmospheric pressure, is measured in millibars and is relatively insensitive to volumetric expansion or temperature. The ***saturation vapor pressure*** is simply the pressure that water vapor creates when the air is fully saturated.

When we think of air as being saturated with moisture we often say that the air is "holding all the moisture it can". This implies that once the air has reached saturation it won't "accept" anymore water by evaporation. This is wrong. So long as there is water available evaporation will continue even when the air is fully saturated. Let's examine the concept of saturation in more detail.

Imagine a beaker filled halfway with water. Let's put a top on it to constrain the movement of water molecules and eliminate the influence of wind on evaporation. As the water absorbs heat it begins to change phase and enter the air as water vapor. Above the surface, water vapor molecules dart about suspended in the air. However, near the surface water molecules are attaching themselves back the surface, thus changing back into liquid water (condensation) (A). As evaporation occurs the water level in the beaker decreases (B). This occurs because evaporation exceeds condensation of water back onto the surface. After some time, the amount of water entering the air from evaporation is equal to that condensing (C). When this occurs the air is said to be saturated.

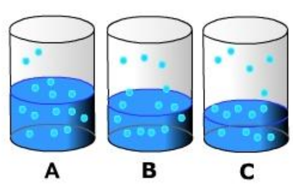


Figure 7.2.3.1: Evaporation and condensation in an enclosed beaker of water.

The saturation level of the air is directly related to the air's temperature. As air temperature increases, more water can remain in a gas phase. As temperature decreases, water molecules slow down and there is a greater chance for them to condense on to surfaces. The graph below shows the relationship between air temperature and vapor pressure, a measure of the humidity, at saturation.

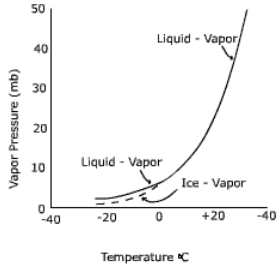


Figure 7.2.3.2: Relationship Between Air Temperature and Vapor Pressure

Note that below zero degrees Celsius the curve splits, one for the saturation point above a liquid surface (liquid-vapor) and one for a surface of ice (ice - vapor). The first thing you might be wondering is how water can exist as a liquid below the freezing point. Water that is not frozen below 0^{o} C is called "super-cooled water". For water to freeze, the molecules must become properly aligned to attach to one another. This is less likely to occur especially with small amounts of water, like cloud droplets. Thus in clouds where temperatures are below freezing it is common to find both super-cooled liquid water and ice crystals.

Notice that the saturation vapor pressure at -20^{o} C is lower for ice than for a liquid surface. Why would this be so? You may recall that to convert water from a liquid to a gas requires about 600 calories per gram. To convert water from a solid to a gas requires about 680 calories, hence it is more difficult to "liberate" a molecule of water from ice than water. Therefore, when the air is saturated, there are more molecules above a water surface (i.e. more vapor pressure) than an ice surface (i.e. less vapor pressure).

Dew point temperature is the temperature at which condensation takes place and is used as a measure of moisture content. The dew point temperature depends on the amount of moisture in the air, the more moisture in the air, the higher the dew point temperature. It gets its name "dew point" because dew will form on surfaces when the air reaches saturation.

Have you ever noticed that even though it's 100% relative humidity out, it feels a lot drier during the winter than the summer? To see why, we have to examine relative humidity. ***Relative humidity*** is the ratio of the amount of water vapor in the air to its saturation point. Often relative humidity is defined as the amount of water vapor in the air to "how much it can hold" at a given temperature. The notion of a holding capacity is dispelled when one considers what saturation really means. Regardless, what we do know is that the saturation level of the air with respect to water vapor depends on the air's temperature. We know that as air temperature increases, the ability for the air to keep water in its vapor state is easier. That is, as the air temperature increases it can keep more water in the vapor state. So why does saturated cold air feel drier than warm air at saturation? Let's look at an example.

Continental polar air (cP) has an average temperature of 5^{o} C (41^{o} F). Its saturation mixing ratio is 6 g/kg. So continental air at 100% relative humidity is

RH = 6 g/kg (in the air) / 6 g/kg (saturation)

The average temperature of maritime tropical air (mT) is 22o C (71.6o F) with a saturation mixing ratio of 16 g/kg. So maritime tropical air at 100% relative humidity is

RH = 16 g/kg (in the air) / 16 g/kg (saturation)

Therefore, polar air is drier at 100% relative humidity because it has much less moisture in it at saturation than the warmer maritime tropical air.

7.2.4: Condensation

Condensation is the phase change of water vapor into a liquid. During the condensation process, water molecules lose the 600 cal/gm of latent heat that were added during the evaporation process. When latent heat is released it is converted into sensible heat which warms the surrounding air. Warming the air increases its buoyancy and fuels the development of storms. Condensation takes place in the presence of condensation nuclei and when the air is nearly saturated.

Water vapor is darting around so fast in the air that the molecules tend to bounce off one another without bonding. Even if a few pure water molecules were to collide and bind together, the surface tension created by such a tiny sphere is so great that it is extremely difficult for additional water molecules to become incorporated into the mass. Hence ***condensation nuclei*** act as a platform for condensation to take place, increasing the size of a droplet and decreasing surface tension. Water absorbent clay minerals and sea salt are good condensation nuclei. Sulfates and nitrates are water absorbent and are responsible for creating acid rain.

The air must be at or near its saturation point for condensation to take place. Air can become saturated in two ways, 1) add water to the air by evaporation thus bringing it to saturation given its present temperature, or 2) cool the air to its dew point temperature. Cooling the air is the most common way for condensation to occur and create clouds. Air can be cooled through contact with a cold surface or by uplift. ***Contact cooling*** occurs when air comes in contact with a cooler surface and conduction transfers heat out of the air.

Uplift Mechanisms

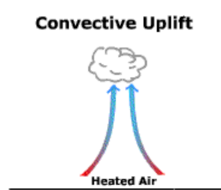


Figure 7.2.4.1: Convective uplift

Adiabatic cooling occurs when air is uplifted from the surface causing the air to lose heat through the work of expansion. A parcel of air is uplifted when it initially gains heat from the surface causing ***convective uplift***. When the air is warmed by the surface it will expand and become less dense relative to air that surrounds it. Being less dense than the air that surrounds it, the air becomes buoyant and begins to rise. Because atmospheric pressure decreases with height, the parcel of air expands and cools. If the air cools to its dew point temperature saturation occurs and condensation begins. The elevation above the surface where condensation begins is called the ***condensation level***.

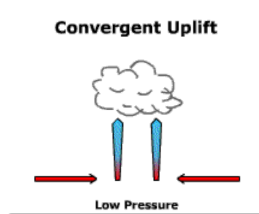


Figure 7.2.4.2: Convergent uplift

Convergent uplift occurs when air enters a center of low pressure. As air converges into the center of a cyclone it is forced to rise off the surface. As the air rises it expands, cools, and water vapor condenses. Convergent and convective uplift are the two most important uplift mechanisms for condensation in the tropics. Under the intense sun, surface heating causes the moist tropical air to rise. Convergence of the trade winds in the Intertropical convergence zone creates copious rainfall in the wet tropics as well.

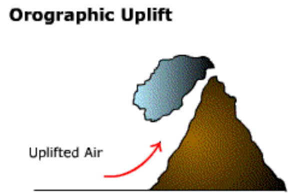


Figure 7.2.4.3: Orographic uplift

Orographic uplift is the forced ascent of air when it collides with a mountain. As air strikes the windward side, it is uplifted and cooled. Windward slopes of mountains tend to be the rainy sides while the leeward side is dry. Dry climates like steppes and desert are often found in the "rain shadow" of tall mountain systems that are oriented perpendicular to the flow of air.A rainshadow in the lee of the tradewinds as they cross the mountainous northwest portion of the Big Isand of Hawaii (Figure 7.2.4.4). Cloud formation and green vegetaton identifies the windward, while the reddish brown indicates the dry leeward side.

Figure 7.2.4.4: Rainshadow on the Big Island of Hawaii. (Source NASA EOS)

Frontal uplift occurs when greatly contrasting air masses meet along a weather front. For instance, when warm air collides with cool air along a warm front, the warm air is forced to rise up and over the cool air. As the air gently rises over the cool air, horizontally developed stratus-type clouds form. If cold air collides with warm air along a cold front, the more dense cold air can force the warmer air ahead to rise rapidly creating vertically developed cumulus-type clouds.

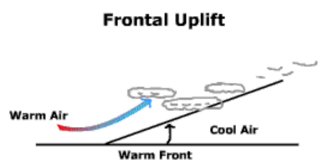


Figure 7.2.4.5: Frontal uplift

7.3: Adiabatic Temperature Change and Stability

In "The Atmosphere" we discovered that air temperature usually decreases with an increase in elevation through the troposphere. The decrease in temperature with elevation is called the ***environmental lapse rate of temperature*** or ***normal lapse rate of temperature***. Recall that the ***normal lapse rate of temperature*** is the average lapse rate of temperature of .65^{o} C / 100 meters. The ***environmental lapse rate of temperature*** is the actual vertical change in temperature on any given day and can be greater or less than .65^{o} C / 100 meters. Also recall that the decrease in temperature with height is caused by increasing distance from the source of energy that heats the air, the Earth's surface. Air is warmer near the surface because it's closer to its source of heat. The further away from the surface, the cooler the air will be. It's like standing next to a fire, the closer you are the warmer you'll feel. Temperature change caused by an exchange of heat between two bodies is called ***diabatic temperature change***. There is another very important way to change the temperature of air called adiabatic temperature change.

Adiabatic temperature change of air occurs without the addition or removal of energy. That is, there is no exchange of heat with the surrounding environment to cause the cooling or heating of the air. The temperature change is due to work done on a parcel of air by the external environment, or work done by a parcel of air on the air that surrounds it. What kind of work can be done? The work that is done is the expansion or compression of air.

Imagine an isolated parcel of air that is moving vertically through the troposphere. We know that air pressure decreases with increasing elevation. As the parcel of air moves upward the pressure exerted on the parcel decreases and the parcel expands in volume as a result. In order to expand (i.e.. do work), the parcel must use its internal energy to do so. As the air expands, the molecules spread out and ultimately collide less with one another. The work of expansion causes the air's temperature to decrease. You might have had personal experience with this kind of cooling if you've let the air out of an automobile or bicycle tire. Air inside the tire is under a great deal of pressure, and as it rushes outside it moves into a lower pressure environment. In so doing, the parcel quickly expands against the outside environment air. By placing your hand in front of the valve stem, you can feel the air cool as it expands. This is called ***adiabatic cooling***.

As air descends through the troposphere it experiences increasing atmospheric pressure. This causes the parcel volume to decrease in size, squeezing the air molecules closer together. In this case, work is being done on the parcel. As the volume shrinks, air molecules bounce off one another more often ricocheting with greater speed. The increase in molecular movement causes an increase in the temperature of the parcel. This process is referred to as ***adiabatic warming***.

The rate at which air cools or warms depends on the moisture status of the air. If the air is dry, the rate of temperature change is 1^{o}C/100 meters and is called the ***dry adiabatic rate*** (DAR). If the air is saturated, the rate of temperature change is .6^{o}C/100 meters and is called the ***saturated adiabatic rate*** (SAR). The DAR is a constant value, that is, it's always 1^{o}C/100 meters. The SAR varies somewhat with how much moisture is in the air, but we'll assume it to be a constant value here. The reason for the difference in the two rates is due to the liberation of latent heat as a result of condensation. As saturated air rises and cools, condensation takes place. Recall that as water vapor condenses, latent heat is released. This heat is transferred into the other molecules of air inside the parcel causing a reduction in the rate of cooling.

Stability of Air

Adiabatic temperature change is an important factor in determining the stability of the air. We can think of air stability as the tendency for air to rise or fall through the atmosphere under its own "power". Stable air has a tendency to resist movement. On the other hand, unstable air will easily rise. What gives air "power" to rise? The tendency for air to rise or fall depends on the adiabatic and environmental lapse rates.

Stable air

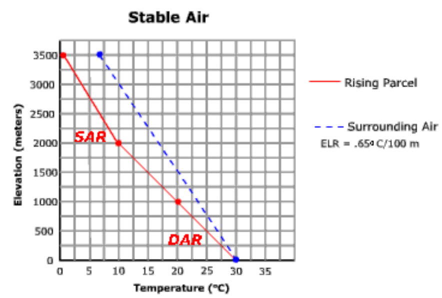


Figure 7.3.1: Stable Atmospheric Conditions

Stable atmospheric conditions prevail when the environmental lapse rate is less than the saturated adiabatic rate. An example of this condition is shown in Figure 7.3.1. At the surface (0 meters) both the parcel of air (red line) and the air of the surrounding environment (blue line) have the same temperature. The surrounding air is changing its temperature at a rate of .65°C/100 meters. The parcel on this day is "dry" and will rise and cool at a temperature of 1°C/100 meters. After giving the parcel a slight upward push, it rises to a level of 1000 meters where it cools to a temperature of 20°C. A measurement of the air surrounding the parcel shows a temperature of 23.5°C. In other words, the parcel is colder (and more dense) than the surrounding air at 1000 meters. If the uplift mechanism ceased, the parcel of air would return to the surface.

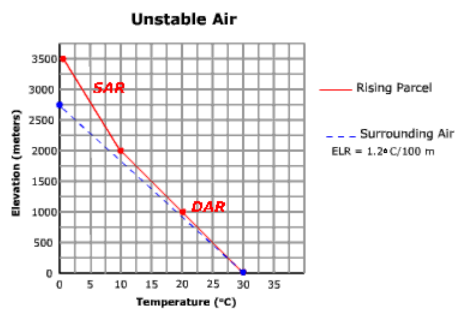
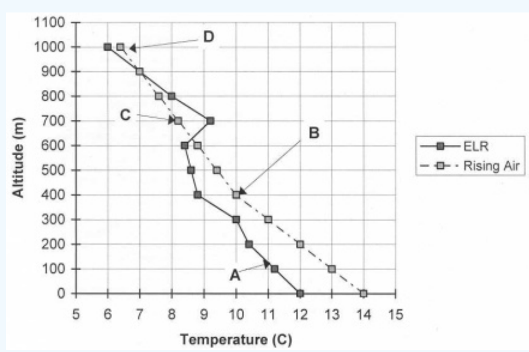


Figure 7.3.2: Unstable Atmospheric Conditions

Unstable air

Air is unstable when the environmental lapse rate is greater than the dry adiabatic rate. Under these conditions, a rising parcel of air is warmer and less dense than the air surrounding it at any given elevation. Figure 7.3.2 depicts unstable conditions. Follow up the graph for the rising parcel of air. Note that at any elevation above the surface the parcel temperature is higher than the air that surrounds it. Even as it reaches the dew point temperature at 2000 meters, the air remains warmer than the surrounding air. As a result it continues to rise and cool at the saturated adiabatic rate. Vertically developed clouds are likely to develop under unstable conditions such as this.

? Concept Check 7.3.1



According to the graph above, the air is absolutely stable at letter A, B, C, or D?

Answer

C

SECTION OVERVIEW

7.4: Clouds and Precipitation

Condensation occurs either near the surface or aloft and results in the formation of small droplets of water. Condensation at the surface results in **dew** formation when the near surface air temperature drops to the dew point temperature. This often occurs at night under cloudless skies when the air is humid. Under cloudless skies, emitted terrestrial radiation penetrates to space, cooling the surface which then cools the near surface air.

7.4.1: Fog

7.4.2: Clouds

7.4.3: Precipitation Process

7.4.1: Fog

Fog is a cloud that forms near the ground. Fog, like any other product of condensation, requires the air temperature to decrease to the dew point temperature where upon the air is at saturation. Cooling of the near surface air is accomplished either through contact cooling (a diabatic process) or adiabatic cooling.

Figure 7.4.1.1: Fog partially obscures the Golden Gate Bridge (Source: NOAA)

An ***advection fog*** forms when warm and moist air travels over a cool surface. Warm air overlying a cool surface creates a temperature gradient directed toward the surface. Sensible heat is transferred out of the air toward the ground thus cooling the air above the surface. If the air cools to the dew point temperature, condensation will likely result. Advection fogs are quite common. In the Midwest United States during the spring, warm, moist air from the Gulf of Mexico (mT air) streams over the cooler, often snow covered surface. As it does it cools and the water vapor condenses into a fog. San Francisco, California is noted for its fogs as mT air masses from the Pacific travel over the cold California Current as they move toward the coast.

Radiation fog forms during the evening under cloudless skies and with little to no wind. Under these conditions, terrestrial longwave radiation is readily emitted to space without absorption by clouds. The loss of longwave radiation causes the surface temperature to decrease inducing a negative sensible heat transfer between the cooling surface and the slightly warmer air in contact with the surface. As the near surface air cools to the dew point the fog forms.

Figure 7.4.1.2: Radiation fog

A radiation fog is shown in Figure 7.4.1.2above. To the left of the picture is a grass field and to the right is an asphalt parking lot. As the sun heats the surface during the early morning it "burns off" the fog. Because the grass field has a higher albedo and cooler surface, the fog is closer to the surface than over the warmer parking lot.

Figure 7.4.1.3: Steam fog forms over a southern lake. (Source: NOAA)

Steam fog occurs when cool dry air settles over a warm, moist surface. Such is the case shown in Figure 7.4.1.3where a steam fog is forming over a lake. When the drier air lies above the moist surface a moisture gradient enables water to evaporate and humidify the air. Because the air's saturation point is low due to the cool temperature, the water vapor condenses and a steam fog forms.

An ***upslope fog*** forms when moist air if forced up a slope. These certainly occur as the air encounters hilly terrain and is forced to rise, or if moist air travels up a very long slope. Such might be the situation when air moves out of the Gulf of Mexico traveling west up the Great Plains toward the east slope of the Rocky Mountains. As the air rises it expands and adiabatically cools. Once the air temperature reaches the dew point temperature the air becomes saturated, and condensation occurs to form the fog.

Frontal fogs are associated with weather fronts, especially a warm front. Warm, moist air rises up and over cooler, drier air at the surface along a warm front. As precipitation falls from the warmer air into the drier air some of the water evaporates and humidifies the cooler air. As the humidification process brings the cooler air to its saturation point a fog forms.

Geographical Patterns of Fog

There is a definite geographical pattern to the formation of fogs. Figure $7.4.1.4$ shows the spatial pattern of fogs over the United States. First note that radiation fog is pretty common over much of the country as no special landscape features like mountains or ocean currents are needed to create it. Advection fog is common along coasts where air originating over warm water travels over cooler water or land surfaces to induce condensation and cloud formation near the ground. Upslope fog is common through the western Great Plains and eastern slope of the Rocky Mountains as warm and moist air, often originating in the Gulf of Mexico, works its way toward higher elevation. The gentle uplift provided induces adiabatic cooling and saturation of the air with subsequent condensation and fog formation.

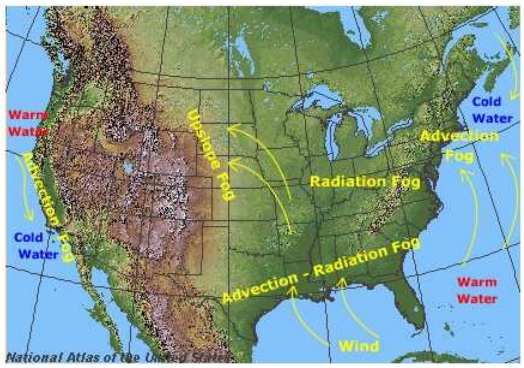


Figure $7.4.1.4$: Geographical distribution of fogs over North America.

7.4.2: Clouds

Clouds form by the condensation of water into extremely small droplets of liquid or ice. Clouds are classified according to the height at which they form and their structure. High clouds form above 7,000 m (23,000 ft) and are primarily composed of ice crystals. Meteorologists call these cirro-form clouds. Mid-level clouds form between 2,000 and 7,000 m. The prefix alto is applied to these clouds. Low clouds form between the surface and 2,000 m.

Clouds are also classfied based on their form or structure. If they take on a layered appearance they are strati-form. If they show vertical development they are cumulo-form. To indicate they are precipitating, meteorologists apply the prefix nimbo or suffix nimbus to their name. There are many other terms used to describe cloud form but they are beyond the scope of this textbook.

High clouds

High clouds are cirro-form clouds being composed mostly of ice. Generally found above 7,000 meters, these clouds include: cirrus, cirrostratus and cirrocumulus.

Figure 7.4.2.1: Cirrus clouds

Cirrus clouds appear as wispy thin veils or detached filaments composed mostly of ice. Strong winds aloft often create the fibrous ice trails which tend to curl at their ends. Cirrus clouds with hooked filaments are sometimes called "mare's tails". Cirrus clouds are associated with an approaching warm front.

Figure 7.4.2.2: Cirrostratus Cloud

Cirrostratus is a transparent, whitish veil of cloud that usually covers much of the sky. Sometimes cirrostratus clouds are so transparent that you can barely see them. They often create a halo around the sun or moon. Cirrostratus clouds thicken and grade into altostratus clouds with the approach of a warm front.

Figure 7.4.2.3: Cirrocumulus Clouds

Cirrocumulus clouds appear as white patches made up of very small cells or ripples. The globules of cloud are arranged in a regular pattern and are commonly called "mackerel sky" for their similarity to the scales of a fish.

Middle Clouds

Clouds found in the middle levels of the troposphere have the prefix alto attached to their name. Two clouds are described here: altocumulus and altostratus.

Figure 7.4.2.4: Altocumulus cloud (Source: NOAA.)

Altocumulus form as large masses in patches or rows that may or may not merge with one another. Individuals usually have a sharp outline as they are composed of water and not ice. Altocumulus clouds are easily confused with cirrocumulus and stratocumulus clouds. Cirrocumulus are smaller and less dense than altocumulus. Elements of stratocumulus are larger than altocumulus. If you extend your arm in the direction of the cloud, altocumulus tend to be the size of your thumbnail, while stratocumulus are the size of your fist.

Figure 7.4.2.5: Altostratus cloud

Altostratus are a formless layer of grayish cloud that cover most if not all the sky. Altostratus clouds are more dense than the cirrostratus. The sun is barely visible through altostratus clouds giving the appearance of a "watery sun". Where enough light shows through cirrostratus clouds to create shadows, it does not with altostratus. Altostratus thicken into nimbostratus as a warm front approaches your location.

Low Clouds

Low clouds are those that form from the surface up to 2,000 meters. Low clouds include: stratus, stratocumulus, and nimbostratus.

Figure 7.4.2.6: Stratus cloud (Source NOAA.)

Stratus clouds appear as a uniform dark-gray layer of clouds covering the entire sky. Stratus clouds often form along warm fronts and can give way to nimbostratus as the front approaches your location. Stratus clouds may also form by the lifting of a fog bank.

Figure 7.4.2.7: Stratocumulus cloud (Source NOAA.)

Stratocumulus clouds appear as lumpy, low lying clouds that cover much of the sky. They form patches or rows of clouds with some blue sky between the individual cloud units.

Figure 7.4.2.8: Nimbostratus cloud (Source NOAA.)

Nimbostratus clouds are dark-gray layer of clouds that cover the entire sky. The prefix "nimbo" indicates that these clouds are precipitating. Nimbostratus clouds are typically found along a warm front producing low intensity precipitation that lasts for several hours.

Vertically Developed Clouds

Cumulus-type clouds are those that primarily exhibit vertical development. Two of the more common types are the cumulus and cumulonimbus.

Figure 7.4.2.9: Cumulus clouds

Cumulus clouds appear as small, cotton ball-like clouds that generally form by convection. Cumulus are also called "fair-weather" clouds as pleasant conditions usually prevail while they are around.

Figure 7.4.2.10: Cumulonimbus cloud (Source NOAA.)

Cumulonimbus clouds form during very unstable conditions. They are the tallest clouds, and can reach to the stratosphere. Cumulonimbus clouds are associated with thunderstorms capable of generating locally high winds, hail, lightning, and torrential down pours.

7.4.3: Precipitation Process

The word precipitation in chemistry refers to material falling out of suspension. The same definition can be applied when studying weather. Precipitation from a meteorological stand point is water in some form, falling out of the air, and settling on the surface of the earth. This allows us to distinguish between forms of condensation in the atmosphere and condensation that occurs at the surface. Dew is condensation at the surface and thus is not a form of precipitation. Rain, snow, hail, sleet, freezing rain are all forms of precipitation. Meteorologists have developed two models of precipitation formation. They are the ***collision-coalescence*** and ***ice crystal*** models. An important distinction between the two processes is the temperature of the cloud. ***Warm clouds*** are ones whose mass lies above the freezing level while ***cold clouds*** primarily exist where the temperature is below freezing.

Collision - coalescence

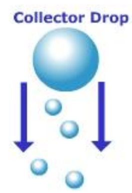


Figure 7.4.3.1: Collision-coalescence of raindrops

The collision-coalescence model applies to warm clouds that form in the tropics. Warm clouds are those that form at altitudes where the air temperature is above freezing. For precipitation to form under this model, there needs to be a variety of different size condensation nuclei. Large condensation nuclei will create large water droplets while smaller condensation nuclei create small ones. In order for the droplets to make their way to the surface they have to be heavy enough to overcome the resistance imposed by upwardly rising air that is fueling the development of the cloud. The smaller, lighter droplets are easily suspended in the updrafts of air, while the larger heavy collector droplets fall and collide with the smaller ones. Upon collision, the droplets coalesce into a bigger droplet. As the droplet falls, resistance by the air flattens the droplet to the point where it becomes unstable and breaks apart. With enough collisions, the droplet achieves a size sufficient to fall all the way to the surface.

Ice – crystal model

The ice-crystal model, or Bergeron process, is the process of precipitation formation in the middle and high latitudes. Here, clouds form at altitudes where the temperatures are below the freezing point of water. In these clouds, water exists in its liquid form even though the temperatures are cold enough to freeze water. Water that has a temperature below freezing but is still in a liquid state is called "***super-cooled water***". Water in extremely small amounts such as cloud droplets can exist in such a state. Ice crystals are found co-existing with the super-cooled water in cold clouds. When this occurs, the ice crystals will grow at the expense of the water droplets. Why? Examine the saturation curve in Figure 7.4.3.2 It shows that at temperatures below freezing the saturation vapor pressure of ice is less than that over a droplet of water. This means that a water vapor gradient exists between the droplet and the ice. Water can evaporate off the droplet and deposit on the ice in response to the water vapor gradient. The droplet will dissipate in size while the ice crystal grows into a snow flake. Once the snow flake is large enough, it will fall to the surface. Thus, precipitation that falls in the middle and high latitudes starts out as snow. Whether it hits the surface as snow or rain depends on the temperature conditions through which the snowflake falls.

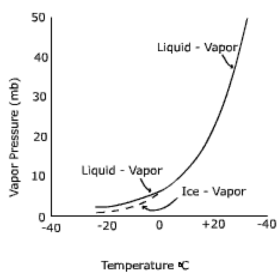


Figure 7.4.3.2: Relationship between air temperature and vapor pressure at saturation

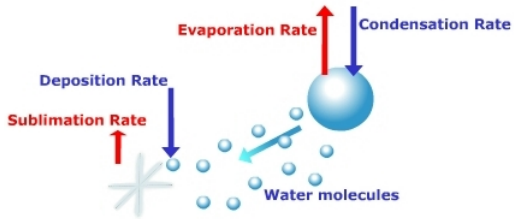


Figure 7.4.3.3: Growth of ice crystals by deposition

Forms of precipitation

There are a variety of different types of precipitation but we'll only treat four of the more common ones here. The kind of precipitation received depends on the variation of temperature above the surface. ***Rain*** is precipitation in liquid form. ***Snow*** is precipitation in solid form as (typically) a hexagonal crystal shape. Size and shape of the crystal is dependent on moisture content and temperature of the air. Recall that in the middle and high latitudes rain begins as snow. If the air temperature near the surface is above freezing, the snow will melt into rain and fall in liquid form. If the air temperatures are below freezing on its journey toward the surface, precipitation will be in the form of snow. ***Sleet*** occurs when snow falls through a warm layer of air and melts. Before reaching the ground, the precipitation passes through a cold layer of air causing the water to refreeze and fall as sleet. ***Freezing rain*** occurs when snow melts upon passing through a warm layer of air and then freezes on the surface whose temperature is at or below freezing. Significant amounts of freezing rain coats the surface with a glaze of ice making roadways treacherous and toppling trees and downing power lines. ***Hail*** falls as rounded pellets or balls of ice from severe thunderstorms. Vertical motions up-and-down through the storm create concentric rings of ice around the hail stone.

Figure 7.4.3.4: A heavy cover of ice and snow bring down these power lines (Source: NOAA)

7.5: Global Patterns of Precipitation

As we are well aware, moisture availability from precipitation is unequally distributed across the Earth. The geographic pattern of precipitation is explained by examining the spatial distribution of air masses, water availability through evaporation, and uplift mechanisms. One of the most important climate elements is the influence of the global pressure systems.

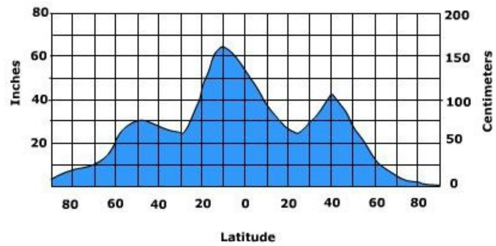


Figure 7.5.1: Latitudinal distribution of precipitation.

Precipitation near the equator is high due in part to the influence of the Intertropical Convergence Zone. Here, convection and low pressure dominate and provide lift for the air throughout much of the year. At about 30º north and south latitude precipitation decreases due to the presence of the subtropical high pressure systems. Subsiding air from high pressure suppresses uplift which inhibits the formation of precipitation. Precipitation increases in the midlatitudes where vastly contrasting air masses collide along weather fronts to cause precipitation. As one approaches the poles, precipitation decreases on account of the cold temperature and its associated low saturation point. This is obviously a gross exaggeration of the true geographical distribution of precipitation. Orientation of winds, mountain systems, and air mass dominance play important roles in the pattern of precipitation. What is missing from our description is the temporal variation of precipitation over the Earth.

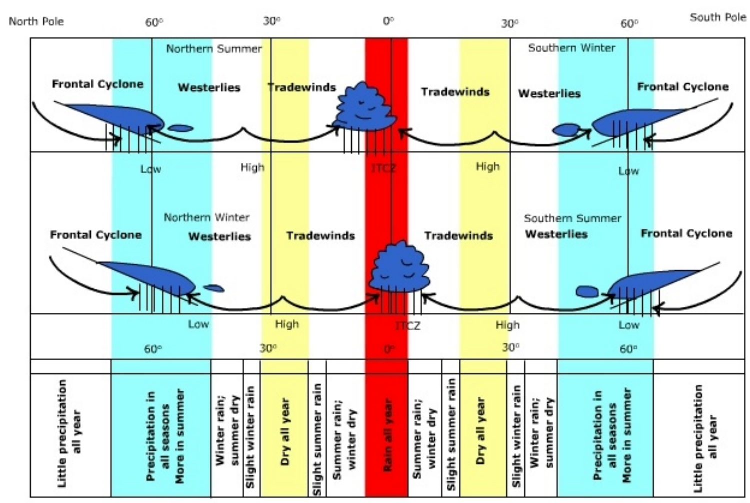


Figure 7.5.2: Seasonal migration of surface wind and pressure (Modified from Trewartha, Robinson, Hammond & Horn, 1977)

The temporal variation in global precipitation is directly linked to the seasonal changes in the heating of the Earth and its effect on the movement of global pressure systems and air masses. The migration of the ITCZ across the Equator keeps this region very moist. As one moves poleward, the precipitation becomes more variable as the drying effect of the subtropical is experienced. A dry region is found near 20 degrees of latitude as a result of the subtropical high. The north - to - south shifting creates summer dry climates poleward of the subtropical high but summer wet - to the equator ward side. Once into the midlatitudes, frontal activity keeps most seasons humid and moist. In the cold Arctic or Antarctic air little moisture is available for precipitation formation. The seasonal changes in precipitation are illustrated in the animation below. Areas of high precipitation coded in red and yellow are seen moving north and south during the year following the migration of global pressure and wind systems.

Animation: Seasonal changes in global precipitation

7.5.1: The Equator to the Subtropics

7.5.2: Midlatitudes to the Poles

7.5.1: The Equator to the Subtropics

In general, precipitation decreases poleward away from the equator as one moves toward the subtropical regions. The largest annual precipitation totals straddle the equator while the driest regions on Earth lie near the Tropic of Cancer. In addition, precipitation becomes more seasonal as one moves away from the Equator. This is primarily due to the shifting locations of global wind and pressure systems.

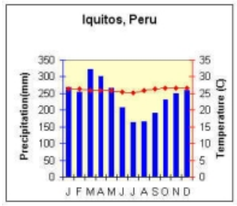


Figure 7.5.1.1: Climograph for Iquitos, Peru

Climates straddling the equator experience some of the highest annual precipitation amounts of all climates on Earth. This is depicted by the blue bar graph in the climograph for Iquitos, Peru located at 3^{o}S. Here the year 'round high sun heats the Earth and sets off convective thunderstorms in the warm, moist, and unstable equatorial air. Here too is found the Intertropical Convergence Zone (ITCZ). The ITCZ is the region where tradewinds originating in the semi-permanent subtropical highs converge causing air to rise. The combination of convergence and convection lifts the air causing it to adiabatically cool, ultimately condensing the moisture into clouds and promoting precipitation. Iquitos, like many places located near the equator, receives over 2800 mm (100 in) of precipitation a year.

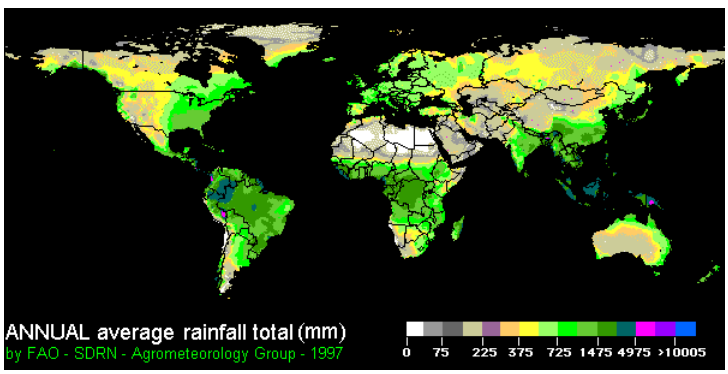


Figure 7.5.1.2: Annual Average Rainfall (Courtesy FAO)

Moving poleward, precipitation becomes more seasonal. In the tropics (10^{o} - 23.5^{o}) the maximum amount of precipitation falls during the high sun (summer) season. During the summer, the ITCZ shifts poleward bringing precipitation with it. As the Sun's most intense rays shift equatorward during the low sun season, the ITCZ moves out of the region and a dry season sets in. The length and intensity of the dry season tends to increase toward the poleward limits of the tropics.

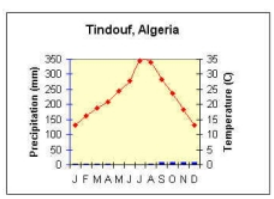


Figure 7.5.1.3: Climograph of Tindouf, Algeria

Depending on location, the subtropics (23.5^{o}- 35^{o}) can be very dry or wet. The equatorward side of the subtropics tends to be quite dry. As one moves poleward the amount of precipitation increases though has a seasonal character. Within the continental interior of Africa at about 23.5^{o} N the great Sahara Desert can be found. These conditions are represented in the climograph for Tindouf, Algeria. Tindouf has a meager amount of precipitation for the year that averages 43.8 mm (1.74 in) over the course of a year. The extremely dry conditions are a result of being dominated by the subsiding conditions in the subtropical high.

But when you move to the poleward limits of the subtropics, especially on the east coast of a continent, annual precipitation increases. The increase in precipitation in these regions is due to the presence of moist mTu air masses that blow onshore. As they come on shore, convection lifts the air to promote cooling, condensation, and precipitation. In addition, the poleward limits of the subtropics border the midlatitudes where polar front cyclones produce precipitation.

7.5.2: Midlatitudes to the Poles

Beginning along the northwest coast of the United States (coastal Oregon and Washington) and the west coast of Canada (British Columbia) we see a narrow strip of high annual precipitation. The large amount of precipitation is due to the orographic uplift of west-to-east flowing air masses from the ocean. These moist maritime polar air masses are forced to rise up the windward side of north-south oriented mountain chains inducing them to drop copious amounts of precipitation. In many places the amount of precipitation can exceed 100 inches rivaling the amounts found in the tropical rain forests. A short distance inland on the leeward side shows much less precipitation. The lee side of a mountain sits in the "rain shadow".

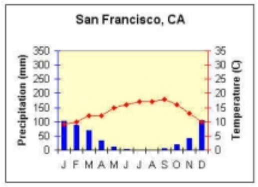


Figure 7.5.2.1: Climograph for San Francisco, CA.

Traveling down the coast we experience a decrease in precipitation once we get to the southwestern coast of North America around southern California. The annual rainfall map doesn't gives us a very good picture of what the actual precipitation regime is like in this part of the world though. Examine the climograph for San Francisco, California (Figure 7.5.2.1). San Francisco is located in what's called the dry summer subtropical climate. The dry summer is due to the presence of the subtropical high that migrates into this region during the summer. The subsidence of the subtropical high keeps air from rising off the surface and dries the air through adiabatic warming. Additionally, as maritime air streams toward land it passes over the cold California Current. The cold ocean current chills the air near the surface and steepens the environmental lapse rate of temperature in the air mass making it stable (mT_s). The combined effect of these factors inhibits precipitation formation and thus creates the dry summer typical of this region. Winter is the wet season as subtropical high pressure slides south and the polar front with its accompanying cyclonic activity migrates into this region.

Proceeding into the desert of the southwestern portion of the United States a noticeable decrease in precipitation occurs. The meager amount of precipitation found in this region is in part due to the lack of available water for evaporation. The desert is located on the leeward side of mountains which also accounts for part of the dryness. Additionally, a high–level high pressure pattern over the western United States is responsible for the summer-time dry conditions. At the surface, heating creates a shallow region of low pressure. Though air can be uplifted by convection and the convergence of air into the low at the surface, an upper–level high helps to suppress cloud development and precipitation.

Figure 7.5.2.2: Clouds rising along the windward slopes of the Colorado Front Range.(Image courtesy Michael Ritter)

Moving eastward across the western states one experiences an alternating pattern of lower and higher amounts of precipitation. This pattern is due to the orographic uplift on the wet windward slopes and then drier leeward slopes. The fact that one is a great distance from the source region for moist air also decreases the likelihood for precipitation in the intermountain west.

High annual precipitation and humid conditions prevail in the southeastern part of the United States. The source region for maritime tropical air is located over the Gulf of Mexico and the Caribbean. When this air mass streams over land, convective uplift can create significant precipitation. Along the southeast coast the air mass travels over the warm Gulf Stream which increases the instability of the air. The effect of location with respect to the source region can be seen in the pattern of precipitation. Precipitation decreases as one moves inland toward the northwest. Figure 7.5.2.3 illustrates the effect of location on the seasonal variation of precipitation as one moves away from the ocean. As one moves poleward the precipitation decreases and becomes more seasonal.

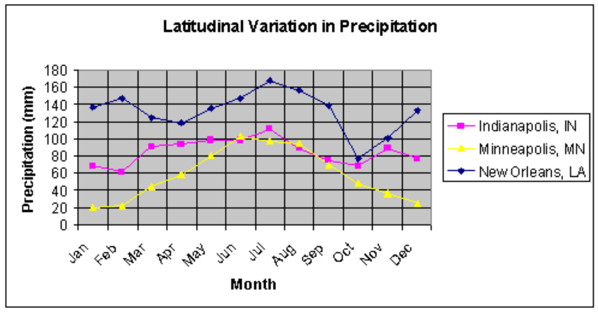


Figure 7.5.2.3: Latitudinal variation of precipitation through the U.S.

A moderate amount of precipitation occurs in the central US increasing toward the east and northeast coast of the United States and Canada. This region is dominated by the polar front and cyclonic activity. The clash of cold air masses from the north and warmer ones to the south creates frontal uplift and precipitation. Precipitation decreases northward through Canada as air temperature and its associated saturation point decreases.

Moving through the subarctic, Arctic and Polar geographical zones precipitation decreases as temperatures decrease along with the saturation point of air masses. The increasing influence of the polar high helps to suppress precipitation as well. Coastal areas may receive slightly more precipitation due to their proximity to water.

Europe and Asia experience broadly similar patterns as North America, with precipitation decreasing toward the interior of the continent and as one proceeds toward higher latitudes. But there are some very distinct differences too. One of the most notable differences is the penetration of moist conditions farther into the western side of the Eurasian continent than along the western side of North America. While much of western Europe lies in the domain of the westerlies as does the United States, the orientation of the mountains in Europe and North America are quite different. The mountains in North America, especially along the west coast tend to run North-to-South perpendicular to the prevailing winds. This orientation forces air to rise, creating precipitation on the western slope and drier "rain shadow" conditions on the eastern slopes. Mountains tend to be oriented in an east-to-west fashion and thus do not create a barrier to marine time air masses pushed along by the westerlies. This creates moister condition further inland in Europe than North America.

The sheer size of the Eurasian continent creates much drier conditions in the interior than what occurs in North America. Far removed from the ocean, with the imposing barrier of the Himalaya Mountains, interior deserts like the Gobi and Taklimakan, can be found. Like North America, drier conditions become more prevalent as one proceeds towards bone-chilling temperatures near the Arctic Circle and beyond.

7.6: Future Geographies - Global Precipitation Patterns

Changes in the the global distribution of precipitation will result from increased atmospheric water vapor originating from warmer oceans, especially in the tropics. Rising temperatures will increase evaporation and drive the hydrologic cycle at a more vigorous pace. Not only will the amount of precipitation change, so will the kind and timing. More precipitation now falls as rain than snow in northern regions. The average rainfall in parts of northern Europe has increased by 50%. Between 1900 and 2005, significantly more precipitation has fallen in the eastern parts of North and South America, and northern and central Asia than normal. Total snow cover has on average decreased in both hemispheres.

Figure 7.6.1: Flash flood on Twenty-five Mile Wash on Hole-in-the-Rock Road. Maximum water depth is approximately 8 feet. The rain which caused this flood fell 68 miles west. (Courtesy USGS)

Precipitation variability causing droughts and floods alike will be widespread due to global warming. Some regions like the Sahel, the Mediterranean, southern African and parts of southern Asia have already experienced decreased precipitation. Though they experience little annual precipitation overall, many dry places receive much of their rainfall in a few brief, but intense storms. Intense precipitation events accompanied by flash flooding are predicted to be more frequent even in regions where annual precipitation is forecast to decrease. Longer dry spells between intense precipitation events are also expected.

Current models suggest that precipitation is likely to increase in some tropical wet regions of the continents, and the tropical Pacific Ocean. Drier conditions are expected in the subtropics while high latitudes will experience an increase in precipitation. Upper midlatitude and high latitude increases in precipitation is due to the displacement of the jet stream to a more northerly track.

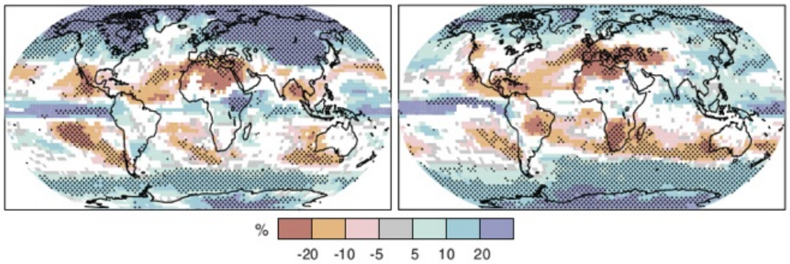


Figure 7.6.2: Relative Changes in precipitation for period 2090-2099 relative to 1980 - 1999. December to February on left, June to August on right. (Courtesy IPCC)

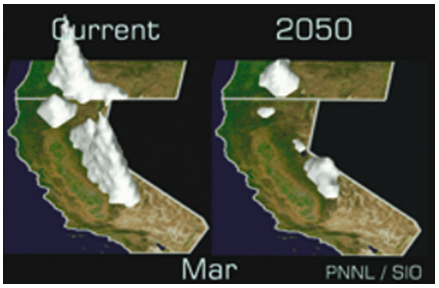


Figure 7.6.3: Computerized projections of western United States snowfall levels in 2050 compared to present day. (Source: Scripps)

The likelihood that precipitation falls as rain than snow increases as air temperatures increase. This is especially true during the fall and spring and in places where temperatures hover near freezing. Changes in the type of precipitation has been observed in many places, but especially in the middle and high latitudes of the Northern Hemisphere. Increased rain has meant reduced snowpacks and difficulty managing reduced water supplies through the dry summer months. California for example, depends on snowpack in the Sierra Mountains for water supply during the summer. But changes in the precipitation will require new infrastructure and changes in how water resources are governed. Water managers will have to balance the need to fill reservoirs for water supply or maintain reservoir space to winter flood control.

Figure 7.6.4: View of monsoon rain in Kerela (Source: Wikimedia)

Precipitation associated with the monsoons is predicted to change into the next century as a result of global warming. Models predict increased precipitation and interannual precipitation variability for the Asian monsoon southern part of the west African Monsoon. A decrease in precipitation is expected in the Sahel in the northern summer. Precipitation is expected to increase in the Australian monsoon. Monsoon precipitation in Mexico and Central America is is expected to decrease due to increasing precipitation over the eastern equatorial Pacific from Walker Circulation and local Hadley Cell circulation changes.

7.7: Looking Ahead

In this chapter we became familiar with the processes that determine the humidity of the air, the process of formation and reasons for the geographical pattern of precipitation. The presence of moisture in the atmosphere and the geography of precipitation are dependent on the earth's energy balance, temperature, atmospheric pressure, and air circulation. This dependency reflects the interaction between the various spheres that comprise the earth system.

Chapters 4 through 7 deal with elements of weather and climate. They set the stage for chapter 8 "Weather Systems". In "Weather Systems" we'll focus on how the day-to-day changes in the atmosphere. Chapter 8 integrates the weather elements to explain the daily changes in atmospheric conditions. It will also examine the processes that create, and geographical patterns of, powerful storm systems like tornadoes and hurricanes.

Figure 7.7.1: Monsoonal thunderstorm over Arizona. (Courtesy NOAA (Source))

Weather and climate are elements of physical geography that impact all of our lives. That's why an understanding of the potential effects of climate change is important to all of us. If we stay on our present course, geoscientists predict that storm systems in some parts of the world will become more severe. The patterns of both weather systems, and climates could radically shift, causing significant changes in natural habitats, agricultural systems, population distribution, and the economic stability. Geographers will be at the forefront of understanding how these changes will take place, where they will happen, and how we might address them.

Before proceeding to the Chapter 8, take some time to review chapter 7. You may wish to review chapter 5 "Air Temperature", and Chapter 6, as the contents of these chapters along with Chapter 7 comprise the components of weather systems.

7.8: Review and Additional Resources

Review

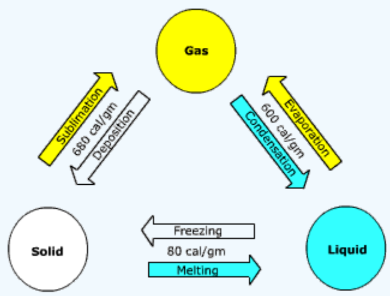
A rocky peak rises from a sea of fog in an Arizona valley
Courtesy NOAA

Figure 7.8.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Then, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts 7.8.1

- **Phase change**



Phase Changes of Water

- **Evaporation**
  the phase change of a liquid to a gas
- **Transpiration**
  the transfer of water into the air via leaf pores or stomata.
- **Humidity**
  a measure of the water vapor content of the air.
- **Saturation**
  "holding all the moisture it can"
- **Specific humidity**
  the weight of water vapor in the air per unit weight of air, which includes the weight of water vapor.
- **Mixing ratio**
  the weight of water vapor per unit weight of dry air.
- **Vapor pressure**
  the partial pressure created by water vapor.
- **Saturation vapor pressure**
  the pressure that water vapor creates when the air is fully saturated.

- **Relative humidity**
  the ratio of the amount of water vapor in the air to its saturation point.
- **Condensation**
  the phase change of water vapor into a liquid
- **Condensation nuclei**
  act as a platform for condensation to take place, increasing the size of a droplet and decreasing surface tension.
- **Dew**
  small droplets of water that form as a result of condensation.
- **Fog**
  a cloud that forms near the ground
- **Radiation Fog**
  forms during the evening under cloudless skies and with little to no wind
- **Steam Fog**
  occurs when cool dry air settles over a warm, moist surface
- **Advection Fog**
  forms when warm and moist air travels over a cool surface.
- **Upslope Fog**
  forms when moist air if forced up a slope
- **Frontal Fog**
  associated with weather fronts, especially a warm front.
- **Saturated Adiabatic rate**
  If the air is saturated, the rate of temperature change is .6^{o}C/100 meters.
- **Dry Adiabatic Rate**
  If the air is dry, the rate of temperature change is 1^{o}C/100 meters.
- **Stable air**
  Stable atmospheric conditions prevail when the environmental lapse rate is less than the saturated adiabatic rate.
- **Unstable air**
  Air is unstable when the environmental lapse rate is greater than the dry adiabatic rate.
- **Cirrus cloud**
  appear as wispy thin veils or detached filaments composed mostly of ice.
- **Cirrostratus**
  a transparent, whitish veil of cloud that usually covers much of the sky.
- **Altostratus**
  formless layer of grayish cloud that cover most if not all the sky.
- **Stratus**
  appear as a uniform dark-gray layer of clouds covering the entire sky.

- **Cumulus**

  appear as small, cotton ball-like clouds that generally form by convection.

- **Nimbostratus**

  dark-gray layer of clouds that cover the entire sky. The prefix "nimbo" indicates that these clouds are precipitating.

- **Cumulonimbus**

  form during very unstable conditions.

? Self-Assessment Quiz 7.8.1

1. The highest relative humidity for the day
   A. is usually around sunrise when the air temperature is coolest.
   B. is usually later in the afternoon when the air temperature is the warmest.
   C. is right at noon
   D. is at midnight
2. If the temperature of the air increases without additional water vapor being added to the air the relative humidity will likely
   A. increase
   B. decrease
   C. stay the same
   D. temperature has no impact on relative humidity
3. On a day in mid-June a parcel of air and the air that surrounds it at ground level are found to have the same temperature. You also find that the ELR is greater than the DAR on that day. If the parcel is given an upward push
   A. the air would be stable
   B. the air would be unstable
   C. the parcel and surrounding air will still have the same temperature
   D. none of the above
4. A fog that forms when warm, moist air comes in contact with a cool surface is called
   A. a steam fog
   B. an upslope fog
   C. a radiation fog
   D. an advection fog
5. The ice crystal growth model
   A. applies to cold clouds
   B. applies to mid and high latitude situations
   C. requires the presence of super-cooled water
   D. all the above
6. The weight of water vapor per unit weight of dry air is
   A. the mixing ratio
   B. the relative humidity
   C. the absolute humidity
   D. the vapor pressure
7. Thin, wispy high clouds composed of ice crystals are
   A. cumulus clouds
   B. cirrus clouds
   C. stratus clouds
   D. cumulonimbus clouds
8. Latent heat
   A. is stored in water molecules when condensation occurs

B. is converted to sensible heat when water vapor condenses
C. is used to raise the temperature of the water
D. relates to none of the above

9. Radiation fog
   A. is more likely to form during the day
   B. is more likely to form at night
   C. forms when it is windy
   D. none of the above
10. Frost is a product of
   A. evaporation
   B. condensation
   C. sublimation
   D. deposition

Answer

1. A
2. B
3. B
4. D
5. D
6. A
7. B
8. B
9. B
10. D

Additional Resources

Use these resources to further explore the world of geography

A World of Change: El Niño, La Niña, and Rainfall (*NASA Earth Observatory*)

Readings

Every cloud has a Filthy Lining (NASA EOS)

CHAPTER OVERVIEW

8: Weather Systems

Learning Objectives

By the end of the chapter you should be able to:

- Describe the conditions favorable for an air mass source region.
- Describe the characteristics of, and locate the source region for, cP, mP, mT, cT, cA, cAA mE air masses.
- Explain how air masses are modified when they leave their source region.
- Describe the characteristics of fronts.
- Identify cold, warm, stationary and occluded fronts from a weather map.
- Interpret weather conditions from weather maps symbols.
- Describe the polar front theory of cyclogenesis.
- Draw profile views of cold, warm and occluded fronts.
- Explain the relationship between jet streams and surface cyclones.
- Describe the weather changes that occur as a midlatitude cyclone passes.
- Compare and contrast conditions during the cumulus, mature, and dissipating stages of thunderstorm development.
- Describe how lightning forms.
- Describe the conditions necessary and location for hurricane development.
- Describe the potential impact of global warming on severe weather.

> *"Forecast for this evening...dark" - George Carlin*

Weather is the day-to-day state of the atmosphere. The weather of the humid tropics is very similar throughout the year as a constant flow of energy keeps temperatures uniformly high. However, the daily weather is quite variable in the midlatitudes. Here, huge air masses collide to create powerful storm systems that affect global heat distribution, the shaping of the earth surface, and our daily livelihood. In this chapter we'll examine weather systems at a variety of geographic scales that affect our daily lives.

See if you are prepared for this chapter by "8.0: Getting Ready for Chapter 8"

8.1: Getting Ready for Chapter 8
8.2: Air Masses
8.3: Fronts
8.4: Wave Cyclones (Cyclogenesis)
8.5: Weather and Wave Cyclones
8.6: Severe Weather
8.6.1: Thunderstorms
8.6.2: Lightning
8.6.3: Tornadoes
8.6.4: Hurricanes
8.7: Future Geographies - Severe Weather and Global Warming
8.8: Review and Additional Resources

8.1: Getting Ready for Chapter 8

Chapters 4 through 7 dealt with elements of weather and climate and set the stage for chapter 8 "Weather Systems". In chapter 8 we'll focus on how these weather elements explain the daily changes in our daily weather. We'll also examine the processes that create, and geographical patterns of, powerful storm systems like tornadoes and hurricanes.

Figure 8.1.1: Monsoonal thunderstorm over Arizona. (Courtesy NOAA (Source))

Weather and climate are elements of physical geography that impact all of our lives. That's why an understanding of the potential effects of climate change is important to all of us. If we stay on our present course, geoscientists predict storm systems in some parts of the world will become more severe. The patterns of both weather systems, and climates could radically shift, causing significant changes in natural habitats, agricultural systems, population distribution, and the economic stability. Geographers will be at the forefront of understanding how these changes will take place, where they will happen, and how we might address them.

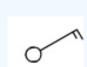
What you should already know ...

Weather systems, like any other natural system, are composed of many interacting components. Temperature, moisture, pressure and air circulation combine to create systems that affect our day-to-day weather. We'll focus mostly on the impact of cyclonic systems that form in the mid- to high latitudes in association with jet streams. We'll also look at severe weather systems, thunderstorms, tornadoes, and hurricanes.

The elements of these systems were presented in Chapter 5, Chapter 6, and Chapter 7. In particular, you should have a handle on the basic concepts of humidity, precipitation formation, cloud types, air pressure, and wind.

Use the quiz below to assess your understanding of a few key topics from these chapters.

? Quiz 8.1.1

1. Which of the following is considered a cold, dry airmass?
   - A. mT
   - B. mP
   - C. cP
   - D. cT
2. Wind direction is described as
   - A. where the wind comes from.
   - B. where the wind is blowing to.
3. Low pressure systems in the Northern Hemisphere exhibit
   - A. surface convergence and subsidence
   - B. suface convergence and uplift
   - C. surface divergence and subsidence
   - D. surface divergence and uplift
4. The approximate wind direction and speed (assume north at top of page) 
   - A. SW, 20 knots

B. NE, 15 knots
C. SW,15 knots
D. NE, 20 knots

5. Circulation in a cyclone in the Northern Hemisphere is

   A. clockwise and outward from the center
   B. clockwise and inward toward the center.
   C. counterclockwise and inward toward the center.
   D. counterclockwise and outward from the center

6. ____ uplift occurs when two unlike air masses collide.

   A. Orographic
   B. Convective
   C. Convergent
   D. Frontal

7. A steep pressure gradient would exhibit ___ isobars on a weather map.

   A. closely spaced
   B. widely separated

8. What type of cloud is shown here?

   A. Cirrus
   B. Stratus
   C. Cumulonimbus
   D. Altostratus

9. If the surface air pressure is 1010 mb it would be considered ______ pressure.

   A. high
   B. low

10. _____ flow occurs when the polar front jet stream and equatorward edge of the circumpolar vortex takes on a curving flow.

   A. zonal
   B. meridonal

Answer

1. C
2. A
3. B
4. B
5. C
6. D
7. A
8. A
9. B
10. B

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous material.

If you scored less than 70% you should consider reviewing the previous material and seeking help from your instructor.

8.2: Air Masses

Air mass source regions

An ***air mass*** is a vast pool of air having similar temperature and moisture characteristics over its horizontal extent. An air mass occupies thousands of square miles of the Earth's surface. Air masses are born in a ***source region*** where they take on their characteristic temperature and moisture content. Source regions are often regions of low relief and calm wind that prevent turbulent mixing and allow the air to take on the conditions of the surface over which it forms. Radiation and vertical mixing of heat yield an equilibrium between the conditions at the source region and the properties of the overlying air mass after a period of 3 to 5 days. Areas dominated by high pressure serve as good source regions where subsidence pushes the air toward the surface. High pressure also enables the air to move outward from the source region.

Air mass classification

Atmospheric scientists have created definite temperature and humidity criteria to classify each air mass. We'll classify them based on their general conditions, e.g. warm and wet, cold and dry. The latitude of the source region fundamentally determines the temperature of an air mass. Arctic air masses form between 60º and 90º north latitude. Arctic air masses are characterized as being extremely cold air masses. Polar air masses form between 40º and 60º north or south latitude and are cold air masses but warmer than the higher latitude arctic air mass. Warm tropical air masses are found between 15º and 35º north and south latitude. The exceedingly warm equatorial air masses form near the equator. The type of surface over which air masses form also determines their humidity characteristics. Maritime (oceanic) air masses are typically moist, whereas those forming over the continents are usually dry. However, humidity is also determined by temperature so cooler maritime polar air masses are drier than warm maritime tropical air masses.

Air mass types

Figure 8.2.1 shows the location of the air mass source regions that affect Earth's climate. ***Continental arctic*** air (cA) is typically described as extremely cold and dry. Record setting temperatures in the middle and high latitudes are due to the invasion of this very cold mass of air. At about the same latitude in the Southern Hemisphere is found the ***continental Antarctic*** (cAA) air mass. This too is an exceedingly cold air mass and is drier than its arctic counterpart as the source region is the continent of Antarctica. ***Continental polar*** (cP) air is considered a cold and dry air mass that is warmer than the arctic air mass located to the north. Continental polar air is typically a stable or conditionally stable mass of air. ***Maritime polar*** (mP) air is cool and moist air that brings mild weather to coastal locations. Maritime polar air is warmer than continental polar air in the winter as the surface temperature of the ocean is higher. Similarly, mP air masses are typically cooler than cP air masses during the summer as the continents warm more than the ocean at these latitudes. Maritime polar air masses that enter the west coast are forced to rise up coastal mountain chains causing significant orographic uplift and precipitation. In Europe, mP air masses penetrate further inland due to the east–west orientation of the mountains. Thus smaller temperature ranges and higher humidity typical of maritime climate are found further inland in Europe than in the North America.

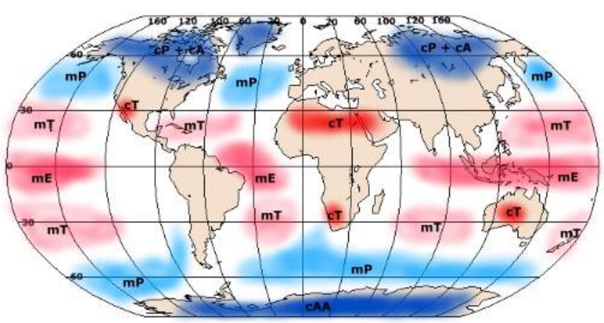


Figure 8.2.1: Global air masses

Maritime tropical (mT) air masses are warm and moist air masses that are responsible for much of the precipitation east of the Rocky mountains in the United States. Precipitation occurs when mT air collides with cP air causing the warmer and less dense mT air to rise, cool, and condense into clouds. In the southeast portion of the United States convective uplift of air also occurs to create precipitation. Over subtropical and tropical continents the source region for the hot and dry ***continental tropical*** (cT) air mass is found. Major source regions are the great deserts of the Earth such as the Sahara, Arabian, and Australian. The extremely low humidity is due to the lack of available water for evaporation as well as the subsidence of the subtropical high. The southwest desert of the United States serves as a source region for cT air too, but only during the summer. Surface temperatures in the winter are too cold to create a continental tropical air mass there. Near the equator the exceedingly warm and humid maritime equatorial air masses form. Convection and convergence of this air mass in the Intertropical Convergence Zone is one for the reasons for the heavy rainfall experienced in the rain forests of this region.

Air mass modification

Figure 8.2.2: Air masses of North America.

The arrows in Figure 8.2.2 indicate the trajectory that air masses affecting North America take as they move out of their source regions. As they traverse the surface, the temperature and moisture content of air masses are modified. Continental air masses traveling south out of central Canada move over warmer surfaces. To indicate that the air mass is colder than the surface over which it is traveling a "k" is added (cPk). Heat transfer into the air mass from the underlying surface creates unstable conditions. In the late fall and early winter cP air masses moving over the open water of the Great Lakes gain heat and moisture. As the air mass strikes the land, the air can be uplifted by topographic barriers causing the lake-effect snows.

Figure 8.2.3: Cloud formation and lake effect snow over Lake Superior and Lake Michigan (Courtesy GSFC)

Off the southwest coast of North America lies a source region for maritime tropical air. This air mass is typically unstable at its source. As it moves toward land the air passes over the cold California Current. As the air mass traverses the cold ocean current, heat is transferred out of the air mass near the surface. In addition, the subsidence of the air aloft due to the presence of the subtropical high in this region causes adiabatic warming of the air at higher elevations. As a result, the environmental lapse rate of temperature decreases or sometimes inverts, making the air stable. To show that the air mass has become stable an "s" is added to its abbreviation, e.g. mT_s. Stable conditions inhibit uplift and reduce the possibility for precipitation. Conversely, off the east coast of the United States the warm Gulf Stream enhances the instability of the maritime air mass and precipitation becomes more likely. In this case, a "u" is added to indicate that the air mass is unstable, e.g. mT_u.

8.3: Fronts

Fronts are boundaries between contrasting masses of air. Atmospheric scientists recognize fronts of different spatial scales. These range from the quasi-stationary fronts along which cyclones form to "weather" fronts embedded in cyclones. Fronts are three-dimensional features. They are not only a boundary between contrasting air masses running along the surface, but extend upwards into the troposphere as we will later learn.

Quasi-stationary fronts

At the global scale are ***quasi-stationary fronts*** found migrating within a particular latitudinal zone throughout most of the year. The ***polar front*** is the boundary between polar-type air and tropical-type air. The polar front migrates between about 35^o and 65^o, following the annual cycle of earth surface heating (Figure 8.3.1). Above the polar front is found the polar front jet stream, a high velocity corridor of wind that controls the development and movement of mid-latitude cyclones.

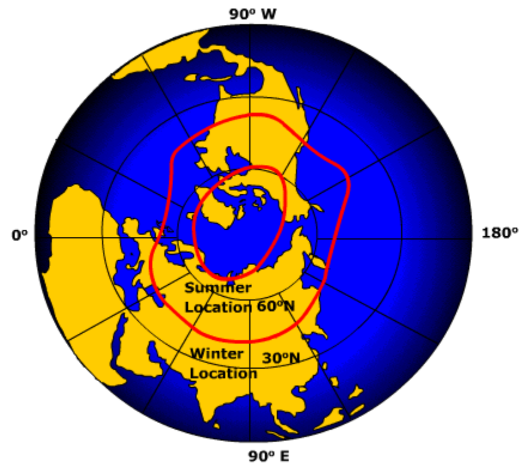


Figure 8.3.1: Summer and winter location of the polar front

During the winter, the polar front slides equatorward along with invading cold air. During the summer, the polar front retreats northward. This seasonal migratory pattern moves cyclones into and out of the middle latitudes giving them quite variable weather conditions over the seasons.

Synoptic Scale Fronts

At a smaller or synoptic scale are the "weather" fronts e.g., cold, warm, occluded, and stationary. ***Cold fronts*** are those where cold air replaces warm air. A ***warm front*** is where warm air replaces cold air. A noticeable difference between warm and cold fronts is the slope of the front above the surface. The frontal surface, the portion extending upward above the surface, is much steeper for the cold front than warm front. The steepness of the frontal surface directly impacts the type of weather one experiences along these fronts.

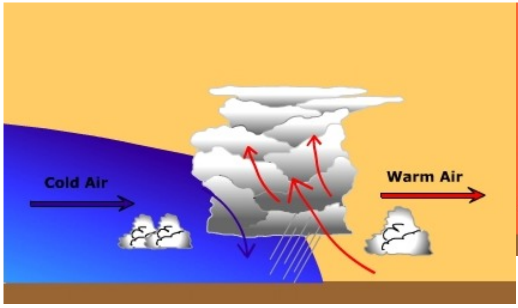


Figure 8.3.2: Profile view of Cold front

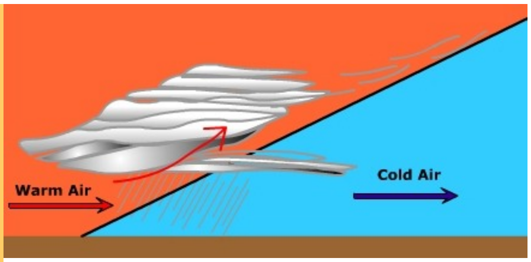


Figure 8.3.3: Profile view of warm front

An ***occluded front*** forms when a cold front catches up with a warm front. Air is often converging at a front producing a trough of low pressure along it. A decrease in pressure is often experienced with their passage. A ***stationary front*** is where no change in air masses or movement of the front occurs. The weather associated with these fronts is discussed later.

Weather Map Depiction

Meteorologists use both symbols and color to distinguish between synoptic scale fronts on weather maps. If printed in color, warm fronts are shown as a line of red semi-circles pointing in the direction of movement. Cold fronts are depicted as a line of blue triangles. Occluded fronts appear in purple with both warm and cold front symbols on the same side. The symbols point in the direction of the front is moving. Stationary fronts are alternating warm and cold front symbols on opposite sides, indicating no movement. A portion of a simplified weather map is shown in Figure 8.3.5. The map depicts a wave cyclone as it is starting to occlude. We see an occluded front trailing southeast from the center branching into cold and warm fronts.

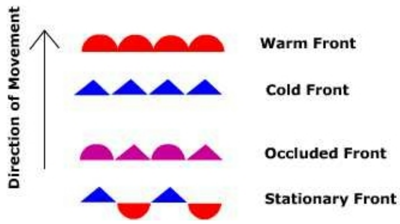


Figure 8.3.4: Front Symbols

The location of air masses on weather maps are identified by their letter abbreviation, e.g., mT, cP, mP. Shading is used to show where areas of precipitation occur. Looking at the local environmental setting can give a clue as to what mechanism caused uplift for precipitation to form. Note that the areas of precipitation in Figure 8.3.5 either occur ahead of a front (frontal lifting) or to the north of the center of the low (convergent lifting).

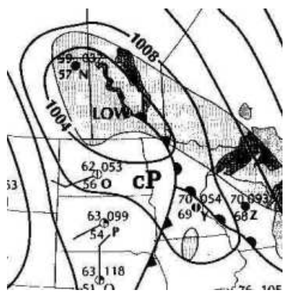


Figure 8.3.5: Simplified Weather Map

The distribution of air pressure is shown by isobars, lines connecting points of equal air pressure. Isobars are drawn in increments of 4 millibars on surface weather maps. Recall that it is the pressure gradient that controls wind speed. *Strong pressure gradients and hence faster winds occur where the isobars are closely spaced. Weak pressure gradients and slow winds occur where the isobars are widely spaced.*

8.4: Wave Cyclones (Cyclogenesis)

The variable nature of weather in the midlatitudes is in part due to the presence of midlatitude or extratropical cyclones. Appropriately called "**wave cyclones**", these systems take the form of an ocean wave when fully developed. Wave cyclones can grow to vast proportions, nearly 1000 miles (1600 km) wide. These vast areas of low pressure are born along the polar front where cold polar air from the north collides with warm tropical air to the south. In so doing, huge spiraling storms move across the surface guided by the polar front jet stream.

Initial Stage - Cyclogenesis

Wave cyclones form where surface convergence predominates. Cyclones often develop in the region of the Aleutian and Icelandic sub-polar low pressure cells. Wave cyclones also develop and intensify on the east slope of the Rocky Mountains, the Gulf Coast and east coasts of North America and Asia.

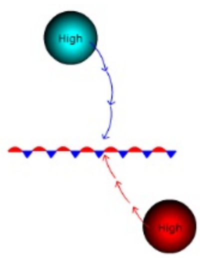


Figure 8.4.1: Air collides along polar front

Especially during the spring and summer in the midlatitudes of North America, high pressure to the north pushes cold polar air southward from Canada. To the south, maritime tropical air streams northward toward the polar air (Figure 8.4.1).The polar front is depicted by the symbols for a stationary front (the alternating red semi-circle and blue triangles). At the location where the opposing streams of air meet, **cyclonic shear** is created from opposing air streams sliding by each other causing the air to spin. You can demonstrate what happens as a result of cyclonic shear by placing a pencil between your hands. Push your right hand away from you (warm southerly flow) and draw your left hand towards you (cold, northerly flow). (Go ahead and try this to see if I'm right.) Examine what happens to the pencil. If you followed directions the pencil should be rotating in a counterclockwise fashion. Click here for more information about the initial stage of cyclone development.

Mature Stage

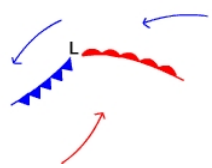


Figure 8.4.2: Open wave form of polar front cyclone

Once the air collides and cyclonic circulation commences, warm air from the south invades where cold air was once located north of the polar front (Figure 8.4.2). A **warm front** develops where warm air replaces the cold air. The position of a warm front on a weather map is depicted (in red) with a line showing the boundary between the air masses and semi-circles indicating the direction the front is moving. To the west of the center of the developing system, cold air is sliding south replacing warm air at the surface. A **cold front** (blue triangles) develops where cold air replaces the warm air. Soon the developing system takes on the characteristic wave form, hence their name "wave cyclone". The lowest pressure is found at the center or apex of the wave.

Figure 8.4.3 depicts the profile view of the open wave along a cross section just to the south of the system center. The less dense warmer air slides up and over the colder more dense air. Surface friction imposed by the ground slows the advance of the front compared to its position aloft yielding a gentle slope to the front.

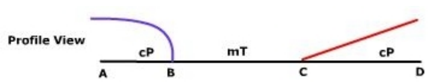


Figure 8.4.3: Profile View through a midlatitude cyclone

Occluded Stage

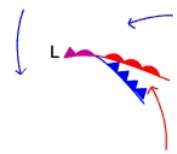


Figure 8.4.4: Occluded front

Being more dense, the air behind the cold front can "bulldoze" the warmer and less dense air out of the way. The advancing warm air along the warm front cannot push the colder air in its path out of the way. Instead, the warm air rises off the surface and glides up and over the colder more dense air ahead of the warm front. As a result, there is less horizontal displacement and the warm front moves slower across the earth than does a cold front. Over time the cold front catches up with the warm front and the cyclone starts to occlude (purple symbol on Figure 8.4.4). Click here to see the life-cycle of a wave cyclone from the initial (cyclogenesis) to occluded stage. Link here to an animated profile view of the occlusion process.

Dissolving Stage

The system enters the dissolving stage after it occludes and the lifting mechanism is cutoff. Without the convergence and uplift, the cyclone dissipates in the atmosphere.

Surface Cyclones and the Jet Stream

Above the polar front lies the polar front jet stream, a zone of faster moving air in the upper troposphere. The jet stream takes on a meandering pattern with regions of faster and slower air. Within the jet stream there are regions air convergence and divergence.

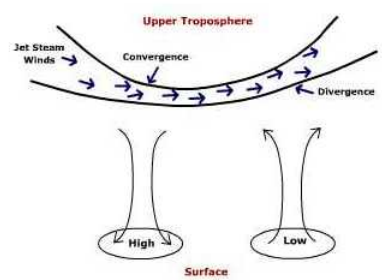


Figure 8.4.5: Jet stream winds and surface systems

Recall that surface air converges and rises in low pressure systems. To maintain low pressure at the surface the rising air must diverge at the top. It is this upper air divergence in the jet stream that "pulls" air upward to help form surface cyclones. In so doing, surface cyclones tend to follow the path of the jet stream. Figure 8.4.5 shows the relationship between upper-level flow and surface pressure systems. We can see that where upper level convergence occurs air sinks to promote high pressure at the surface. Where upper-level divergence occurs air is pulled up from the surface to help create low pressure near the ground. Wave cyclones dissolve when they no longer have the upper level divergence to maintain them.

8.5: Weather and Wave Cyclones

The weather associated with the passage of a wave cyclone is a product of the convergence and frontal uplift found in the system. The wave cyclone can be divided into three sectors: (1) the cool sector ahead of the warm front, (2) the warm sector between the cold and warm fronts, and (3) the cold sector located behind the cold front (Figure 8.5.1).

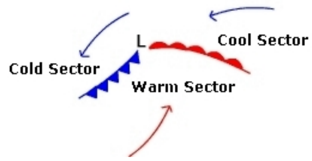


Figure 8.5.1: Wave cyclone

During the spring, summer, and fall, cP air masses tend to occupy the cold and cool sectors while an mT air mass lies in the warm sector. The cold sector generally has the lowest temperatures as cold air is coming from a northerly direction. Air in the cool sector is coming from an easterly direction so it is warmer than the air in the cold sector. In the warm sector air is entering the system from the south so we should expect to find the warmest temperatures in this region. In the next few sections we'll examine the weather associated with the various sectors and fronts.

Weather patterns

Figure 8.5.2 illustrates two views of a wave cyclone, the top portion is a weather map view looking down on the system from above. The bottom portion shows a simple profile (side) view along the line identified as the "Profile Transect" that connects points A, B, C, D on the weather map view.

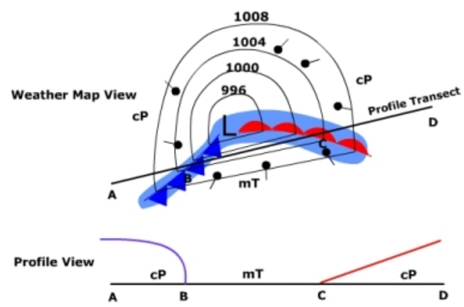


Figure 8.5.2: Two views of a wave cyclone

Let's examine the weather map view first. Isobars have been constructed to show the distribution of pressure around the cyclone. Notice that the lowest pressure is at the center of the system and increases outward. Another thing to note about the isobars is the V-shape where they cross the fronts. This indicates that the front sits in a trough of lower pressure. As a front approaches you will experience a drop in atmospheric pressure. Once a front has passed the pressure will increase.

The flow of air around the system is indicated by the wind direction symbols (black dots with a line pointing in the direction of the wind). The symbols show the characteristic counterclockwise flow around a center of low pressure in the Northern Hemisphere. Ahead of the warm front, in the cool sector, the air is from an easterly direction. In the warm sector, mT air streams out of the south. Behind the cold front air comes from a westerly to northwesterly direction. The light blue area shows the distribution of precipitation. Notice there is a larger band of rain along the warm front than along the cold front.

Warm Front Weather

Figure 8.5.3 shows the profile view of a warm front and its associated weather. The warm front slopes gently up into the troposphere that has a direct bearing on the kinds of clouds that are produced. As the warm air behind the front collides with the cooler air ahead, the warmer less dense air is forced to glide upward.

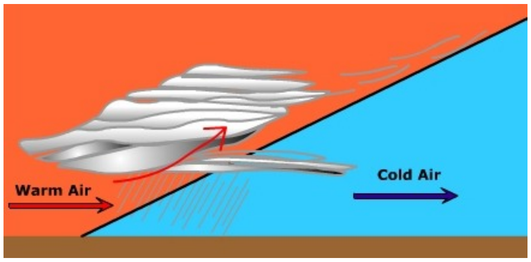


Figure 8.5.3: Profile View of warm front

A typical sequence of clouds develops as a result of this gentle uplift. The first clouds you see as a warm front approaches are the thin, wispy cirrus clouds. As the front approaches the clouds become thicker and the cloud base lowers. As the cirrus clouds pass by you, cirrostratus and then altostratus clouds approach. As the warm front is nearly at your location you will see the clouds completely cover the sky as stratus clouds. Nimbostratus clouds along the front create low intensity precipitation that might last for a long time. Ahead of the front the wind is generally cool and from a easterly direction. As the front passes by you the wind direction shifts toward the southeast and the south. As it does the temperatures start to rise as warm air replaces the cool air at your location.

Warm Sector Weather

Once the warm front passes your location you'll notice an increase in temperature and air pressure. Soon the stratus clouds of the warm front give way to broken and clearing skies. As the warm sector moves into your location you will notice an increase in the humidity of the air. The wind is out of the south so maritime tropical air begins to invade. During the afternoon you might see an occasional puffy cumulus cloud. These "fair weather" clouds are often created by convection and instability in the warm and humid afternoon air.

Figure 8.5.4: Fair weather cumulus clouds

After a while the winds start to shift to the southwest and the humidity continues to rise. You notice the clouds begin to grow in height, merge into larger darker masses. This indicates the air is becoming much more unstable. Once again the air pressure starts to fall. Winds begin to gust and growing cumulus clouds can be seen on the horizon. It would appear that a cold front is approaching.

Cold Front Weather

Weather along an advancing cold front is much different than that along a warm front (Figure 8.5.5). Friction slows the advancing cold air causing a steep slope to the front. The steep slope pushes the air ahead of it rapidly upwards and vertically developed clouds (cumulus) are produced along the front. As with a warm front, you experience a drop in the atmospheric pressure as the front approaches. As the cold front passes you, the winds shift from south to southwest, and finally to a westerly direction.

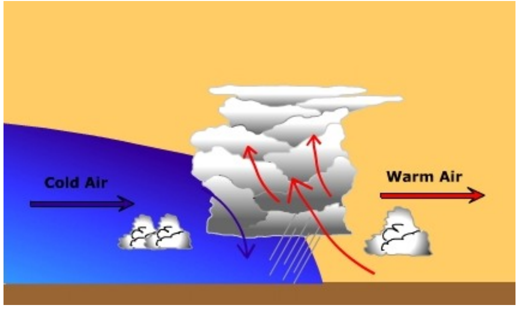


Figure 8.5.5: Profile of Cold Front

Figure 8.5.6: Towering cumulonimbus cloud (Source: R. Kresge, NOAA Used with permission)

With greatly contrasting air masses on either side of the front and potentially unstable conditions, violent weather can form. Towering cumulonimbus clouds are common along cold fronts producing intense downpours of rain lasting for a relatively short period of time. Tornadoes can form under the most extreme conditions ahead of an advancing cold front.

Below is a table that briefly summarizes the weather conditions associated with wave cyclones and their associated fronts. Instead of reading from left to right, read the table from right to left. Doing so will give you the perspective of the system moving through your location with its center to the north along the transect identified in Figure 8.5.2. Click on the cloud abbreviations to get information about them.

Table 8.5.1: Weather changes associated with passage of midlatitude cyclone

Weather Element	Cold Sector		Warm Sector		Cool Sector
Air Mass	cP		mT		cP
Pressure Tendency	rising		falling -- rising		falling
Wind Direction	NW - W		SW - S - SE		SE -- E
Clouds	Clring - Cu		Cb - Cu - Clring		Ns - St - As - Cs - Ci
Precipitation			Intense but short duration at cold front		Light but long duration at warm front

Cloud abbreviations:

- Ci - Cirrus
- Cs - Cirrostratus
- As - Altostratus
- St - Stratus
- Ns - Nimbostratus
- Clring - Clearing
- Cu - Cumulus
- Cb - Cumulonimbus

SECTION OVERVIEW

8.6: Severe Weather

8.6.1: Thunderstorms

8.6.2: Lightning

8.6.3: Tornadoes

8.6.4: Hurricanes

8.6.1: Thunderstorms

Figure 8.6.1.1: Thunderstorm outflow (Source: NSSL - NOAA)

Thunderstorms have awed, intrigued, and inspired humans with their awesome force and power. There are two basic kinds of thunderstorms, air mass and severe. ***Air mass thunderstorms*** are usually created by convective uplift of warm, moist, and unstable air. Have you ever been surprised by a sudden downpour of thunderous rain on what was up to that point a pretty nice day? If so, it was probably an air mass thunderstorm. Air mass thunderstorms typically do not have very high winds, hail, or much lightning associated with them. ***Severe thunderstorms***, however, do and may even spawn tornadoes. Severe thunderstorms tend to form along strong cold fronts where the air on either side is very different, the atmosphere is very unstable, and wind shear aloft is prevalent. Regardless of type, both kinds of thunderstorms tend to go through the same basic stages of development. We'll use the air mass thunderstorm to describe the stages of development here.

Stages of Thunderstorm Development

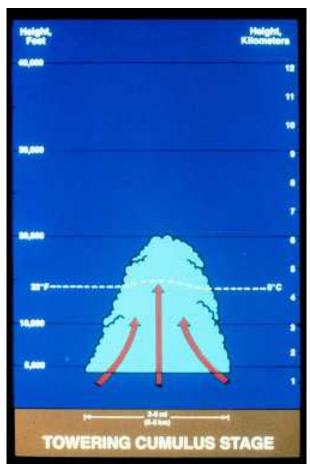


Figure 8.6.1.2: Cumulus Stage. (Image courtesy NSSL - NOAA)

The initial stage of development is called the ***cumulus stage***. During this stage warm, moist, and unstable air is lifted from the surface. In the case of an air mass thunderstorm, the uplift mechanism is convection. As the air ascends, it cools and upon reaching its dew point temperature begins to condense into a cumulus cloud. Near the end of this stage precipitation forms.

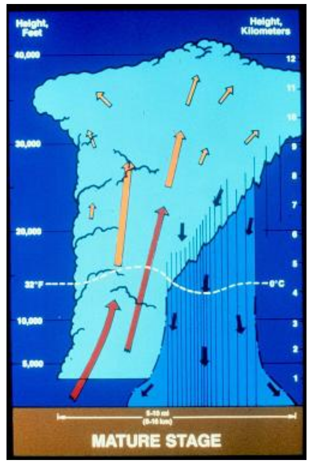


Figure 8.6.1.3: Mature Stage. (Image courtesy NSSL - NOAA)

The second stage is the mature stage of development. During the mature stage warm, moist updrafts continue to feed the thunderstorm while cold downdrafts begin to form. The downdrafts are a product of the entrainment of cool, dry air into the cloud by the falling rain. As rain falls through the air it drags the cool, dry air that surrounds the cloud into it. As dry air comes in contact with cloud and rain droplets they evaporate cooling the cloud. The falling rain drags this cool air to the surface as a cold downdraft.

Figure 8.6.1.4: An approaching thunderstorm with a lead gust front. Cold air from the downdraft pushes warm moist air up forming a "shelf cloud". (Courtesy NOAA Severe Storms Lab. Source)

In severe thunderstorms the region of cold downdrafts is separate from that of warm updrafts feeding the storm. As the downdraft hits the surface it pushes out ahead of the storm. Sometimes you can feel the downdraft shortly before the thunderstorm reaches your location as a cool blast of air.

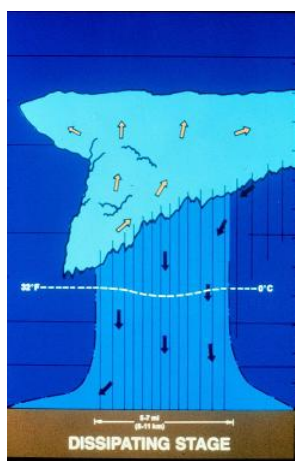


Figure 8.6.1.5: Dissipating Stage. (Image courtesy NSSL - NOAA)

The final stage is the ***dissipating stage*** when the thunderstorm dissolves away. By this point, the entrainment of cool air into the cloud helps stabilize the air. In the case of the air mass thunderstorm, the surface no longer provides enough convective uplift to continue fueling the storm. As a result, the warm updrafts have ceased and only the cool downdrafts are present. The downdrafts end as the rain ceases and soon the thunderstorm dissipates.

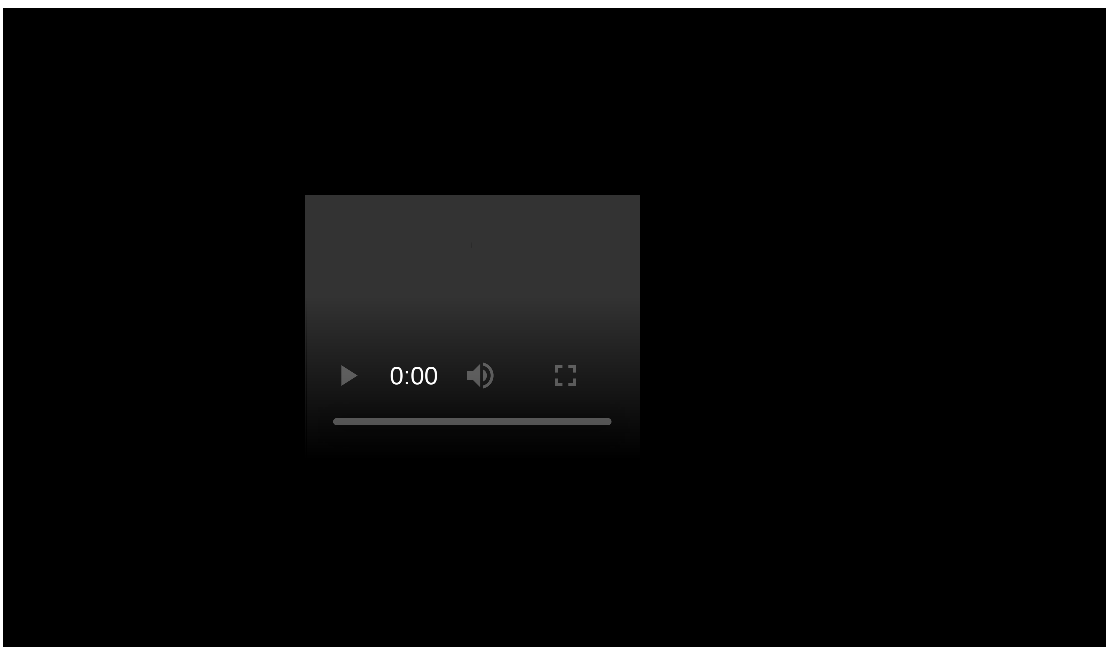
8.6.2: Lightning

Figure 8.6.2.1: Cloud-to-ground lightning. (Image courtesy NSSL - NOAA.)

One of the most spectacular displays of nature is lightning. ***Lightning*** is a massive discharge of electricity in response to a charge differential. The actual cause of lightning is not completely understood, though its propagation is quite well established. What we do know is that lightning occurs in clouds that are located above the freezing level and are precipitating.

For lightning to occur, there must be a charge differential within a thunderstorm, or between a thunderstorm and the ground or another cloud. Studies have shown that a charge transfer occurs across thin films of water present on ice crystals and hailstones when they collide. Solids (e.g. ice, hailstones, graupel) are often coated with an extremely thin film of liquid-water a few molecules thick. The molecules are weakly bound to the solid portion beneath even at temperatures below freezing. When an ice crystal and hailstone collide in a cloud, some of the liquid-water molecules from the hailstone move to the ice. During this process there is a net transfer of positive charges from the hailstone to the ice and negative charges from the ice crystal to the hailstone. The heavier hailstones fall to the base of the cloud while the lighter ice crystals are suspended at higher altitudes creating the charge separation with mostly negative charges near the base and positive charges aloft.

The accumulation of negative charges at the base of the cloud repel the negative charges on objects at the Earth's surface. Thus below the thunderstorm the Earth's surface attains a net positive charge. When the difference in charge is great enough lighting is discharged. The whole process takes a mere fraction of a second and appears to occur from the cloud toward the ground. Actually, the discharge takes place in a series of steps. First, a stream of electrons flow toward the ground in a series of discrete steps called a **step-leader** that creates a branching ionized channel. When the stepped leader comes within 100 meters of the ground a positively charged **return stroke** surges upward. An ionized channel a few centimeters in diameter connects the Earth to the cloud along which electrons flow and illuminate the channel. After the initial electrical discharge, **dart leaders** of electrons follow the same conducting paths to the ground. Return strokes again meet the dart leaders and the path is illuminated once again. The entire lightning sequence takes less than two tenths of a second and can emit 100 million volts. The massive discharge rapidly heats the air sending a shockwave through the atmosphere we hear as **thunder**.



Video: Formation of cloud-to-ground lightning. (Source: Michael Ritter)

8.6.3: Tornadoes

Tornadoes

Figure 8.6.3.1: A tornado rips through Dimmitt, TX (Source: NSSL - NOAA)

Tornadoes are the most powerful weather phenomenon known. A tornado is an intense system of low pressure with violent updrafts and converging winds. Though tornadoes have been intensely studied for years, the mechanism that actually creates them still eludes us. Tornadoes have been documented in most all the regions of the Earth, though they are most prevalent in the United States.

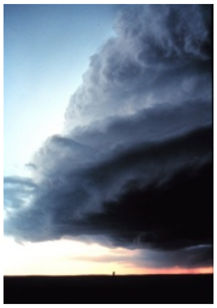


Figure 8.6.3.2: Supercell thunderstorm are especially capable of spawning tornadoes. (Source: NSSL - NOAA)

Tornadoes are spawned from severe thunderstorms. Wind shear, where winds are traveling at different speeds and from different directions aloft cause rotation of air about a horizontal axis within the thunderstorm. The rotating circulation is tilted into the vertical by the updrafts of air in a severe thunderstorm. As the rotating air increases in height and shrinks in size a **mesocyclone** is formed. For whatever reason, a tornado funnel is spawned within the mesocyclone.

The funnel can remain aloft, twisting and turning without wreaking much havoc below, but is most destructive when it touches the ground. A tornado can vary in diameter from a few hundred feet to greater than a mile. Tornadoes typically move across the surface at speeds ranging from 22 - 33 mph (10 - 15 meters per second). [Watch "Hunt for the Supertwister from PBS].

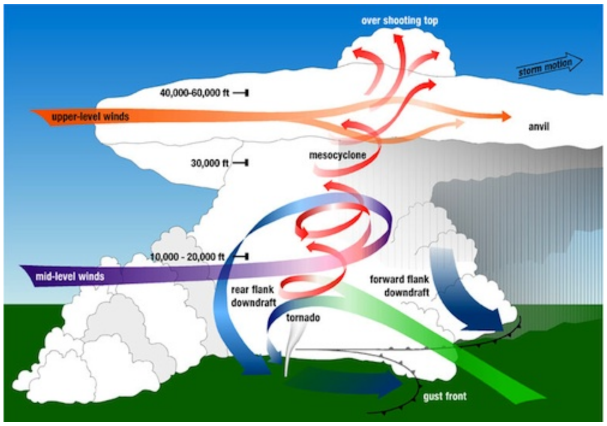


Figure 8.6.3.3: Tornado Formation (Courtesy NOAA NSSL Source)

Tornadoes that develop over water are called **waterspouts**. Waterspouts my orignate over water or a tornado passes from land to water. View the video "Watersputs" for more.

Video: "Waterspouts". (Courtesy of NOAA)

The central U.S. contains a unique mix of topography and weather factors that combine to create these ferocious weather systems. The most favorable situation for these storms to develop is during the months of April through June when there is the most contrast between air masses in the central United States. The region of highest concentration is that of "tornado alley", a region that stretches from eastern Nebraska through central Kansas and Oklahoma in to the panhandle of Texas. The tornado season varies with latitude, with the southeastern U.S. season from January through March and the north central states during July through September. On April 3, 1974 148 tornadoes struck 13 states leaving a swath of death and destruction across the U.S.

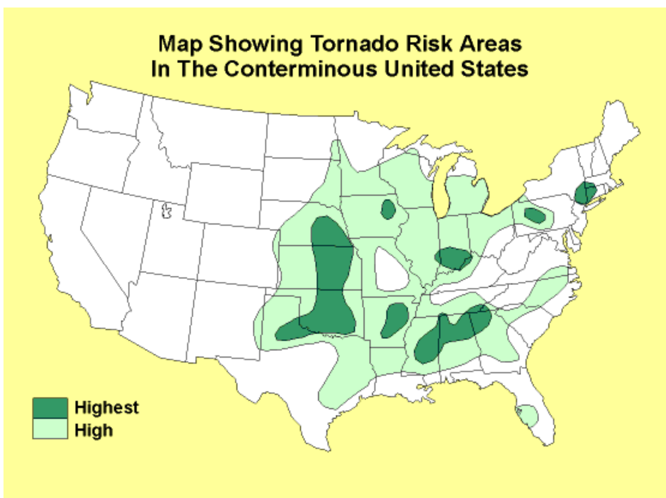


Figure 8.6.3.4: Tornado risk in the United States

Tornadoes are categorized on the basis of their destruction by the Enhanced Fujita scale. The scale assigns a tornado a 'rating' based on estimated wind speeds and related damage. Several damage indicators, e.g., trees, motels, strip malls are used to estimate wind speeds and classify the tornado. In the May 24, 2013 NPR Talk of the Nation segment "Tracking Killer Tornadoes" , Marshall Shepherd, the president of the American Meteorological Society, describes the ingredients of major tornadoes, and how they are predicted.

Video: Get inside a tornado. (Courtesy of National Geographic)

Learn more about the destructive effect of tornadoes by "Digging Deeper: The April 27, 2011 Southern USA Tornado Outbreak".

Digging Deeper: The April 27, 2011 Southern USA Tornado Outbreak

April 27-28, 2011 the southeastern United States was struck by an estimated 211 tornadoes. Wreaking havoc over eight states, more than 340 people lost their lives as whole towns were destroyed across Alabama, Arkansas, Georgia, Mississippi, North Carolina, Tennessee, and Virginia. It was the most deadly day since March 18, 1925 when 747 people died.

Video: GOES satellite image animation. (Courtesy NASA Earth Observatory)

The perfect conditions for tornado development were closely monitored by the National Weather Service days prior to the events of April 27-28. Warm, moist air at the surface streamed ashore from the Gulf of Mexico. With cold air aloft, highly unstable atmospheric conditions ahead of a strong cold front sweeping drier air behind it. A strong westerly jet stream aloft combined with surface winds from the south and east triggered strong vertical wind shear providing lift to the air. Using composite indices based on these conditions, NOAA's Storm Prediction center issued a "high risk" alert for tornadic conditions more than 12 hours in advance. Beginning in the afternoon of the 26th, thunderstorms exploded in the unstable air. The National Weather Service's worst nightmare was about to come true.

Video: April 27, 2011 Tornado Outbreak (Courtesy NOAA Weather Partners Video Library)

Across the southern United States roared a storm system producing some of the largest tornadoes on earth, supertwisters. A rare EF-5 tornado a half mile wide ripped through the community of Smithville, Mississippi at 3:44 pm on the April 27. With estimated peak winds of 205 mph, dozens of homes and businesses were pulled from their foundations. The town's water system was destroyed. Most trees were broken, twisted and stripped of their bark. A second F5 tornado touched down near Hackleburg, Alabama. It was the first time since 1990 that two F5 supertwisters formed on the same day.

Figure 8.6.3.5: Slab foundation stripped of house. Debarked hardwood trees in background. (Courtesy NOAA Weather Forecast Office Memphis (Source))

Barely a month later, Joplin Missouri was struck by a multi-vortex EF5 tornado on May 22, 201. Estimated at 1.21 km (.75 miles) wide, as it tracked at least 11 km (7 miles) across the city. With winds over 200 mph. Over 125 people were killed and hundreds injured making it the deadliest since modern records have been kept and the eighth-deadliest single tornado in U.S. history.

Figure 8.6.3.6: St. John's Hospital: Before (Courtesy NOAA, Source)

Figure 8.6.3.1: St. John's Hospital: After (Courtesy NOAA, Source)

8.6.4: Hurricanes

A ***hurricane*** (or typhoon) is a large rotating cyclonic system born in the tropics. They are the largest and most destructive storms on Earth. Most associate high winds with the devastation that these massive storms create, yet dangerous flooding, tornadoes, lightning often accompany or are spawned by a hurricane.

Hurricane Formation

A hurricane develops from a tropical disturbance once it reaches sustained winds in excess of 74 mph (64.3 knots) . Most hurricanes form poleward of 10o latitude as the Coriolis effect is too weak closer to the equator. Hurricanes form in a uniform mass of warm air over tropical oceans with temperatures of 80^{o} F (26.5^{o} C) through a depth of 200 feet (60 meters). Hurricanes thus do not exhibit fronts like extratropical cyclones of the mid- and high latitudes. The "fuel" for a hurricane comes from the enormous amount of latent heat released from the warm ocean water.

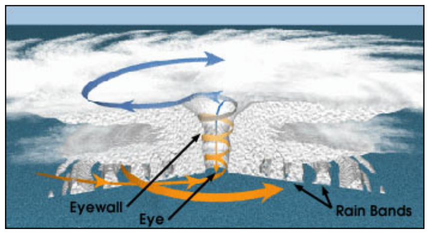


Figure 8.6.4.1: Internal structure of a hurricane (Source: NOAA)

A hurricane is a warm-core low pressure system that weakens rapidly with altitude to be replaced by anticyclonic airflow above the hurricane. The center or eye of the hurricane is an area of nearly cloudless skies, subsiding air, and light winds. The eye ranges from 12 to 40 miles across (20 - 65 kilometers). At the periphery of the eye is a ring of cumulonimbus clouds that produce torrential rains and extremely strong winds. Surrounding the core of storms are the typical spiraling rain bands.

As a hurricane moves over a colder surface or land, it loses its source of energy and dissipates. However, the system can remain an organized storm for several days as it moves inland, inundating the interior with rainfall causing severe flooding. Destructive tornadoes often accompany hurricanes as the move ashore.

Video: "Hurricanes" (Courtesy Met Office)

Hurricane Risk and Hazards

The Saffir-Simpson hurricane intensity scale is used to classify hurricanes. Though much damage from hurricanes is due to the strong wind and tornadoes they often spawn when making land fall, it is the storm surge that creates the most. The ***storm surge*** is the high water level that accompanies a hurricane as it comes ashore. The storm surge is created by the force of the wind pushing up the water level. Storm surges cause flooding of low lying areas and much damage to property and life. Weak hurricanes can produce storm surges of 3 to 6.5 feet (1 to 2 meters), while intense systems can create high water levels of over 16.5 feet (5 meters). The Bathurst Bay hurricane produced a 42 ft (13 m) surge in Bathurst Bay, Australia in 1899. 2005’s Hurricane Katrina poured a 25 ft (7.6 m) storm surge across Bay St. Louis, Mississippi.

Figure 8.6.4.2: Storm surge from Hurricane Eloise that struck the Florida coast in 1975 (Source: NOAA)

Flooding from a hurricane storm surge that hit Galveston, Texas on September 8, 1900 killed 6,000 people. On November 13, 1973 the vast coastal plain of Bangladesh was inundated with storm surge flooding that claimed an estimated 300,000 lives by drowning.

Video: Hurricane Storm Surge (Courtesy NOAA)

The storm surge is only a portion of the total water level associated with a hurricane. The normal rise and fall of tides affect the severity of the storm surge. The highest storm surges occur with an incoming high tide. Wave run up adds to the water level along a coast. Heavy rainfall before the hurricane causes freshwater river levels to rise and leads to widespread flooding. Such was the case when Hurricane Sandy's nearly 4.23 m (13.88 ft) surge sent the East River in New York over its banks, flooding large sections of lower Manhattan. Huge waves crashed on the shores carrying massive amounts of eroded sand into beachfront communities like Seaside Heights, New Jersey

Hurricane risks to the United States

The greatest risk for hurricanes in the United States is for those living along the southeastern Atlantic seaboard where the warm waters of the Gulf stream provides fuel for storms. Hurricanes rarely affect the west coast with only four storms striking California in the last hundred years. Storms that do affect the west coast are usually remnants of tropical cyclones. Two primary reasons for so few incidences of tropical cyclones are cool coastal waters and the the direction of the prevailing winds. The presence of cold coastal water inhibits the formation or diminishes the strength of any storm that approaches land. Water temperatures along the coast of southern California rarely rise above 24°C (75°F) and usually don't get above 17°C (63°F). The upper level steering winds in the eastern Pacific winds move storms away from the coast. Tropical cyclones in the eastern Pacific generally move north-westward or westward due to steering by the prevailing upper level winds, which takes them far out to sea and away from the west coast of North America. Many living inland from the coast may feel relatively secure from the ravages of a hurricane. But as it moves onshore, severe thunderstorms, lightning, and tornadoes becomes a threat.

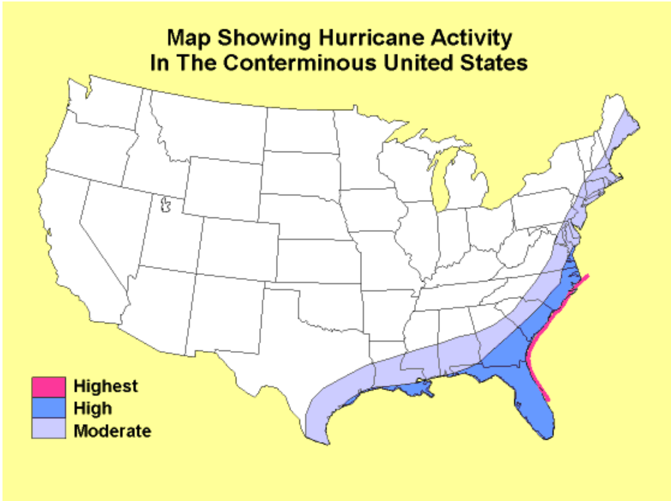


Figure 8.6.4.3: Hurricane risk for the United States

8.7: Future Geographies - Severe Weather and Global Warming

The unusually active 2005 Atlantic hurricane season sparked a debate as to whether we were glimpsing into future conditions brought on by global warming or it was part of a natural cycle of hurricane intensity. Heat that drives global warming can provide the trigger for the development of hurricanes and thunderstorms. A disturbing outcome of global warming may be the increased likelihood of severe weather in the form of stronger and more frequent storm systems.

Figure 8.7.1: 2005 Atlantic Hurricane Tracks (Courtesy NOAA. Source)

Hurricanes

Coastal inhabitants from the the midlatitudes to the tropics live with the threat of tropical cyclones. Two factors are important in determining future hurricane activity, high ocean surface temperatures and the effect of El Niño/La Niña. As discussed in this chapter, hurricanes derive their power from water ocean water. If climate change continues to warm the oceans, we should expect more active hurricane seasons and powerful storms.

Measures of the destructive potential of hurricanes have shown a substantial increase, though the cause is still debated in the climate science community. Evidence seems to indicate that the severity of hurricanes has increased over the last several years as a result of increasing ocean temperatures. The number of category 4 and 5 hurricanes has increased 75% since 1970, with the largest increases in the North Pacific, Indian, and Southwest Pacific oceans. Model simulations indicate the trend toward more severe hurricanes continuing over the next century.

Complicating the ability to predict future hurricane activity is the influence of El Niño/La Niña. Generally, Atlantic hurricane activity is lower during an El Niño, and increases during La Niña. The influence of global warming on El Niño, however, is not well-understood and thus prediction of hurricane activity related to it remains problematic.

Thunderstorms and Tornadoes

The processes that create thunderstorms and tornadoes occur at geographic scales too small to be reproduced in most climate models. Geoscientists can, however, project the number of days with conditions conducive to thunderstorm development from their models. Global warming will likely lead to an increase in humid conditions near the ground, the fuel for thunderstorms. Humid coastal and regions that already experience a significant number of storms, will increase their chances for experiencing thunderstorms. Favorable conditions for thunderstorms are predicted to occur during the same seasons that they do today, leading to a more intense storm season.

Tornado formation is not well-understood, making future prediction practically impossible. Hurricanes that make landfall often spawn tornadoes. Recent modeling by climate scientists has shown that four factors are good predictors of hurricane-induced tornado formation, hurricane size, intensity, track direction and the moisture gradient strength at midlevels in the storm. They found a 35 percent increase in the size of tropical cyclones occurred between 1948 and 2008 from the Gulf than between 1924 and 1948, resulting in a doubling of the number of tornadoes produced per storm. When tested against actual storms, their model correctly predicted the 33 tornadoes spawned by Hurricane Ike in 2008 and 56 of the 58 tornadoes produced by Katrina in 2005.

An unusually mild winter followed by devastating tornadoes early in the spring ushered in 2011. Raging wildfires and devastating drought gripped much of the United States in 2012. 🔈 Listen to Kevin Trenberth, distinguished senior scientist at the National

Center for Atmospheric Research, discuss the correlation between climate change and extreme weather with NPR *Talk of the Nation* host Neil Conan (April 5, 2012).

8.8: Review and Additional Resources

Review

Mammatus clouds.- often a precursor to severe weather.
Courtesy NOAA

Figure 8.8.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

✓ Important Terms and Concepts 8.8.1

- **Air mass**
  a vast pool of air having similar temperature and moisture characteristics over its horizontal extent.
- **Air mass source region**
  where air masses are born; where they take on their characteristic temperature and moisture content
- **cP air mass**
  Continental polar (cP) air is considered a cold and dry air mass that is warmer than the arctic air mass located to the north. Continental polar air is typically a stable or conditionally stable mass of air.
- **mP air mass**
  Maritime polar (mP) air is cool and moist air that brings mild weather to coastal locations. Maritime polar air is warmer than continental polar air in the winter as the surface temperature of the ocean is higher.
- **cA air mass**
  Continental arctic air (cA) is typically described as extremely cold and dry.
- **cAA air mass**
  an exceedingly cold air mass and is drier than its arctic counterpart as the source region is the continent of Antarctica.
- **cT air mass**
  Found over subtropical and tropical continents the source region for the hot and dry
- **Air mass modification**
  As air masses move out of their source region the temperature and moisture content of air masses are modified.
- **Front**
  boundaries between contrasting masses of air.
- **Cold front**
  where cold air replaces warm air.
- **Warm front**

where warm air replaces cold air.

- **Occluded front**

  forms when a cold front catches up with a warm front.

- **Stationary front**

  where no change in air masses or movement of the front occurs.

- **Quasi-stationary front**

  found migrating within a particular latitudinal zone throughout most of the year.

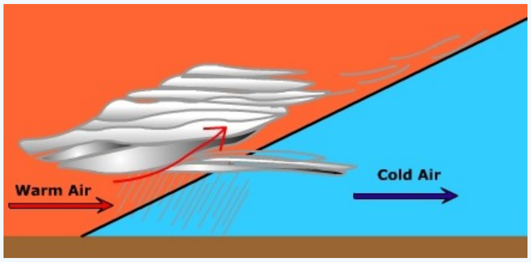
- **Polar front**

  the boundary between polar-type air and tropical-type air.

- **Arctic front**

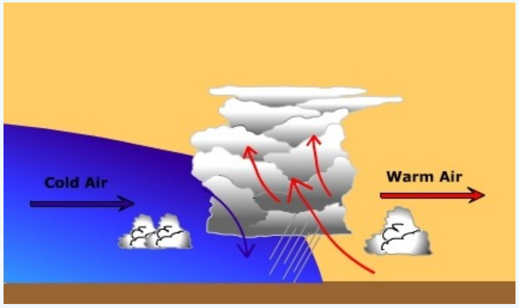
  the boundary between cold arctic air mass and the warmer air of the polar cell.

- **Warm front weather**



Profile view of warm front

- **Cold front weather**



Profile of Cold Front

- **Warm sector weather**

  increase in the humidity of the air; "fair weather" clouds are often created by convection and instability in the warm and humid afternoon air. After a while the winds start to shift to the southwest and the humidity continues to rise.

- **Cyclogenesis**

  the development and intensification of a cyclone

- **Initial Stage - Cyclogenesis**

  opposing streams of air meet and create a cyclone shear

- **Wave Stage- Cyclogenesis**

  Once the air collides and cyclonic circulation commences, warm air from the south invades where cold air was once located north of the polar front. The developing system takes on the characteristic wave form

- **Occluded Stage- Cyclogenesis**

    Being more dense, the air behind the cold front can "bulldoze" the warmer and less dense air out of the way. The warm air rises off the surface and glides up and over the colder more dense air ahead of the warm front. there is less horizontal displacement and the warm front moves slower across the earth than does a cold front. Over time the cold front catches up with the warm front and the cyclone starts to occlude.

- **Dissolving Stage- Cyclogenesis**

    The system enters the dissolving stage after it occludes and the lifting mechanism is cutoff. Without the convergence and uplift, the cyclone dissipates in the atmosphere.

- **Thunderstorm - Cumulus stage**

    The initial stage of development. During this stage warm, moist, and unstable air is lifted from the surface. As the air ascends, it cools and upon reaching its dew point temperature begins to condense into a cumulus cloud. Near the end of this stage precipitation forms.

- **Thunderstorm - Mature Stage**

    The second stage - During the mature stage warm, moist updrafts continue to feed the thunderstorm while cold downdrafts begin to form. The downdrafts are a product of the entrainment of cool, dry air into the cloud by the falling rain. As rain falls through the air it drags the cool, dry air that surrounds the cloud into it. As dry air comes in contact with cloud and rain droplets they evaporate cooling the cloud. The falling rain drags this cool air to the surface as a cold downdraft.

- **Thunderstorm - Dissipating Stage**

    The final stage - the thunderstorm dissolves away. By this point, the entrainment of cool air into the cloud helps stabilize the air. In the case of the air mass thunderstorm, the surface no longer provides enough convective uplift to continue fueling the storm. As a result, the warm updrafts have ceased and only the cool downdrafts are present. The downdrafts end as the rain ceases and soon the thunderstorm dissipates.

- **Lightning**

    a massive discharge of electricity in response to a charge differential.

- **Thunder**

    a shockwave through the atmosphere caused by lightning

- **Tornado**

    an intense system of low pressure with violent updrafts and converging winds.

- **Hurricane**

    a large rotating cyclonic system born in the tropics.

- **Storm Surge**

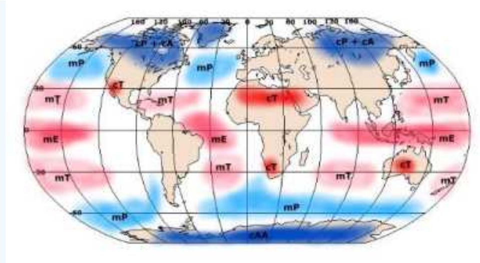
    the high water level that accompanies a hurricane as it comes ashore.

? Review Questions 8.8.1

Describe the characteristics of an air mass source region.

Answer

An air mass source region is one that has flat terrain and dominated by high pressure



Describe two ways in which air masses can be modified.

Answer

Air masses are modified by the surface over which they travel. For example, an mT air mass that passes over a cold ocean current is chilled at the surface enhancing stability. Cold air masses traveling over warm surface are heated enhancing their instability.

Describe the characteristics of a front.

Answer

A front is boundary between contrasting masses of air. They are a zone of converging air and lower pressure.

Compare and contrast mP, cP, mT, cT air masses.

Answer

mP air masses are cool and moist forming over oceans at about 60^o N and S.

cP air masses are cold and dry forming over continents at about 60^o N.

mT air masses are warm and moist air masses forming over oceans at about 30^o N and S.

cT air are warm and dry air masses forming over continents at about 30^o N and S.

Describe the process of cyclogenesis.

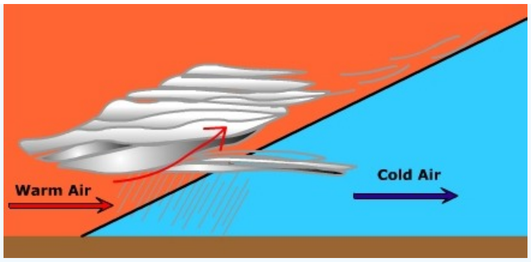
Answer

Cyclones form along frontal boundaries like the polar front where air is converging from opposite directions. A twisting motion is created as cyclonic shear takes place between the converging air streams. The surface convergence is supported by upper level divergence in the jet stream. The spiraling storm creates a cold front as cold air pushes into regions once occupied by warm air. A warm front is spawned where warm air intrudes into regions once dominated by cold air. Through time the cold front and warm front merge to form an occlusion. Finally the storm dissipates.

Describe the weather changes (e.g. temperature change, pressure tendency, clouds, wind direction) associated with the passage of a warm front.

Answer

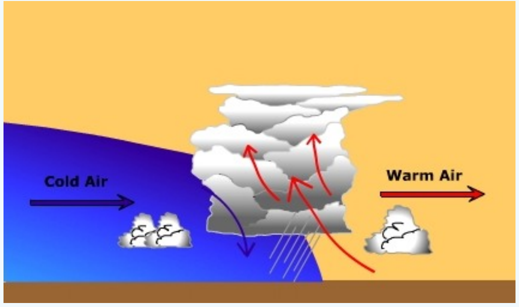
A change in cloud cover from cirrus, to cirrostratus, altostratus, and stratus is typical of the approach of a warm front. Air pressure decreases as the front approach, then increases after passage. Nimbostratus clouds are present along the warm front if it is precipitating. Low intensity/long duration precipitation is typical of nimbostratus clouds. Wind are likely to shift from an easterly direction to a southerly direction as the warm from passes. Air temperatures rise upon the passage of the front.



Describe the weather changes (e.g. temperature change, pressure tendency, clouds, wind direction) associated with the passage of a cold front.

Answer

The air ahead of a cold front is generally from the south in the warm sector. Pressure drops as the front approaches. Cumulus clouds grow into cumulonimbus clouds and intense, but short-lasting precipitation occurs. As the front passes, wind shifts from a southerly/southwesterly direction toward the west and possibly northwest. Temperatures decrease as the front passes. After passage, cloud cover dissipates.



Compare and Contrast the kind of precipitation associated with cold and warm fronts.

Answer

Precipitation along warm fronts tends to be low intensity and long in duration. Precipitation along cold fronts tends to be high intensity and short in duration.

Describe the three stages of thunderstorm development.

Answer

Cumulus stage: Creation of a cumulus cloud by updrafts of warm, moist air

Mature stage: Updrafts of warm moist air fuels the developing storm. Downdrafts of cold dry air is created by precipitation entrainment.

Decay stage: Downdrafts predominate as uplift of warm moist air ceases.

Describe the conditions under which tornadoes form.

Answer

There is much we do not know about tornadoes. Tornadoes are most common during the Spring when greatly contrasting air masses collide to produce severe storm systems. Wind shear within the severe thunderstorm causes rotation of air about a horizontal axis. The rotating circulation is tilted into the vertical by the updrafts in the thunderstorm. As the rotating air increases in height and shrinks in size a **mesocyclone** is formed. For whatever reason, a tornado funnel is spawned within the mesocyclone.

Under what conditions are hurricanes most likely to form?

Answer

A hurricane develops from a tropical disturbance once it reaches sustained winds in excess of 75 mph (65 knots). Most hurricanes form poleward of 10^o latitude as the Coriolis effect is too weak closer to the equator. Hurricanes form in a uniform mass of warm air over tropical oceans with temperatures of 80^o F (26.5^o C) through a depth of 200 feet (60 meters).

What creates the most damage from a hurricane?

Answer

The high water level that precedes the hurricane called the "storm surge" creates the most damage due to flooding.

Self-Assessment Quiz 8.8.1

1. At a warm front

   A. warm air replaces cold air
   B. a trough of lower pressure is found
   C. stratus - type clouds are found
   D. all the above

2. Which of the following air masses are colder than the surface over which it is traveling?

   A. mTw
   B. mTu
   C. cPk
   D. none of the above

3. The cold sector of a midlatitude cyclone

   A. experiences southerly winds
   B. generates nimbostratus clouds
   C. experiences light precipitation of long duration
   D. none of the above

4. The mature stage of thunderstorm formation

   A. experiences mostly updrafts of air
   B. experiences updrafts and downdrafts
   C. experiences mostly downdrafts
   D. none of the above

5. Which of the following is not a characteristic of a source region

   A. a region of little to no windiness
   B. areas dominated by high pressure
   C. areas dominated by low pressure
   D. regions of low relief

6. A front

   A. is a boundary between contrasting masses of air
   B. is a zone of lower pressure
   C. is a boundary between opposing centers of high pressure
   D. can have all the above characteristics

7. ______ is fundamentally responsible for the creation of midlatitude cyclones.

   A. large pressure gradients
   B. cyclonic shear
   C. large temperature gradients
   D. none of the above

8. Which of the following is not associated with a cold front

   A. cumulonimbus clouds
   B. warm air replacing cold air

C. possibility of intense rain of short duration
D. all the above are associated with a cold front.

9. The wind direction ahead of a warm front is generally
   A. from the east
   B. from the south
   C. from the north
   D. from the west
10. Which of the following is not true about cP air?
   A. cP air is generally unstable air
   B. cP air is generally found behind a cold front
   C. cP air that affects North America has its source in central Canada
   D. cP air is found in the cold sector of a midlatitude cyclone

Answer

1. D
2. C
3. D
4. B
5. C
6. D
7. B
8. B
9. A
10. A

Additional Resources

Focus on The Physical Environment: "Weather Forecasting through the Ages" (*NASA Earth Observatory*)

Connections: "Trees lost to Katrina May Present Climate Challenge" (NPR)

Physical Geography Today: US National Weather Service - NOAA | US National Hurricane Center - NOAA

World of Change: Severe Storms (*NASA Earth Observatory*)

Multimedia

"Super Twisters" (National Geographic)

"Tracking Hurricanes" (PBS) *The News Hour with Jim Lehrer* Oct. 1, 2003 "For years, scientists have worked to develop powerful new tools to predict the paths of hurricanes and monitor their likely impact. Betty Ann Bowser reports on the latest technologies meteorologists are using to keep tabs on these devastating storms and what new tools are being developed."

"Hunting Killer Storms: Flying into the Eye of Isabel WGBH Forum Network Mish Michaels, meteorologist, WBZ-TV4 talks about her adventures chasing tornadoes, flying into hurricanes and trekking to Mt. Washington during the winter. (54:50)

"Tornado Sound " (NPR) *Weekend Edition* May 18, 2003 "Host Liane Hansen speaks with physicist Al Bedard, who studies the sounds of tornadoes at the Environmental Technology Laboratory of the National Oceanic and Atmospheric Administration.

"Looking at Hurricanes" (NASA/GSFC) Explore the "latest" technology for observing hurricanes.

["Storm that Drowned a City" from *NOVA* for an in depth look at Hurricane Katrina's impact on New Orleans, LA.]

Interactivities

- Realtime station model plotting and interpretation (WeatherWise)

Readings

- Tornadoes....Nature's Most Violent Storms

Visualization

- Weather Map Viewer (M. Ritter) - Current weather map slide show.
- "How hurricanes form" (CNN)

Web Sites

- National Weather Service
- NWS National Severe Storms Lab
- NWS National Hurricane Center

CHAPTER OVERVIEW

9: Climate Systems

Learning Objectives

By the end of the chapter you should be able to:

- Explain the difference between weather and climate.
- Compare and contrast empirical, genetic and applied classification systems.
- Describe the major climate classes (A,B,C,D,E) of the Koeppen system of climate classification.
- List and describe the elements of climate.
- Describe the characteristics of global climates and locate them on a world map.

The climate of Earth is a mosaic of temperature and moisture patterns that affect the distribution of plants and animals and shapes the Earth's surface. Much is known about the present climate patterns of the Earth, yet our understanding of the cause of these distributions and change that occurs over time is ever unfolding. Not only do geoscientists like climatologists seek to unravel the interactions between natural phenomena that determine climate, but also seek to understand how human activity determines our climate.

9.1: Getting Ready for Chapter 9
9.2: The Elements of Climate
9.3: Climate Classification
9.4: Low Latitude Climates
  9.4.1: Tropical Rain Forest
  9.4.2: Tropical Monsoon Climate
  9.4.3: Tropical Wet/Dry (Savanna) Climate
  9.4.4: Tropical Steppe Climate
  9.4.5: Tropical Desert Climate
9.5: Midlatitude and Subtropical Climates
  9.5.1: Mediterranean or Dry Summer Subtropical Climate
  9.5.2: Midlatitude Desert Climate
  9.5.3: Midlatitude Steppe
  9.5.4: Humid Subtropical Climate
  9.5.5: Humid Continental Climate
  9.5.6: Marine (Humid) West Coast Climate
9.6: High Latitude Climates
  9.6.1: Subarctic Climate
  9.6.2: Tundra Climate
  9.6.3: Ice Cap Climate
9.7: Urban Climate
9.8: Future Geographies - The Evidence for Climate Change
9.9: Review and Additional Resources

9.1: Getting Ready for Chapter 9

Chapter 8, *Weather Systems*, gave us an insight into how the daily changes of the atmosphere occur, in other words, our weather. Chapter 8 and those that preceded it set the stage for an analysis of climate, the long-term state of the atmosphere. Climate plays an important role in the distribution of plant and animal species, soils, streams and rivers, and affects land forming processes. Having a good grasp of the geographical distribution of climate is necessary in understanding the physical geography of Earth.

Figure 9.1.1: The five main climate types (clockwise), tropical, dry, temperate, continental, polar. (Courtesy: FAO, USFWS, NOAA)

The Earth is potentially facing changes to its climate the likes of which have not seen for thousands of years, and it is most likely the result of human activities. The elements of climate interact with each of the subsystems of the Earth system. A change in any one of the elements of climate can reverberate through the entire system. These changes will have profound effects on the Earth system. Warming oceans and melting ice caps will reshape coastlines. The migratory behavior of animals will change as climate conditions shift. Habitats will vanish along with the plant and animal species that depend on them. Water resources will evaporate from some regions while others may experience floods like they haven't seen in the recent past. Thus it is ever so important for us to understand how the climate system works, and what effect our activities have on it.

What you should already know...

Chapter 9 integrates and builds on the content of previous chapters to develop an understanding of earth's climates. The elements of climate systems were presented in Chapter 4, Chapter 5, Chapter 6, Chapter 7, and Chapter 8. You should have a good understanding of this material before reading Chapter 9.

Use the quiz below to assess your understanding of a few key topics from these chapters.

? Quiz 9.1.1

1. Air masses that pass over a warm ocean current
   - A. will likely become unstable
   - B. will likely to become stable
2. The polar front jet stream
   - A. moves equatorward during the summer
   - B. moves poleward during the summer
   - C. doesn't shift its general location with seasons.
3. Annual temperature range is largest
   - A. in the Sahara desert
   - B. in the central United States
   - C. along the coast of California
   - D. in Antarctica

4. The which of the following uplift mechanisms are most important in the tropics?
   - A. Frontal and convergence
   - B. Convection and frontal
   - C. Convection and convergence
   - D. Only frontal
5. Which of the following air masses is warm, moist and unstable at its source region?
   - A. mP
   - B. cP
   - C. cT
   - D. mT
6. An advection fog is most likely to occur
   - A. along the west coast of the United States
   - B. as mT air moves over the Gulf Stream
   - C. with moist still air on a cloudless night
   - D. none of the above.
7. A subtropical high
   - A. is likely to produce dry conditions
   - B. is likely to create cloudy conditions
   - C. is likely to create very windy conditions
   - D. will create convergence and uplift of air from the surface.
8. If you are located at 15 degrees north latitude you will be influenced by
   - A. the tradewinds
   - B. the westerlies
   - C. the polar easterlies
   - D. none of the above
9. Mountain systems in North America tend to be aligned _____ and in Europe _______.
   - A. east to west; north to south
   - B. north to south; east to west
10. As one moves poleward through the midlatitudes, precipitation ____ and becomes ____ seasonal.
   - A. increases, more
   - B. decreases, more
   - C. increases, less
   - D. decreases, less

Answer

1. A
2. B
3. B
4. C
5. D
6. A
7. A
8. A
9. B
10. B

About your score ....

If you scored 80% or above, Great! ... start reading the chapter.

If you scored 70% to 80% you should consider reviewing the previous material.

If you scored less than 70% you should consider reviewing the previous material and seeking help from your instructor.

9.2: The Elements of Climate

Climatology is the study of the long-term state of the atmosphere, or ***climate***. The long-term state of the atmosphere is a function of a variety of interacting elements. They are:

- Solar radiation
- Air masses
- Pressure systems (and cyclone belts)
- Ocean Currents
- Topography

Solar radiation

Solar radiation is probably the most important element of climate. Solar radiation first and foremost heats the Earth's surface which in turn determines the temperature of the air above. The receipt of solar radiation drives evaporation, so long as there is water available. Heating of the air determines its stability, which affects cloud development and precipitation. Unequal heating of the Earth's surface creates pressure gradients that result in wind. So you see, just about all the characteristics of climate can be traced back to the receipt of solar radiation.

Air masses

Air masses as an element of climate subsumes the characteristics of temperature, humidity, and stability. Location relative to source regions of air masses in part determines the variation of the day-to-day weather and long-term climate of a place. For instance, the stormy climate of the midlatitudes is a product of lying in the boundary zone of greatly contrasting air masses called the polar front.

Pressure systems

Pressure systems have a direct impact on the precipitation characteristics of different climate regions. In general, places dominated by low pressure tend to be moist, while those dominated by high pressure are dry. The seasonality of precipitation is affected by the seasonal movement of global and regional pressure systems. Climates located at 10^o to 15^o of latitude experience a significant wet period when dominated by the Intertropical Convergence Zone and a dry period when the Subtropical High moves into this region. Likewise, the climate of Asia is impacted by the annual fluctuation of wind direction due to the monsoon. Pressure dominance also affects the receipt of solar radiation. Places dominated by high pressure tend to lack cloud cover and hence receive significant amounts of sunshine, especially in the low latitudes.

Ocean Currents

Ocean currents greatly affect the temperature and precipitation of a climate. Those climates bordering cold currents tend to be drier as the cold ocean water helps stabilize the air and inhibit cloud formation and precipitation. Air traveling over cold ocean currents lose energy to the water and thus moderate the temperature of nearby coastal locations. Air masses traveling over warm ocean currents promote instability and precipitation. Additionally, the warm ocean water keeps air temperatures somewhat warmer than locations just inland from the coast during the winter.

Topography

Topography affects climate in a variety of ways. The orientation of mountains to the prevailing wind affects precipitation. Windward slopes, those facing into the wind, experience more precipitation due to orographic uplift of the air. Leeward sides of mountains are in the rain shadow and thus receive less precipitation. Air temperatures are affected by slope and orientation as slopes facing into the Sun will be warmer than those facing away. Temperature also decreases as one moves toward higher elevations. Mountains have nearly the same affect as latitude does on climate. On tall mountains a zonation of climate occurs as you move towards higher elevation.

9.3: Climate Classification

The purpose of classification is to organize a set of data or information about something to effectively communicate it in an informative way. Classification helps synthesize information into smaller units that are more easily understood. When considering the Earth's climate, there is such an enormous amount of information that one has to break it down into areas of commonality to easily understand it. Climatologists have therefore created several ways to organize the wealth of information about Earth's climate to bring order and understanding to it.

Climate classification systems

There are three fundamental types of classifications used in climatology. First there are ***empirical systems*** of classification that are based on observable features. The Koeppen system discussed below is an empirical system based on observations of temperature and precipitation. These are two of the easiest climate characteristics that can be measured, and probably the ones with the longest historical record. It's fairly easy to collect air temperature readings with a thermometer and precipitation with some sort of collecting device that can measure the amount of precipitation. Climates are grouped based on annual averages and seasonal extremes.

Genetic classification systems are those based on the cause of the climate. A genetic system relies on information about climate elements like solar radiation, air masses, pressure systems, etc. The important point here is that we *assume we know* what causes climate. Though atmospheric science is progressing everyday, we still have a long way to go before we have a *complete* understanding of the workings of our climate. These are inherently the most difficult classifications to create and use because of the multitude of variables needed.

Applied classification systems are those created for, or as an outgrowth of, a particular climate-associated problem. The Thornthwaite classification system is one based on potential evapotranspiration and thus groups climates based on water requirements. Research conducted by C.W. Thornthwaite and his associates attempted to formulate a water budget technique that assessed water demand under different environmental conditions. His classification system grew out of the issue of trying to predict the supply and demand for water in different climate regions.

Köppen climate classification system

The Köppen climate classification system one of the most widely used systems for classifying climate because it is easy to understand and data requirements are minimal. It is an empirical system largely based on annual and monthly means of temperature and precipitation.

The Köppen system uses a letter coding scheme to classify climate. There are three levels of letter coding except for the A-type climates. The five main groups of climates are designated by capital letters, all but the dry climates being thermally defined. These are:

A. Tropical climates (sometimes identified as "equatorial" climates)
B. Dry climates (sometimes identified as "arid" climates)
C. Warm temperate climates
D. Subarctic climates (sometimes identified as "snow" or "boreal" climates)
E. Polar climates

The second letter relates to the seasonality of precipitation and the third to an additional temperature qualifier. For the B-type (dry) climates the first two letters are combined, BW for desert and BS for steppe. The third letter is used to subdivide these on the basis of temperature.

As you read through this text you'll notice that the names given to some of the climates reflects the vegetation found there, like tropical rainforest or savanna. The Köppen system has undergone several changes since it was first created and the names have been changed to ones that reflect climate rather than vegetation.

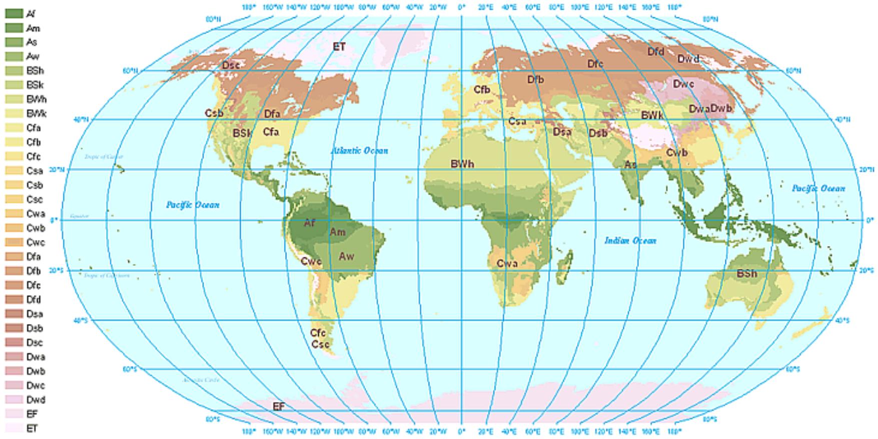


Figure 9.3.1: World Climate patterns according to Köppen (Courtesy NOAA (Source))

SECTION OVERVIEW

9.4: Low Latitude Climates

9.4.1: Tropical Rain Forest

9.4.2: Tropical Monsoon Climate

9.4.3: Tropical Wet/Dry (Savanna) Climate

9.4.4: Tropical Steppe Climate

9.4.5: Tropical Desert Climate

9.4.1: Tropical Rain Forest

The tropical rain forest climate supports one of the most lush and diverse environments on Earth. Its location near the equator dominates all aspects of the climate. Year-round warm temperatures and copious rainfall characterize the rain forest climate.

Figure 9.4.1.1: Rain forest of Uganda (Source: FAO Used with permission)

Geographical Distribution

The rain forest climate is generally found straddling the equator and along tropical coasts that are backed by mountains and exposed to the trade winds. The climate tends to be restricted to low elevations (below 1000 meters) because at higher altitudes temperatures are too cool. Large regions of rain forest climate are found in the Amazon River basin of South America, the Congo River basin of Africa, the east coast of Central America and Madagascar. Malaysia, Indonesia, and the Philippines are dominated by rain forest climate.

Controlling Factors

The equatorial location of the tropical rain forest places it in a region of high annual insolation. High sun angles throughout the year make for high annual temperatures with very little seasonal variation. Located in the heart of the Intertropical Convergence Zone and near mE and mT source regions, high annual precipitation is experienced in all months.

Distinguishing Characteristics

Temperature

The low latitude location of the rain forest promotes constant high temperatures throughout the year. Being located near the equator, the incidence angle of the noon sun is always high. In addition, the direct rays of the sun pass over the climate twice throughout the year creating two periods of maximum insolation. Given that the circle of illumination bisects the equator, day length tends to be nearly the same day-after-day.

Annual temperatures in the rain forest average between 20^o - 30^o C (68^o - 86^o F). Annual temperature range rarely exceeds 3o to 4o F. In fact, the daily range of temperature is often larger (10^o - 12^o F) than the annual range in temperature. The larger daily ranges are due to the sunny mornings and cloudy afternoons of cooling rain.

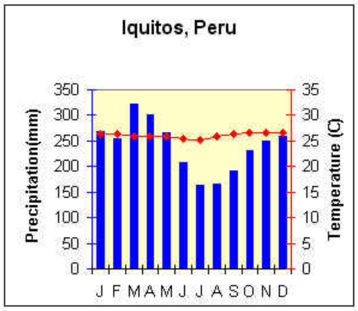


Figure 9.4.1.2: Iquitos, Peru. Iquitos, Peru's climograph displays the distinguishing characteristics of the rain forest climate: high annual temperatures and ample rainfall.

Precipitation

The rain forest is noted for its copious rainfall occurring in all months of the year. Over 200 cm (80 in) of precipitation annually falls in the rain forest. Abundant precipitation occurs in each month and is fairly evenly distributed between high and low sun seasons. However, some locations have one month of highest precipitation. Precipitation occurs on more than half the days and is largely generated by convective uplift of warm, moist equatorial air (mE). A distinctive diurnal pattern of cumulus cloud development in the morning, precipitation in the early afternoon, followed by dissipating clouds towards the late afternoon is typical. Thunderstorms are usually concentrated in small areas, so their duration is short but intense. Coastal locations and islands on the poleward limits of the rain forest experience hurricanes, but they do not occur near the equator or inland.

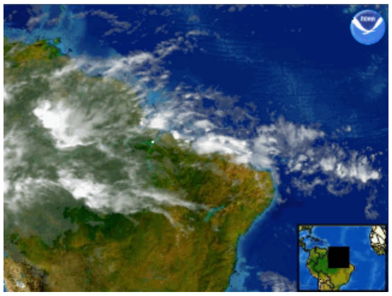


Figure 9.4.1.3: Convective thunderstorms over Brazil (July 2002) (Source: Copyright 2002 EUMETSAT)

Humidity in the rain forest can be oppressive with dew point temperatures ranging from 15^{o}C - 20^{o}C (59^{o}F- 68^{o}F). Since humidity is so high during the day, when cooling occurs at night, early morning radiation fogs form and heavy dew drips from the rain forest vegetation. These condensation products evaporate into the air as the Sun rises, thus increasing the air's humidity. Under these conditions, the air is oppressive and sultry most of the day and well into the evening. The rate of evaporation and transpiration are exceedingly high requiring a correspondingly greater amount of precipitation to support satisfactory conditions for plant growth due to the high temperature.

9.4.2: Tropical Monsoon Climate

The tropical monsoon climate experiences abundant rainfall like that of the tropical rain forest climate, but it is concentrated in the high-sun season. Being located near the equator, the tropical monsoon climate experiences warm temperatures throughout the year.

Geographical Distribution

The monsoon climate is found along the coastal regions of southwest India, Sri Lanka, Bangladesh, Myanmar, Southwestern Africa, French Guiana, and northeast and southeastern Brazil.

Controlling Factors

The major controlling factor over the monsoon climate is its relationship to the monsoon circulation. Recall that the monsoon is a seasonal change in wind direction. The "classic" monsoon circulation of Asia exhibits an onshore flow of air (air moving from ocean towards land) during the summer or high-sun season, and offshore air flow (air moving from land toward water) during the winter or low-sun season. The change in direction is due to the difference in the way water and land heat.

Changing pressure patterns that affect the seasonality of precipitation also occur in Africa. During the high-sun season, the ITCZ induces rain while the subtropical high creates dry conditions. The monsoon climate of Africa, and South America for that matter, are typically located along tradewind coasts.

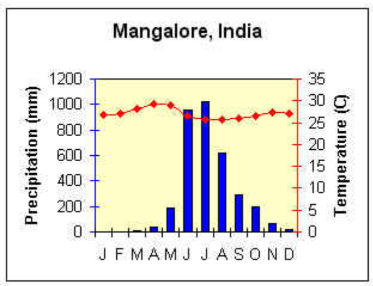


Figure 9.4.2.2: Climograph for Mangalore, India

Lat/Long = 12.53° N, 74.52° E
Average Annual Temperature (°C) = 27.05
Annual Temperature Range (°C) = 3.6
Total Annual Precipitation (mm) = 3409.2
Summer Precipitation (mm) = 3115.9
Winter Precipitation (mm) = 293.3

Distinguishing Characteristics

Temperature

Like in the tropical rain forest climate, temperatures remain high all year in the monsoon climate. As shown in the climograph for Mangalore, India (Figure 9.4.2.1), the average annual temperature is 27.05°C (80.7°F) but only has an annual temperature range of 3.6°C (2°F). The monsoon climate's temperature range is somewhat similar to that of the rain forest, but it exhibits a slightly different temporal pattern. In the rain forest we noted two periods of maximum temperature in association with the migration of the Sun's vertical rays. The monsoon climate tends to have its highest temperature just before rainy period. Once the rainy period starts, clouds block incoming solar radiation to reduce monthly temperatures.

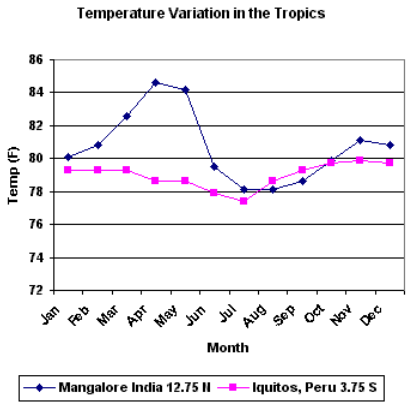


Figure 9.4.2.3: Comparison of monthly temperature in the rain forest (Iquitos) and monsoon climates (Mangalore).

Precipitation

Seasonality of its precipitation is the hallmark and most well-known characteristic of the monsoon climate. Many think that the term "monsoon" means wet weather, when in fact it describes an atmospheric circulation pattern. Though the annual amount of precipitation is quite similar to that of the rain forest, monsoon precipitation is concentrated into the high-sun season. Maritime equatorial and maritime tropical air masses travel from the ocean on to land during the summer, where they are uplifted by either convection or convergence of air to induce condensation. Locally, orographic uplift is an important mechanism for promoting precipitation. As air travels into the Indian subcontinent, it is uplifted by the Himalayas, causing cloud development and precipitation.

The low-sun season is characterized by a short drought season when high pressure inhibits precipitation formation. In the case of the Asian monsoon, the replacement of the thermal low with the subsidence of the Siberian High suppresses uplift. Air masses that dominate this period are dry given their continental origin (cT, cP) or stability (mTs).

9.4.3: Tropical Wet/Dry (Savanna) Climate

Figure 9.4.3.1: Impala on the Savanna. (Source: FAO)

The Tropical Wet/Dry climate is located on the poleward sides of the tropical wet climates, positioned between them and the tropical dry climates. This location places the climate at an intermediate position between the ITCZ and the Subtropical High. As a result, the climate experiences a distinct seasonality to its precipitation like that of the tropical monsoon climate. Also known as the "Savanna" climate, it supports a ground cover of drought resistant grasses with scattered trees, but not enough rainfall to make agriculture a viable, life sustaining activity.

Geographical Location

The Tropical Wet/Dry climate lies at latitudes of about 5^{o} - 10^{o} and 15^{o} - 20^{o}. Broad expanses of the savanna exist in north and south central Africa, The Llanos of Venezuela, Campos of Brazil, much of northern and eastern India, western Central America, the Caribbean Islands, and south Florida, Myanmar (Burma) and the Indo-Chinese Peninsula

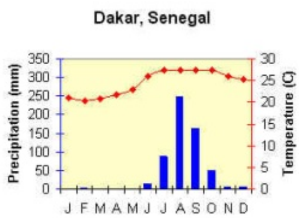


Figure 9.4.3.2: Climograph for Dakar, Senegal

Controlling Factors

Its position at about 15^{o} North or South latitude places the Tropical Wet/Dry climate in a zone between the alternating influence of the Intertropical Convergence Zone (wet season) and the (dry season) subtropical high. The subsidence of the subtropical high suppresses precipitation, creating clear skies allowing much insolation to the surface. Converging air into the ITCZ, in combination with convection, forces air to rise, causing condensation, cloud development, and precipitation.

Distinguishing Characteristics

Temperature

Located at a higher latitude, the variation in insolation is greater and hence this climate has a larger annual temperature range than the other tropical wet climates. However, the average annual temperature is similar to that of the other tropical wet climates. Mean monthly temperatures in the Tropical Wet/Dry climate range from 18^{o}C (64.4^{o}F) to above 25^{o}C (77^{o}F). Like the monsoon climate, the maximum temperature tends to occur in late spring to early summer prior to the onset of the rainy season. There may be a secondary maximum after the rainy period. Annual temperature ranges increase as one moves poleward through the climate. Daily temperature ranges are greatest during the dry season and a bit larger than the rainy tropical climates. Diurnal temperature ranges of 10^{o}C to 15^{o}C during winter are not uncommon. During the summer, high daily temperatures, small temperature ranges, and high humidity create the same uncomfortable conditions as those found in the rainy tropics.

Precipitation

Figure 9.4.3.3: Figure 9.7 A Baobab tree, with its thick trunk and large edible fruit, Dakar, Senegal. (UN/DPI Photo #187250C by Evan Schneider)

The Tropical Wet/Dry climate is the driest of the tropical wet climates. Like the monsoon climate, it has a distinct seasonality to its precipitation. However, its wet season is much shorter and receives far less precipitation than the monsoon climate. The seasonality of precipitation is related to the migratory movement of the ITCZ and Subtropical High. During the high sun season the ITCZ dominates, causing convergent uplift, along with the ever-present convection to promote the production of precipitation. During this period, warm and moist mE and mT air masses dominate.

During the low sun season the ITCZ moves out and the subtropical high moves in suppressing precipitation and initiating the long drought period. The exceedingly warm and dry cT air masses dominate during this time of the year.

Variability of precipitation makes it very difficult for agriculture. Nairobi, Kenya averages 86 cm (33.9 in) of rainfall, but from year-to-year can vary from 50 (9.7 in) to 150 cm. (59 in) The drier the savanna location, the more unreliable the precipitation. Rains are essential in greening the savanna, and animals migrate with the seasonal rhythms in search of water and pasture.

Figure 9.4.3.4: Wildebeest in Masailand, Kenya (Source: FAO Used with permission)

The most famous of these migratory journeys is that of the wildebeest. Rains fall unevenly in the Serengeti and the southeast section dries out more quickly than the northwest. By May the grasses have been chewed low, forcing its inhabitants to seek greener pastures. A million wildebeests accompanied by zebras and gazelle, merging and splitting into columns several kilometers long begin an arduous trek towards better feeding grounds in the northwest. During the headlong rush northward, they plunge across rivers in such numbers and concentrations that many of them drown. More are forced into the water by the pressure from the multitude of wildebeest approaching from behind. Predators ambush them and pick off exhausted and sick animals with ease. After a torturous 200 kilometers or so, they reach the still lush pastures of the Mara in southern Kenya. There they will stay and feed until November when the rains return.

9.4.4: Tropical Steppe Climate

Figure 9.4.4.1: Tropical steppe of Ethiopia (Sources: FAO)

The tropical steppe climate is a transitional climate between the tropical wet and tropical dry climates. The controlling factors of the climate are similar to that of the tropical dry climate, though temperatures are cooler and annual precipitation is higher. This is why we consider a steppe climate semi-arid rather than arid.

Geographical Location

The tropical steppe climate is located on the periphery of deserts. Tropical steppe climate is found bordering the Great Australian desert, the Sahara of northern Africa, and in southwest Asia.

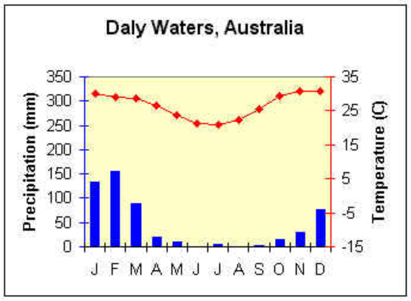


Figure 9.4.4.2: Climograph for Daly Waters, Australia

Latitude/Longitude: 16.25°S N; 133.3°E
Average Annual Temperature (C) = 26.5°
Annual Temperature Range (C) = 10°
Total Annual Precipitation (mm) = 536.2
Summer Precipitation (mm) =500
Winter Precipitation (mm) = 36.2

Controlling Factors

The climate of the tropical steppe is a direct result of its interior continental location and proximity to the subtropical high. The tropical steppe is not as dry as the tropical desert climate as it lies closer to a source of moisture. If on the equatorward side of the desert it is the ITCZ, or the subpolar low and midlatitude cyclones if it is located poleward side.

Distinguishing Characteristics

Temperature

Unlike the midlatitude climates where we mark our seasons by the change from warm temperatures to cold, in the tropical dry climates seasons are distinguished on the basis of it being warm and excessively warm. The generally cloudless conditions that exist in the tropical steppe allows much insolation in to warm the surface. The very high temperatures are also due to the proximity of the climate to cT and mT air mass source regions. Mean annual temperature in the tropical steppe climate is approximately 20°C (68°F). Being located poleward of the tropical wet climates, the annual temperature range increases as the variation in sun angle increases at these locations. Annual temperature ranges vary from 10°C (5.6°F) to above 20°C (11°F). Daily temperature ranges are nearly similar to, or larger than, the annual range of temperature.

Precipitation

The tropical steppe climate is a semi-arid environment. To climatologists, a semi-arid environment can be defined as one where the annual potential evapotranspiration is more than half but less than the total annual precipitation. Potential evapotranspiration is a measure of the demand for water on account of plant transpiration and surface evaporation. In the tropical steppe, much evaporation and plant transpiration would take place if water were available. Meager amounts of precipitation during the relatively long summer droughts stress plants that require water during periods of high temperature. However, during the wet portions of the year, ample precipitation to meet the needs of the natural vegetation usually occurs.

Recall that the steppe climate is a transitional climate between truly wet and truly dry climates. The seasonality of precipitation is similar to that of the closest humid climate. For example, the steppe climate found between the tropical desert and wet/dry tropical climate of Africa has a high sun wet - low sun dry seasonality to its precipitation. During the low sun period the subtropical high migrates into this region and suppresses convection. The subsiding air lowers the relative humidity making it difficult to bring air to its saturation point. Life sustaining rains come with the movement of the ITCZ into the tropical steppe. However, the tropical steppe located between the tropical desert and the dry summer subtropical (Mediterranean) climate is just the opposite, high sun dry - low sun wet. During the high sun season the tropical steppe is dominated by the subtropical high. During the low sun season cyclones associated with the subpolar low and polar front dominate.

Some regions having a tropical steppe climate are found on the lee side of mountains. As air ascends the windward slopes, water vapor condenses and precipitation occurs. Places located on the leeward side are thus in the "rain shadow" and are dry.

9.4.5: Tropical Desert Climate

Figure 9.4.5.1: Grand Erg Desert.

The tropical desert is an environment of extremes: it is the driest and hottest place on earth. Rainfall is sporadic and in some years no measurable precipitation falls at all. The terribly dry conditions of the deserts is due to the year-round influence of subtropical high pressure and continentality.

Geographical Distribution

Deserts are typically found in continental interiors of the subtropics and on the lee side of mountains in the midlatitudes. Cool coastal deserts are found where cold water upwells along a coast, stabilizing the air and preventing moisture formation like that near coastal Chile. Vast deserts cover much of north Africa (The Sahara), Saudi Arabia to Iran, Pakistan and western India. Tropical deserts are found in Baja California and interior Mexico in North America.

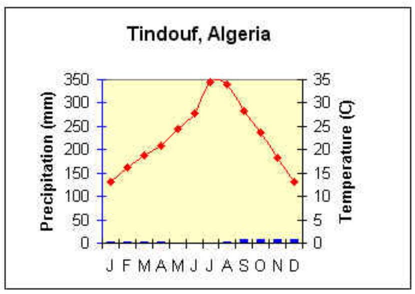


Figure 9.4.5.2: Climograph for Tindouf, Algeria

Latitude/Longitude: 27.7° N; 8.1° W

Average Annual Temperature (°C) = 22.8

Annual Temperature Range (°C) = 21.2

Total Annual Precipitation (mm) = 43.8

Summer Precipitation (mm) =11.8

Winter Precipitation (mm) = 32

Controlling Factors

The most important controlling factor of the climate characteristics of the tropical desert climate is the year-round presence of subtropical high pressure. The descending air of the subtropical high adiabatically warms causing the air to dry out and inhibit condensation. Aridity also arises as distance from moisture sources increases. Leeward situations places one in the rain shadow which also promotes dry conditions. Cool coastal deserts are found along coasts where cold water is upwelling.

Distinguishing Characteristics

Temperature

The tropical desert has the highest mean annual temperature of any climate on Earth. The high temperatures are a result of the high sun angles throughout the year and having the highest percentage of sunshine of any climate. No month has an average temperature below 18°C (64.4°F) and many places have consecutive average monthly temperatures in the mid 30°s Celsius (90°F). Daytime temperatures can reach 50°C (120°F) at low elevation inland deserts.

The sky in the tropical desert remains cloud-free due to the subsiding air of dominant high pressure resulting in large amounts of insolation. The cloudless skies during the day lets insolation in, but also lets much heat out at night. Without the absorptive blanket of clouds, longwave radiation emitted from the Earth readily escapes to space, chilling the nighttime desert air. The high energy input during the day and large loss at night results in an extremely large daily temperature range.

Precipitation

Precipitation in the tropical desert is very irregular and unreliable. Low latitude deserts average less than 25 cm (10 in) in a year. An entire year's worth of rain may fall in one downpour. The continental location of many tropical deserts places them far from a source of moisture, the ocean. Combine continentality with the strong subsidence of the subtropical high and you have one of the driest places on earth. Air subsiding from the subtropical high is adiabatically warmed which reduces the relative humidity of the air. Relative humidity can drop to 10% or less. The extremely low relative humidity causes evaporation of what little surface water there is. The subsiding air also promotes atmospheric stability, further inhibiting precipitation.

Figure $9.4.5.3$: Oasis in Mauritania. (Image courtesy FAO)

Climatologists describe the desert as an "arid" climate. An arid climate, as defined on the basis of the soil moisture balance, is one in which the annual precipitation is less than half of the annual potential evapotranspiration. In the tropical desert the only substantial source of surface water other than exotic streams is an **oasis**, where the groundwater table is near the surface.

SECTION OVERVIEW

9.5: Midlatitude and Subtropical Climates

9.5.1: Mediterranean or Dry Summer Subtropical Climate

9.5.2: Midlatitude Desert Climate

9.5.3: Midlatitude Steppe

9.5.4: Humid Subtropical Climate

9.5.5: Humid Continental Climate

9.5.6: Marine (Humid) West Coast Climate

9.5.1: Mediterranean or Dry Summer Subtropical Climate

The Dry Summer Subtropical climate, is also known as the "Mediterranean" climate because the land that borders the Mediterranean Sea is a type locality for this climate. The wet winter/dry summer seasonality of precipitation is the defining characteristic of this climate. Summer drought places a great deal of stress on the local vegetation, but plant structures have evolved to adapt to it. The small, thick evergreen leaves of the schlerophyll forest combat water loss during the drought conditions of the dry summer.

Geographic Distribution

The dry summer subtropical climate is found on the west side of subtropical continents and on the coast of the Mediterranean Sea. The largest area of dry summer subtropical climate is on the border lands of the Mediterranean. For Americans especially, the lure of "sunny" coastal central and southern California's dry summer subtropical climate is a draw for tourism and habitation. Mediterranean climate is also found in the Cape Town area of South Africa, central Chile, and southwestern Australia.

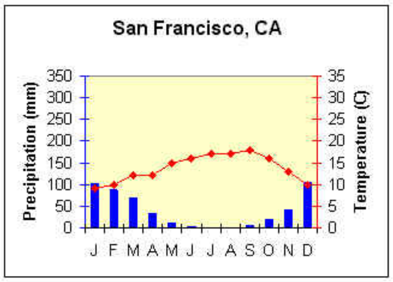


Figure 9.5.1.1: Climograph for San Francisco, CA
Latitude/Longitude = 37.45 N; 122.26 W
Average Annual Temperature (C) = 13.75
Annual Temperature Range (C) = 9
Total Annual Precipitation (mm) = 475
Summer Precipitation (mm) = 54
Winter Precipitation (mm) = 421

Controlling Factors

The main controlling factor over the characteristics of the dry summer subtropical climate is the alternating influence of the subtropical high in summer and Westerlies during the winter. During the summer, the subtropical high has expanded to its largest extent and most poleward position, exerting its influence on subtropical west coasts between 30^o and 40^o N and S latitude. Subsiding air from the high creates stable atmospheric conditions when coupled with cold ocean currents along these coasts. During the summer, stable maritime tropical air masses and cT air masses dominate.

During the winter the subtropical high shifts to the south and its influence is replaced by the Westerlies associated with the subpolar low. During this period, mT, mP, and cP air masses invade the climate. Midlatitude cyclones formed in the Westerlies bring much needed precipitation during the winter.

Distinguishing Characteristics

Temperature

It's no wonder the cradle of civilization is found in the dry summer subtropical climate. The temperature is moderated by nearby large bodies of water making for comfortable conditions throughout most of the year. Temperatures around the Mediterranean coast are higher than the dry summer subtropical climates bordered by colder ocean water. No monthly temperature falls below 0^{o}C (32^{o}F) and has at least 3 months that average above 10^{o}C (50^{o}F). Warmest monthly means are in the upper 20^{o}s C (70^{o}F to 80^{o}F). The stable atmosphere creates cloudless conditions giving the dry summer subtropical climate many days of sunshine. The cloudless conditions commonly experienced during both the daytime and night cause significant heat gain and loss over the course of the day. As a result, this climate experiences a large daily temperature range during the summer. Though the climate is typified by its mild temperatures, frost danger does occur during the winter when cP air masses penetrate the region.

Precipitation

The most distinguishing characteristic of the dry summer subtropical climate is its seasonal precipitation regime. As discussed above, the dry summer is due to the presence of the subtropical high. The subsidence of the subtropical high suppresses cloud development and precipitation. Additionally, the presence of a cold ocean current along the western coast of the United States helps to stabilize the air, further reducing the chances for rain. The cloudless skies during summer, however, increase the absorption of insolation by the polluted atmosphere of many large urban centers in places like southern California causing problems of photochemical smog.

During the winter, the subtropical high shrinks and moves away from the climate and the subpolar low with its associated cyclone belts moves in. Uplift provided by cyclonic circulation brings much needed rain to this region. However, intense down pours can cause rapid runoff and initiate landslides on unstable slopes.

Many coastal dry summer subtropical climate regions experience frequent fogs. In North America, the dry summer subtropical is strongly influenced by a cold ocean current. As warm, moist Pacific air travels over the colder ocean water of the California Current it is chilled. Cooling the air by contact brings the air to its saturation point causing condensation and the development of an advection fog.

9.5.2: Midlatitude Desert Climate

The midlatitude desert shares many of the same climatic characteristics as the tropical deserts, and for many of the same reasons. While the tropical desert climates are considered "hot" deserts following Köppen's classification (BWh), midlatitude deserts are "cold" deserts (BWk).

Figure 9.5.2.1: Shrub desert of Arizona (Source: USGS DDS21)

Geographic Distribution

The midlatitude desert is found in inner Asia with great expanses in northern (Gobi desert) and northwestern China (Takla Makan desert), Kazakhstan, and Uzbekistan. The interior western United States (Southern Utah and Nevada, Arizona, New Mexico) has a midlatitude desert climate.

Controlling Factors

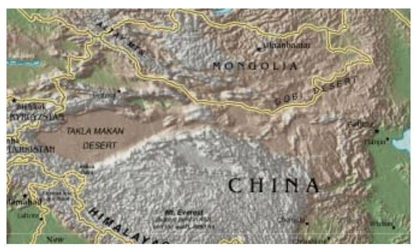


Figure 9.5.2.2: Interior location of Takla Makan and Gobi Desert. (Source: CIA World Factbook)

The midlatitude desert climate is controlled by the same factors as the tropical desert climates, the influence of high pressure, interior position, and rain shadow location. The Takla Makan desert exhibits this influence well as it lies in a depression ringed by mountains preventing even the most meager amount of moisture to penetrate to this interior location.

In the United States, the midlatitude desert lies in a region where high-level subsidence, especially pronounced in the summer, inhibits precipitation. During the winter, these regions are effectively cut-off from moist mT air masses and cold high pressure dominates the region. The midlatitude desert climate is found in the Great Basin of the United States. Here, east facing slopes lie on the leeward sides of mountains in the rain shadow of the westerly winds.

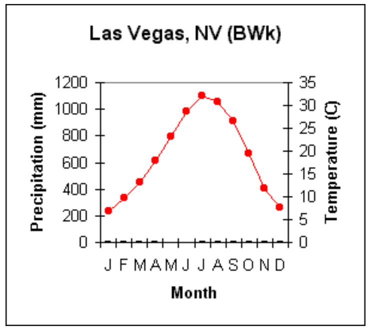


Figure 9.5.2.3: Climograph for Las Vegas, NV

Latitude/Longitude = 36N, 115 W
Average Annual Temperature (C) = 19
Annual Temperature Range (C) = 25.2
Total Annual Precipitation (mm) = 101.5
Summer Precipitation (mm) = 42.4
Winter Precipitation (mm) = 58.6

Distinguishing Characteristics

Temperature

Like its tropical equivalent, the midlatitude desert enjoys a high percentage of sunshine throughout the year. Dominant high pressure and lack of moisture combine to inhibit the production of clouds. The midlatitude desert similarly experiences large daily temperature ranges due to cloudless day and nights. However, the midlatitude desert experiences a larger annual temperature than the tropical desert. The southwest desert of the United States serves as a source region for cT air only during the summer because it is too cold to produce such an air mass during the winter. Wintertime incursions of cold cP is not uncommon.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Mean Annual Temp**	**Annual Temp Range**
Las Vegas, NV (BWk) (oC)	6.9	9.8	13.2	17.9	23.2	28.6	32.1	30.9	26.5	19.5	11.9	7.6	19	25.2
In Salah, Algeria (BWh) (oC)	14.3	16.8	20.9	25.2	30.5	35.7	36.8	36.5	33	26.8	20.2	14	26.1	22.8

Precipitation

The midlatitude desert is considered an arid climate in which the total annual precipitation is less than half the annual potential evapotranspiration. Precipitation is sparse as the interior location is distant from a source of moisture. Or, the lack of rainfall is due to its leeward, rain shadow location. Like the tropical desert, precipitation is irregular and unreliable. Relative humidity is quite low when the region is dominated by cT air masses during the summer. Precipitation does fall during the U.S. southwest desert's "monsoon season" in July and August as Gulf air masses penetrate into this region. Combined with cyclonic precipitation during the winter the midlatitude desert receives much more precipitation than its tropical counterpart (Figure 9.5.2.4).

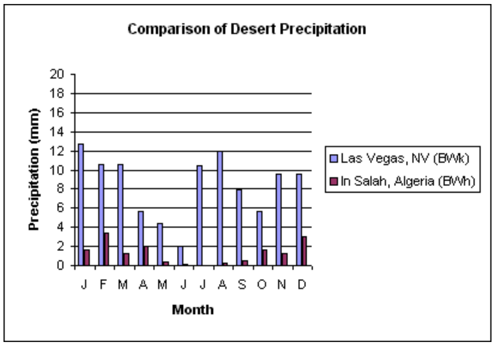


Figure 9.5.2.4: Comparison of Desert Precipitation

9.5.3: Midlatitude Steppe

Figure 9.5.3.1: Sheep grazing on grass the eastern confines of the Horquin Desert (Inner Mongolia). (Source: J.Y. Piel FAO #17947 Click image to enlarge)

The midlatitude steppe climate shares many of the same characteristics that the tropical steppe has. Both are semi-arid climates that are affected by their interior continental or leeward orographic position. However, the midlatitude steppe experiences larger temperature ranges and receives more total rainfall than the tropical steppe climate.

Geographic Distribution

Midlatitude steppes are found on the periphery of midlatitude deserts and the leeward side of mountain systems in inner Asia, South America, and the Western United States. Much of the Great Plains of the United States lies in the midlatitude steppe climate. Broad expanses of steppe climate run through Mongolia and Kazakhstan.

Controlling Factors

The controlling factors over the geographical distribution and climatic characteristics of the midlatitude steppe are similar to that of the midlatitude deserts. The climate is found in the interior of the vast midlatitudes continents of the Northern Hemisphere, far removed from sources of moisture. Midlatitude steppe climate is located in the rain shadow of tall mountain chains like the Rocky and Andes Mountains in North and South America respectfully. These mountain systems act as a barrier to westerly flowing moist air.

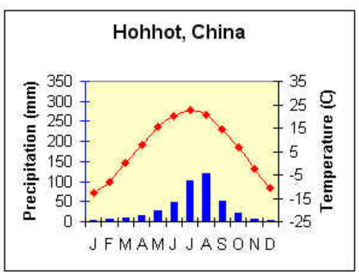


Figure 9.5.3.2: Climograph for Hohot, China
Average Annual Temperature (C) = 6.1
Annual Temperature Range (C) = 35.5
Total Annual Precipitation (mm) = 404.6
Summer Precipitation (mm) =362.8
Winter Precipitation (mm) = 44.1

Distinguishing Characteristics

Temperature

Temperature in the midlatitude steppe climate varies considerably with latitude, elevation, and continentality. Temperatures can range from -40^{o}C (-40^{o}F) in winter to above 40^{o}C (104^{o}F) in summer. Due to their continental position, the steppe climates of the northern Great Plains and Siberia generally experience the lowest temperatures of this climate. As one might expect, temperature increases as one travels toward the equatorward margin of the climate. Cooler temperatures also prevail as one moves toward high elevation. The temperature range for central Asian locations can be as much as 40^{o}C (22^{o}F), yet along the Argentine coast as small as 12^{o}C (6.7^{o}F). Though places like Santa Cruz, Argentina have a moderately small temperature range due to their near-coastal location, they lie in the rain shadow of the Andes and hence experience very little precipitation.

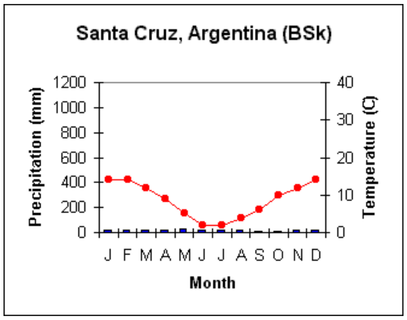


Figure 9.5.3.3: Climograph for Santa Cruz, Argentina
Average Annual Temperature (C) = 8
Annual Temperature Range (C) = 12
Total Annual Precipitation (mm) = 202
Summer Precipitation (mm) =94
Winter Precipitation (mm) = 104

Precipitation

With annual precipitation greater than half the annual potential evapotranspiration, the midlatitude steppe is considered a semi-arid climate. Precipitation ranges from 100 to over 300 mm in a year. There are few generalities that can be made about the precipitation regime of this climate. The seasonality of precipitation is similar to the nearest humid climate. Generally speaking, if the steppe climate borders the humid continental climate it is likely to have a summer maximum while bordering the humid subtropics a winter maximum may occur. Those steppe climates located closer to the coast may not have significant variability in their precipitation.

9.5.4: Humid Subtropical Climate

Geographic Distribution

Figure 9.5.4.1: Humid subtropical climate of North Carolina

The humid subtropical climate is found on the east coast of continents between 20^o and 40^o N and S latitude. The humid subtropical climate can be found in the southeastern United States, southeastern South America; coastal southeast South Africa; eastern Australia; eastern Asia from northern India through south China to Japan.

Controlling Factors

The east coast location of the Humid Subtropical climate places it near the source region for maritime tropical air. Additionally, warm ocean currents paralleling these coasts further enhance the instability of the air. These factors combine to produce moderate amounts of precipitation in most months of the year. The humid subtropical climate is subject to cold temperatures during the winter as cP air masses embedded in cyclonic storms pass through this region.

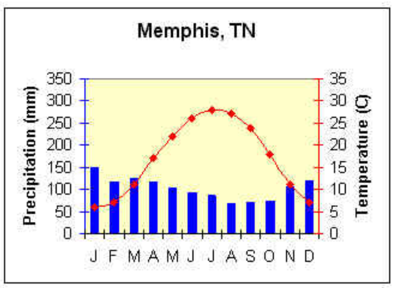


Figure 9.5.4.2: Climograph for Memphis, TN
Latitude/Longitude = 35^{o}N; 90^{o}W
Average Annual Temperature (^{o}C) = 17
Annual Temperature Range (^{o}C) = 22
Total Annual Precipitation (mm) = 1222
Summer Precipitation (mm) = 536
Winter Precipitation (mm) = 686

Distinguishing Characteristics

Temperature

The humid subtropical climate is noted for its warm summer months, and relatively mild winters. Summer temperatures average between 21^o (69.8^{o}F) to 26^{o}C (78.8^{o}F) and no winter month has an average temperature below 0^{o}C (32^{o}F). Many days the temperature can hit 32^{o}C (90^{o}F) or higher. Moving poleward through the various climates of the earth, one notices the distinct development of a seasonal cycle of temperature, especially toward the poleward limits of the climate. The high humidity experienced in the humid subtropical climate makes warm days feel oppressive. The daily temperature range tends to be very small as the evening does not cool down much during the summer. Winter temperatures will dip into the single digits with the relatively frequent invasions of cP air masses, especially on the poleward side of the climate.

Precipitation

The humid subtropical climate gets its name from the high humidity experienced in this environment. Dominance of the warm and moist maritime tropical air creates summers similar to the humid tropics. Precipitation is generally evenly distributed throughout the year. Annual precipitation varies from 254 cm (100 in) near the coast to 63.5 cm (25 in) inland. Frost is generally only a problem in winter when very cold cP air masses penetrate this region, a real hazard for fruit and vegetable growers in the southeastern United States. A monsoon influence is experienced in Asia.

9.5.5: Humid Continental Climate

The humid continental climate is found over great expanses in the temperate regions of the mid-latitudes. The humid continental climate is noted for its variable weather patterns related to cyclonic storms and its large temperature range due to its interior location in mid-latitude continents.

Controlling Factors

The humid continental climate is known for its variable weather conditions due to its location in the midlatitudes and the year-round influence of the polar front. This climate lies in the boundary zone between many different air masses, principally polar and tropical ones. Polar-type air masses collide with tropical type air masses causing uplift of the less dense and moister tropical air resulting in precipitation. Colliding along the polar front, these air masses turn and swirl into large extratropical cyclones steered by the polar front jet stream lying high in the troposphere. These huge systems generally work their way across the surface in a west to east fashion, embedded in the dominate wind flow of the westerly wind belt.

Figure 9.5.5.1: Overlooking the Wisconsin River

Continentality is an important controlling factor over the characteristics of this climate. The humid continental climate is primarily located within the interior of most midlatitude continents. Being removed from the moderating influence of the oceans, the climate experiences great swings in seasonal temperature. Annual temperature ranges can exceed 40^{o}C (82^{o}F). Where the periphery of the climate borders the ocean, summer temperatures are slightly cooler and winter temperatures slightly warmer than the interior. During the winter, the polar high expands in area to influence the northern portion of the continental humid climate. Record-setting cold temperatures occur during winter when continental arctic air masses sweep into the region. Otherwise, continental polar air masses dominate for much of the winter.

Figure 9.5.5.2: Agriculture has replaced nearly all the natural prairie grass found in the drier portion of the humid continental climate. (Courtesy: NRCS)

Precipitation in the humid continental climate is primarily due to invasions of maritime tropical air. In North America, the Gulf of Mexico and the Caribbean Ocean serve as source regions for maritime tropical (mT) air masses. Much of the precipitation east of the Rocky Mountains is due to the humid nature of the mT air, whether this be during the summer or the winter. A noticeable decrease and seasonality to the precipitation occurs as distance from the source region increases.

Warm Summer Subtype

The warm summer subtype of the humid continental climate in North America lies on the eastern and midwestern portion of the United States from the Atlantic to the 100th Meridian. The climate is also found in east central Europe, northern China, and northern Korea. The warm summer subtype is noted for its hot, humid summers and occasional winter cold waves.

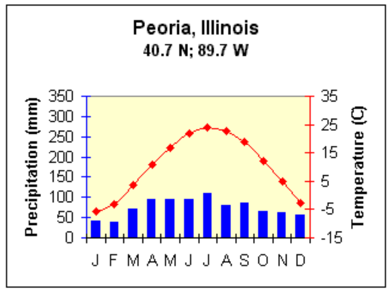


Figure 9.5.5.3: Climograph for Peoria, Illinois

Peoria, Illinois lies in the warm summer subtype with an average annual temperature is 10.4°C (50.7°F). It has a rather large annual temperature range of 29.8°C, summer temperatures average 19.2°C (65.5°F), while winter temperatures are 1.6°C (35°F). Typical of the humid continental climate most of its precipitation falls during the summer when air masses are warmer and wetter.

Cool Summer Subtype

The cool summer subtype of the humid continental climate in North America is found in New England, throughout much of the Great Lakes region and upper Midwest extending into south and south central Canada. Much of Scandinavia, eastern Europe and Russia fall into the cool summer subtype as well.

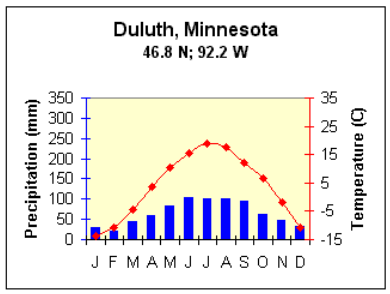


Figure 9.5.5.4: Climograph for Duluth, Minnesota

Duluth, Minnesota well represents the cool summer subtype of the humid continental climate. Like the warm summer subtype, most of its precipitation falls in the summer half of the year. However, it receives less precipitation due to the colder temperatures and their associated lower humidity.

There is a noticeable decrease in the temperature from that of the warm summer subtype too. Average annual temperature at Duluth is a cold 3.8°C (39°F). The cool summer subtype not only has cooler summertime temperatures, but very cold temperatures during the winter, with many months averaging below 0°C (32°F).

The humid continental climate supports a diversity of ecosystems, the type of which depends on their geographic location within the boundaries of the climate. Mixed broadleaf deciduous forest is common in the southern and eastern portions of the climate in the United States. Toward the west where the precipitation is less, forests give way to grasslands. The tall grass prairies of central Iowa and Illinois flourished in the climate long before white settlers inhabited the region.

Figure 9.5.5.5: Mixed broadleaf deciduous and pine forests are typically found in the cool summer subtype of the humid continental climate.

The temperate climate and fertile soils found in the humid continental climate has created the most productive region for agriculture. The agricultural breadbasket of North America has historically been found in this climate. Settlers in North America cleared the large expanses of deciduous forest and plowed the fertile prairies. Corn, soy beans, are widely grown. In the colder, less suitable northern portions, dairy farming has been a long agricultural tradition.

9.5.6: Marine (Humid) West Coast Climate

Figure 9.5.6.1: Coastal Oregon, USA (Source: NOAA)

The marine or humid west coast climate is exactly what its name describes. This climate is found on the west coast of midlatitude continents and is very humid through most of the year. Its geographic location places it in the path of westerly winds from the ocean that bring cloudy skies, much precipitation, and mild temperatures. The distribution of the climate is greatly influenced by the orientation of mountain systems in North America and Europe.

Geographical Distribution

The marine west coast climate is found along a relatively narrow strip of coastal Oregon, Washington, British Columbia, and southern Alaska in North America. It is likewise found along coastal Chile in South America. The marine west coast climate extends further inland into northwest Europe than in North America due to the orientation of mountains. This climate is also found on the southeast coast of Australia and New Zealand.

Controlling Factors

The most important control over the climate characteristics of the marine west coast is its west coast location in the midlatitudes. Here maritime polar air masses are constantly coming ashore bringing mild temperatures and high humidity. In some cases like northern Europe, warm ocean currents moderate the temperature of the site.

As noted above, the orientation of mountains has a large effect on the geographic distribution of the climate. In North and South America, mountains tend to be north-south oriented, whereas in Europe they tend to run more west to east. The north-south orientation acts as barrier to oceanic air masses in the Westerlies forcing them to rise and cool producing cloudy, rainy conditions along the coast. In Europe, the oceanic air masses can penetrate further inland, moderating the climate of a much larger region.

A significant difference in the climate situations at Vancouver and London (below), both Marine West Coast climates, arises from location, local topography, and ocean current influence. The dry summer in Vancouver is due in part to subsiding, subtropical high pressure lying to the south. Precipitation is nearly double that of London due to local orographic uplift of air. Milder winter temperatures in London arise from the moderating influence of the North Atlantic Drift.

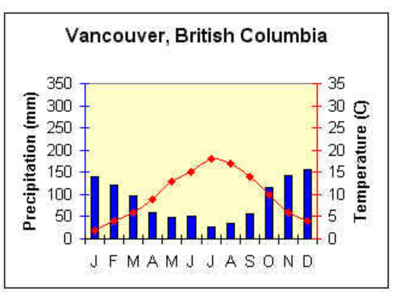


Figure 9.5.6.2: Climograph for Vancouver, British Columbia

Latitude/Longitude = 49.1^{o}N; 123.06^{o}W

Average Annual Temperature (^{o}C) = 9.8

Annual Temperature Range (^{o}C) =16

Total Annual Precipitation (mm) =1048

Summer Precipitation (mm) = 277

Winter Precipitation (mm) = 771

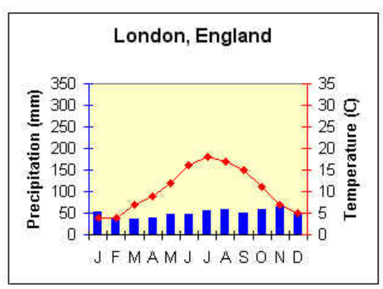


Figure 9.5.6.3: Climograph for London, England

Latitude/Longitude =51.3^{o}N; .07^{o}W

Average Annual Temperature (^{o}C) = 10.4

Annual Temperature Range (^{o}C) = 14

Total Annual Precipitation (mm) = 595

Summer Precipitation (mm) = 295

Winter Precipitation (mm) =300

Distinguishing Characteristics

Temperature

The marine west coast is noted for its mild summers and winters and, as a result, a small annual temperature range. Its location on the west coast of a continent in the midlatitudes places the climate in the path of the Westerlies. In this situation, the climate receives a constant influx of oceanic air throughout the year. The mild temperatures are a direct result of the moderating influence of ocean bodies on air temperatures. The is especially true for those situations where a warm ocean current borders the continent, like the North Atlantic Drift's effect on northwestern Europe. Temperature ranges increase as one moves away from the coast.

Precipitation

Not only is the marine west coast noted for its mild temperatures but also for its heavy cloud cover and high humidity through much of the year. This is especially true for the marine west coast climate of North America where orographic uplift is an important climate control. Maritime polar air masses forced to rise up the windward, western slope create significant cloud cover and precipitation. The marine west coast climate is dominated by cyclonic activity embedded in the Westerlies. Frequent cyclonic storms bring prolonged periods of rain, drizzle and fog to these west coast locations. In some locations it is not uncommon to receive as much as 2540 mm (100 in) of precipitation in a year, an amount that rivals the rainy tropics.

SECTION OVERVIEW

9.6: High Latitude Climates

9.6.1: Subarctic Climate

9.6.2: Tundra Climate

9.6.3: Ice Cap Climate

9.6.1: Subarctic Climate

Deep in the interior of high latitude continents lies the subarctic climate. Like the humid continental climate, continentality plays a major role in determining the characteristics of the subarctic climate. Bitterly cold winters and mild summers result in the largest annual temperature range of any climate on Earth.

Figure 9.6.1.1: Snow covered coniferous forest, typical natural vegetation of the subarctic climate. Conical shape of coniferous trees helps capture insolation from low sun angles typical of the subarctic. (Photo credit: T. Smylie, U. S. Fish and Wildlife Service.)

Geographic Distribution

The subarctic climate is only found in the Northern Hemisphere because there is no *large* landmass at the same latitude in the Southern Hemisphere. Vast expanses of the subarctic climate stretch across northern North America from Newfoundland to Alaska. Subarctic climate is found in northern Eurasia from Scandinavia through most of Siberia.

Controlling Factors

Located in a large continental landmass between 50º to 70º latitude the subarctic climate is removed from any moderating influence of an ocean. It therefore experiences a very large range in annual temperatures. During the summer it is dominated by the Westerlies and cyclonic activity, during the winter it is the Polar High and Easterlies. The subarctic climate is noted for its long cold winters, no wonder given that it is found in the source region for continental polar air masses. Other air masses of significance are maritime polar and continental arctic.

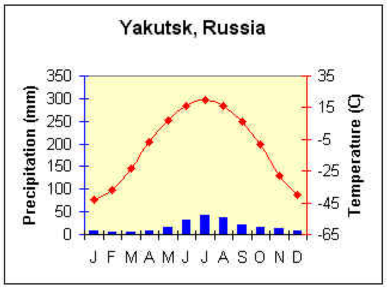


Figure 9.6.1.2: Climograph for Yakutsk, Russia

Latitude/Longitude = 62.1ºN; 129.49ºW
Average Annual Temperature (ºC) = -10.08
Annual Temperature Range (ºC) = 63
Total Annual Precipitation (mm) =213
Summer Precipitation (mm) = 157
Winter Precipitation (mm) = 56

Distinguishing Characteristics

Temperature

The subarctic climate has brief, cool summers and bitterly cold winters. The subarctic experiences the lowest temperatures outside of Antarctica, and the largest annual temperature range of any climate. Though the summer is short, the day length is quite long with June days lasting 18.8 hrs at 60°N. Daytime temperatures can rise above 25°C (77°F), while dropping to 10°C (50°F) during the evening. The freeze free period is of course short, being only three months long. However, a freeze can occur in any month.

Precipitation

Total annual precipitation in the subarctic is fairly small, amounting to no more than 380 mm (15 in) to 500 mm (21 in) over the year. Most of the precipitation is cyclonic in origin and concentrated during the warmer months (except along coasts) where air masses are more humid. Notice that the summer precipitation at Yakutsk is three times that of winter. The extremely cold temperatures, coupled with the subsidence of the Polar High, are responsible for the meager precipitation that falls during the winter.

9.6.2: Tundra Climate

The tundra climate is a transitional climate between the Subarctic and Ice cap climates. It is a region of rolling to nearly level terrain almost entirely devoid of trees. Polar climates like the tundra are characterized by very cold temperatures and generally dry conditions. Temperatures never rise above 10^{o}C (50^{o}F) during the summer. The tundra located near the Arctic and Antarctic Circle, experiences times when the Sun never rises above the horizon.

Figure 9.6.2.1: Ice mounds in the Alaskan tundra. Ice mounds are a product of ground heave caused by alternating freezing and thawing of permafrost. (Source: USGS Digital Data Series CD-ROM DDS-21 Used with permission)

It is so cold in the tundra that ***permafrost*** is a prominent feature. Permafrost is soil, rock, or peat that has been frozen for more than two years. Near the surface the "active" layer thaws during the summertime and subsides or moves down slope. During the winter, the surface heaves as it refreezes. The alternating freeze-thaw cycles make it difficult to build structures on such a surface. More importantly, permafrost stores vast amounts of carbon in slowly decomposing organic matter. Disturbed by warming, greenhouse gases are released. For more about the role of permafrost in environmental change, try "Digging Deeper: Permafrost and Climate Change" or skip and continue reading.

Digging Deeper: Permafrost and Climate Change

As discussed in Chapter 3, surface features and human activities play are role in the composition of earth's atmosphere. Permafrost currently covers 24% of the exposed land in the high latitudes of Northern and Southern Hemispheres. Climate change scientists are carefully watching the impact of global warming on the seasonally and permanently frozen soil of the Arctic and subarctic.

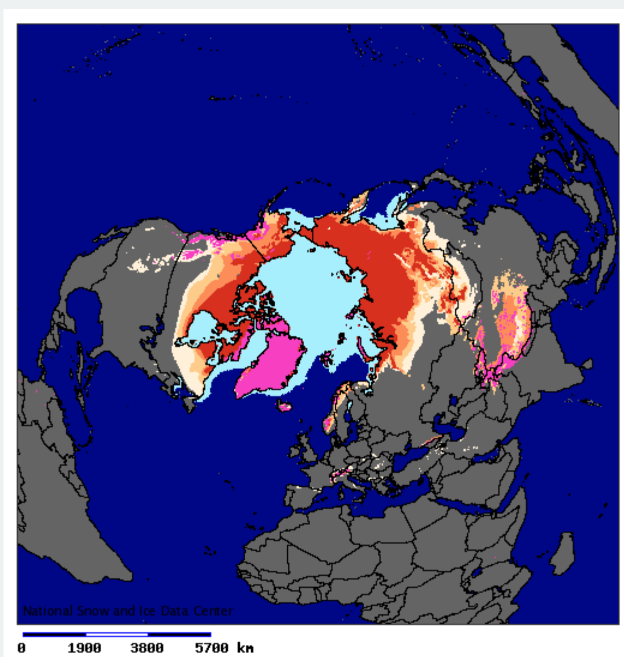


Figure 9.6.2.2: Northern Hemisphere Permafrost (Courtesy National Snow and Ice Data Center, Source)

The estimated maximum extent of seasonally frozen ground in non-permafrost regions has decreased by approximately 7% in the Northern Hemisphere, with up to 15% decrease during the spring. Degradation of permfrost appears to be resulting from increased summer air temperatures and changes in snow depth and duration. The active layer of permafrost measured at over

30 stations in Russia between 1956 to 1990 exhibited a 21 cm deepening. Records are too short in other parts of the world to show any kind of trend in active layer deepening.

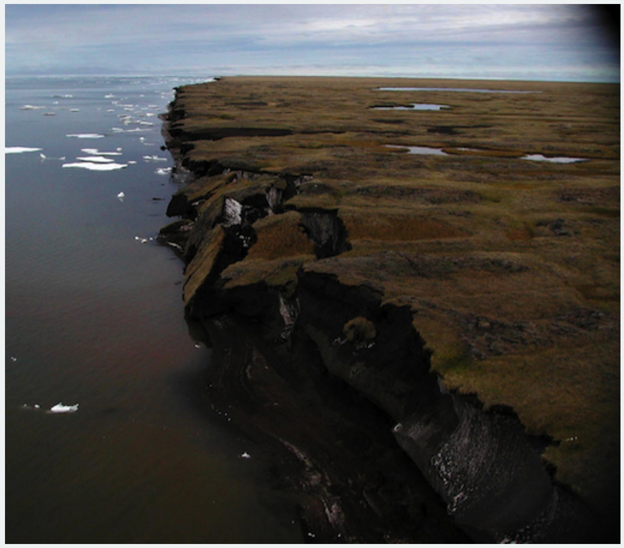


Figure 9.6.2.3: Crumbling coastline from melting permafrost at Drew Point, Alaska (Courtesy USGS, Source)

Results from a variety of IPCC climate scenarios point to a likely decline in the area of Northern Hemisphere permafrost of 20 - 35% by the mid-21st century. An average seasonal depth of thawing is expected to increase by 15-25% by 2050 and 30-50% over most permafrost regions.

It is estimated that northern circumpolar regions store twice the amount of carbon that is held in the atmosphere as CO2. As frozen soils thaw under warmer conditions, carbon dioxide, methane, and nitrous oxide is released into the atmosphere. Most of this is a product of the decomposition of organic matter that has built up over many years under colder temperatures. Warmer temperature in Arctic and subarctic ecosystems has created longer growing seasons, stimulating plant growth, resulting in increasing carbon emissions. It is expected that carbon emissions will eventually exceed that of storage and encouraging further warming.

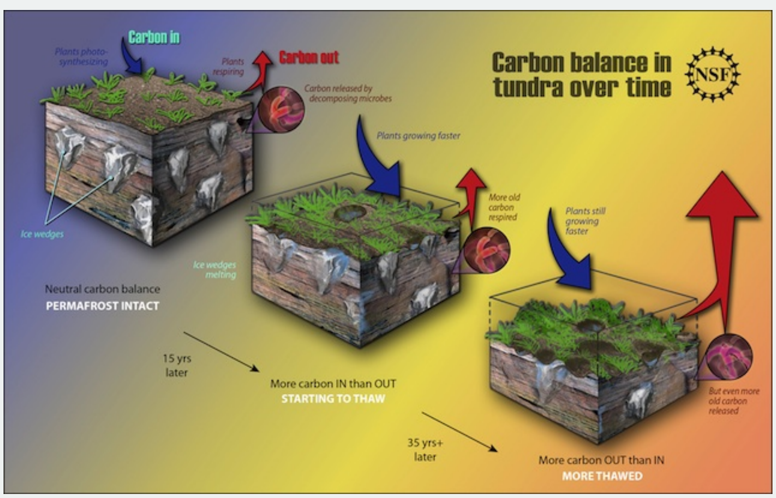


Figure 9.6.2.4: Carbon Balance in the Tundra Over Time (Courtesy Zina Deretsky, National Science Foundation, Source)

Geographic Distribution

The tundra climate is found as a nearly unbroken ribbon of land on the Arctic ocean border lands of North America and Eurasia, and along the margins of Greenland. Though nearly exclusive to the Northern Hemisphere, it can be found on peninsular land of Antarctica.

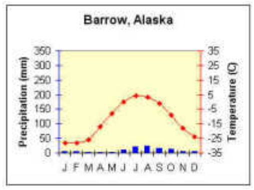


Figure 9.6.2.5: Climograph for Barrow, Alaska

Controlling Factors

The tundra climate is directly tied to its location in high latitudes. Here, the subsidence and divergence of the polar anticyclone is an important control over the climate. The subsidence associated with high pressure decreases the chances for precipitation. Located at such a high latitude creates low temperatures that reduces moisture content of the air. Arctic front cyclones bring moisture bearing winds to the tundra climate.

Figure 9.6.2.6: Aerial view of tundra (Source: NRCS Used with permission)

Temperature

Being a polar or high latitude climate, the tundra is noted for its low temperature. The tundra is basically summer-less, having no monthly temperature averaging above 10^{o}C, and having at least nine months below freezing. These temperatures preclude the growth of trees. Even though temperature ranges are high, they aren't as large as the Subarctic climate to the south. The smaller temperature ranges are due to the moderating influence of the ocean. Diurnal temperature ranges tend to be small because of the uniformly high insolation during the summer and uniformly low insolation during the winter. The seasonal lag in temperature is delayed by a month for the tundra found in eastern North America and western Eurasia due to the influence of the ocean. Here the warmest month is August but it is July for the remaining tundra climate. Similarly the coldest month is also delayed until March for much of coastal western Siberia, though eastern Siberia experiences its coldest temperatures in February.

Precipitation

The very cold temperature creates absolute humidities that are lower than those found in the tropical desert. As a result, precipitation is characteristically light, usually less than 250 mm (10 in) a year. However, eastern and western reaches in North America and Eurasia have nearly double this amount due to the influence of the ocean. For instance, Nome, AK receives 18.4 inches a year while Point Barrow receives only 508 mm (4.3 in). Precipitation is concentrated in the summer months with July receiving the most precipitation for inland stations and August for most coastal stations. Some marine stations in Norway receive most of their precipitation during the winter months of February and March. Coastal locations are susceptible to fogs as maritime air drifts onshore and is chilled to its dew point by the cold land surface.

9.6.3: Ice Cap Climate

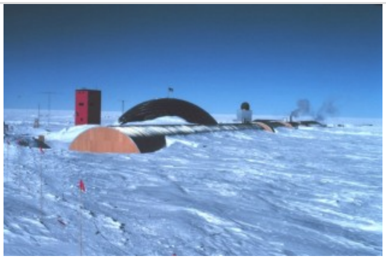


Figure 9.6.3.1: South Pole Station, 1978. (Courtesy NOAA)

The ice cap climate experiences the coldest temperatures on earth. Located near the poles, this climate experiences bitterly cold temperatures throughout the year, especially during the long polar night. The resulting humidity levels are so low that precipitation amounts may be similar to most deserts. In fact, climatologists have described the ice cap climate as a "polar desert".

Geographic Distribution

The ice cap climate is found over the frozen lands of the Arctic and Antarctic. In the Northern Hemisphere, the ice cap climate is found over the interior of Greenland and the permanently frozen portions of the Arctic Ocean and associated islands. In the Southern Hemisphere, the vast glacier covered continent of Antarctica is the largest expanse of ice cap climate.

Controlling Factors

The high latitude location is the primary cause of the extremely cold temperatures and dry conditions. At such a high latitude, sun angle and insolation intensity is low. Additionally, the sun never rises above the horizon during the long months of the "polar night". The sun that does reach the surface is efficiently reflected away by the light colored permanent cover of snow and ice. The ice cap climate is under the year-round influence of the polar high. The high pressure suppresses the needed uplift to cause condensation.

The ice cap climate is located in the source region for the extremely cold and dry cA air masses. The ice cap climate experiences invasions of cP, and to a lesser extent, mP air masses. The low saturation point of the cA and cP air masses substantially reduces the chance for precipitation.

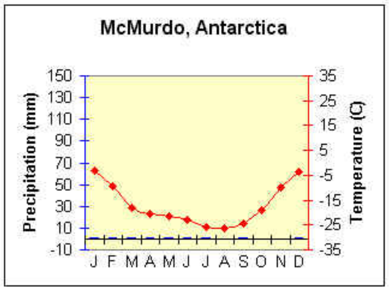


Figure 9.6.3.2: Climograph for McMurdo, Antarctica
Latitude/Longitude = 77°S; 166°E
Average Annual Temperature (°C) = -17.0
Annual Temperature Range (°C) = 23
Total Annual Precipitation (mm) = 7.8
Summer Precipitation (mm) = 3.7
Winter Precipitation (mm) = 4.1

Figure 9.6.3.3: Near McMurdo Station. (Courtesy NOAA)

Temperature

The ice cap climate experiences the coldest temperatures on Earth. In fact, we could say that the ice cap climate is "summer-less", having no average monthly temperature above freezing. McMurdo Station's annual temperature is a bone-chilling -17^{o}C (1.4^{o}F). The ice cap climate receives meager amounts of solar radiation on an annual basis. This coupled with a highly reflective surface means little absorbed insolation. Though the Sun does remain above the horizon for six months of the year, the low sun angle reduces insolation intensity. During the rest of the year the sun never appears above the horizon and temperatures plummet to the coldest experienced on the planet.

Precipitation

The large accumulation of ice makes the ice cap climate's annual precipitation somewhat deceiving. With such a large accumulation of ice, one would expect fairly high annual snowfall. This is not true. The ice cap climate is often described as a "polar desert" because of the meager amount of precipitation it experiences over the course of a year. At McMurdo Station, only 7.8 mm (0.4 in) of precipitation falls. The extremely cold temperature creates very small dew points and hence not much moisture is actually in the air at saturation. The reason there is such a thick cap of ice is that it doesn't melt. The air is also quite stable being dominated by the polar high and cA or cP air masses. It is not uncommon to find low-level inversions which inhibit precipitation.

9.7: Urban Climate

Urbanization has a significant impact on all elements of the atmosphere. Replacing natural vegetation with artificial surfaces alters the heat balance and hydrology of the local environment. Urban canyons affect wind speed and increased particulate content enhances precipitation down wind of a city.

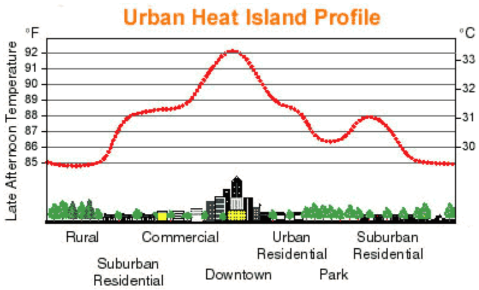


Figure 9.7.1: Urban Heat Island. (Courtesy EPA Source)

The concentration of human activities in urban areas creates an "island" of heat surrounded by a "sea" of cooler rural areas called the **urban heat island**. Heat is added to the urban atmosphere by industry, transportation, exhaust heat, and air conditioning among other things. Artificial surfaces with low albedo absorb much insolation, heating the surface more than if it were a natural surface like grass. The additional heat can create differences in air temperature between the city and countryside of 10ºC (18ºF) or more. Consequently, snow disappears earlier and vegetation bloom earlier in the city. Sunlight is trapped within the "urban canyon" by reflective surfaces. Building materials like brick and asphalt have high heat conductivity. Heat loss in the evening can compensate for that which has been gained during the day.

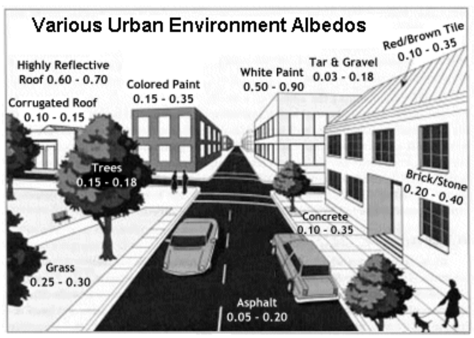


Figure 9.7.2: Typical albedos. (Courtesy NASA (Source))

The warm city surface induces convection that draws urban air upwards, which is then replaced by cool air from the countryside. This rural-urban circulation is more likely to occur when synoptic-scale winds are light. The rising air transports dust and other particulates upward, gathering as a **dust dome**. If synoptic-scale winds are strong enough, the pollutants spill over the city boundary and stretch downwind over the countryside as a **pollution plume**. Particulates concentrated in the urban atmosphere serve as nuclei for the condensation of water. Several studies have shown how precipitation is enhanced downwind of an urban area due to increased particulate content from urban sources.

In rural areas, more available water for evaporation keeps surface temperatures cooler. Impermeable artificial surfaces in the city increase water runoff and reduce infiltration. This results in less moisture available for evaporative cooling and higher sensible transfer than in the surrounding rural areas.

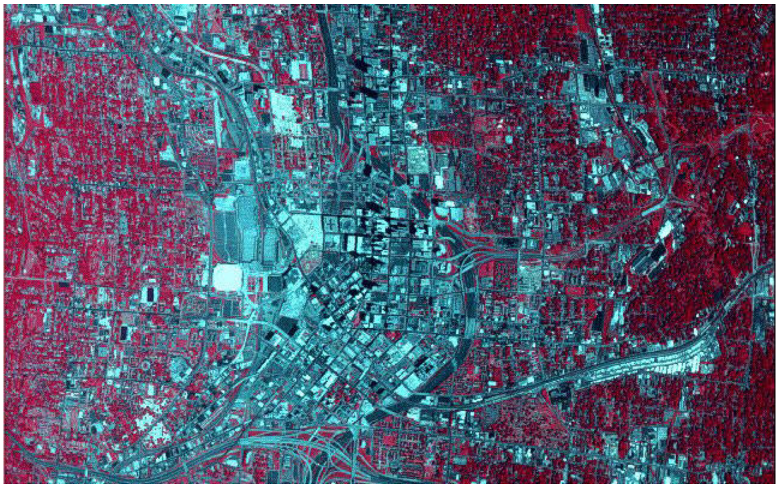


Figure 9.7.3: Atlanta, GA. urban heat island. False-color image, vegetation is red, urban areas blue to black. (Courtesy NASA; Source)

9.8: Future Geographies - The Evidence for Climate Change

It is clear from past research that Earth's climate has varied significantly over time, the causes of which are many and complex. Even over the span of human history, the Earth has undergone significant periods of warming and cooling. Present day global warming however is not, to most scientists, a consequence of natural climate variability. Most recognize that the present change to a warmer climate is a product of human impact on the Earth system.

Video: "Global Warming" (Courtesy of NASA)

Evidence for Global Warming

Though a few scientists remain skeptical, there is a a growing consensus that the present day warming is real and humans are driving it. Evidence for global warming can be found in every part of the Earth system. Besides well documented changes in air temperature, global warming is

- heating the world's oceans
- reducing sea ice extent, especially in the Arctic
- melting glaciers
- causing sea level to rise
- altering habitats and,
- affecting plant and animal distributions

Evidence from the oceans

Global warming has already had a significant impact on the hydrosphere, especially glaciers and oceans. Tide gauge measurements show a worldwide increase of sea level of 15-20 cm (6-8 inches). According to the Intergovernmental Panel on Climate Change (IPCC) suggest the rise is due to the expansion of ocean water due to rising temperatures (contributing about 3 - 7 cm) and the melting of mountain glaciers and small ice caps (contributing about 2 - 4 cm). Sea level is rising so high in locations like the arctic coast of Canada that small villages are threatened.

A 2005 study provided "compelling" evidence that ocean warming over the past 40 years is linked to the industrial release of carbon dioxide. Scientists from Scripps Institution of Oceanography used a variety of scenarios to reproduce the observed rise of ocean temperatures over the last four decades. The rise of ocean temperatures could not be accurately explained by computer models based on the natural climate variability of solar radiation and volcanic emissions. "What absolutely nailed it was greenhouse warming," said Dr Barnett, lead scientist on the study. Their model reproduced the observed ocean temperatures with a statistical confidence of 95%.

Arctic sea ice has experienced a significant decrease in areal extent over the past few decades. Recent NASA research indicates that arctic sea ice is shrinking at a rate of 9.6 percent per decade. September ice coverage between 2000-2005 were 20 percent below the period 1979 - 2000. Such ice thinning and retreat has impacts ocean salinity, heat balance and animal habitat. Polar bear populations are on the decline as ice thins making for precarious hunting conditions. Ice pack break up leaves polar bears stranded further from land. Polar bears are being forced to swim longer distances between ice floes and drowning during the journey.

Video: Arctic Sea Ice, September 1979 to September 2014 (Courtesy NSIDC)

Evidence from glaciers

Evidence for warming is occurring in all parts of the Earth system. Most of the world's glaciers are in retreat as a result of global warming. Evidence for the loss of ice is documented in the journals of the first explorers to Alaska. In the 1790's travelers to the area near Glacier Bay reported only a small embayment of coastline with a large glacier occupying the basin of Glacier Bay. By the 1890's the glacier was in retreat as 40 miles of coastline was now exposed. Today, visitors can still marvel at the great tidewater glaciers, but for how long? Glacier Bay now extends for 60 miles.

Bruce Molinia of the United States Geological Survey has documented the retreat of Alaskan glaciers by comparing present day conditions to photographs taken by geologists and visitors to the region over a century before. The dramatic evidence is seen in photographs of Muir Glacier taken from the same position in 1899 and 2003.

Figure 9.8.1a: Muir Glacier, 1899 (Courtesy USGS)

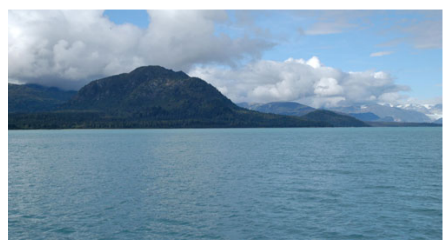


Figure 9.8.1b: Muir Glacier, 2003 (Courtesy USGS)

The BBC's David Shukman reports that scientists have found that the rate of melting on the Greenland ice cap is far greater than what normally occurs during the summer. Sea level is expected to rise by 7 meters should the ice cap melt, drowning coastlines worldwide.

A first ever gravity survey of Antarctica recently revealed that it had lost a substantial amount of mass. Researchers found that the ice sheet covering Antarctica lost 152 (plus or minus 80) cubic kilometers of ice annually between April 2002 and August 2005. The estimated mass loss was enough to raise global sea level about 1.2 millimeters (0.05 inches), about 13 percent of the overall observed sea level rise for the survey period.

Video: Watch James Balog's TED Talks presentation about extreme ice loss due to climate change.

Evidence from plant and animal distributions

Evidence of global warming is appearing in the distribution of plant and animal species. Growing seasons in many parts of the globe have shifted as a result of warmer temperatures. Scientists have observed that plants have been slowly moving toward higher elevations in some mountain regions. This "escalator effect" as it has been called, has pushed some plant species up as much as ten feet (3 meters) in some mountain regions. Because some plant species migrate faster than others, established ecosystems could be severely altered.

Figure 9.8.2: Great Tit (Parus major) (Source: Wikimedia)

Animal species are also responding to habitat changes as a result of global warming. As spring arrives earlier in the year, migrating animals start moving earlier in search of food sources. A recent study of the great tit (Parus major) reported that the birds are laying eggs nearly two weeks earlier than they have over the past fifty years. Doing so enables them to hatch earlier and take advantage of caterpillars which are also appearing two weeks earlier due to warmer spring temperatures.

Geographic Patterns of Global Warming

The effects of global warming will not be the same in all places. The smallest changes in temperature are to occur in tropical regions, while the Arctic and Antarctic will experience considerable changes. The Arctic regions are seen as the "bell weather" of what global warming will bring. [See "The Arctic: Our Global Thermostat" from *Scientific American Frontiers*].

Figure 9.8.3: House damaged by melting permafrost. (Source: Select Committee on Energy Independence and Global Warming)

The arctic is already experiencing the impact of global warming. The melting tundra presents an engineering nightmare to those living in this environment. Coastal erosion of permfrost is destabilizing slopes causing them to fail. Climate scientists fear that the melting permafrost will release millions of tons of stored carbon back into the atmosphere further fueling global warming.

For detailed information on geographic patterns of global warming, see the "Future Geographies ..." sections at the end of each chapter.

9.9: Review and Additional Resources

Review

The Creosote Bush is common in North America's hot deserts. Courtesy USGS

Figure 9.9.1:

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **Climatology**
  the study of the long-term state of the atmosphere, or climate
- **climate**
  the long-term state of the atmosphere
- **climate classification**
  ways to organize the wealth of information about Earth's climate to bring order and understanding to it
- **empirical classification**
  classification systems based on observable facts such as temperature and precipitation.
- **genetic classification**
  classification systems based on the cause of the climate like solar radiation, air masses, pressure systems, etc.
- **applied classification**
  classification systems created for a particular climate-associated problem
- **Koeppen Climate Classification**
  an empirical system largely based on annual and monthly means of temperature and precipitation
- **Tropical rain forest Climate**
  supports one of the most lush and diverse environments on Earth. Located near the equator, it is characterized by year-round warm temperatures and copious rainfall
- **Monsoon Climate**
  abundant rainfall concentrated in the high-sun season, located near the equator with warm temperatures throughout the year
- **Wet/Dry Tropical Climate**
  it supports a ground cover of drought resistant grasses with scattered trees, but not enough rainfall to make agriculture a viable, life sustaining activity.

- **Tropical Steppe Climate**
  transitional climate between the tropical wet and tropical dry climates
- **Tropical Desert Climate**
  an environment of extremes: it is the driest and hottest place on earth. Rainfall is sporadic and in some years no measurable precipitation falls at all.
- **Dry Summer Subtropical Climate**
  also known as the "Mediterranean" climate, wet winter/dry summer seasonality
- **Humid Subtropical Climate**
  found on the east coast of continents, instable air with moderate amounts of precipitation in most months of the year and subject to cold temperatures during the winter
- **Humid Continental Climate**
  noted for its variable weather patterns related to cyclonic storms and its large temperature range due to its interior location in mid-latitude continents
- **Midlatitude Steppe Climate**
  shares many of the same characteristics that the tropical steppe has. Both are semi-arid climates that are affected by their interior continental or leeward orographic position. However, the midlatitude steppe experiences larger temperature ranges and receives more total rainfall than the tropical steppe climate.
- **Midlatitude Desert Climate**
  shares many of the same climatic characteristics as the tropical deserts, and for many of the same reasons. While the tropical desert climates are considered "hot" deserts following Köppen's classification (BWh), midlatitude deserts are "cold" deserts
- **Humid (Marine) West Coast Climate**
  found on the west coast of midlatitude continents and is very humid through most of the year. Its geographic location places it in the path of westerly winds from the ocean that bring cloudy skies, much precipitation, and mild temperatures.
- **Subarctic Climate**
  Bitterly cold winters and mild summers result in the largest annual temperature range of any climate on Earth.
- **Tundra Climate**
  transitional climate between the Subarctic and Ice cap climates. It is a region of rolling to nearly level terrain almost entirely devoid of trees. Polar climates like the tundra are characterized by very cold temperatures and generally dry conditions. Temperatures never rise above 10^o C (50^oF) during the summer.
- **Ice Cap Climate**
  experiences the coldest temperatures on earth. Located near the poles, this climate experiences bitterly cold temperatures throughout the year, especially during the long polar night. The resulting humidity levels are so low that precipitation amounts may be similar to most deserts.

? Review Questions 9.9.1

Compare and Contrast the seasonality of precipitation that falls in the Dry Summer Subtropical climate and the Humid Subtropical climate.

Answer

The dry summer subtropical climate has a dry summer due to the influence of the subtropical high and a wet winter due to midlatitude cyclones embedded in the westerlies. The humid subtropical climate has ample precipitation in all months, decreasing toward the interior of the continent.

Describe how the seasonality of precipitation (generally) varies as one travels from the Equator to the Mediterranean Sea in Africa.

Answer

Along the equator, climates receive much rain fall in each month of the year. The precipitation is relatively evenly distributed between high and low sun seasons. As one moves poleward, annual precipitation decreases and becomes seasonal, falling mostly in the high sun season (ITCZ dominates). Precipitation decreases to a minimum in the Sahara desert where the subtropical high dominates. Precipitation becomes seasonal falling mostly in the low sun season as one proceeds to the Mediterranean Sea (Dry Summer Subtropical climate).

How does the geographical distribution of the Marine West Coast climate in North America differ from that in Europe. What is largely responsible for the difference?

Answer

The marine west coast in North America is confined to a narrow belt along the west coast of the continent by north-south oriented mountains. The orientation presents a barrier to westerly maritime winds, forcing them to rise inducing precipitation. Mountains in Europe tend to be east-west oriented, presenting less of a barrier to westerly wind, thus extending the marine west coast climate further into the continent.

In general, why does the arctic tundra climate have a smaller temperature range than the subarctic climate.

Answer

The arctic tundra is generally bordered by an ocean which moderates the annual temperature variation. The interior location of the subarctic climate results in a larger temperature range even at a lower latitude.

Which climate has the smallest annual temperature range and why?

Answer

The tropical rain forest climate has the smallest annual temperature range. Located near the equator means the sun is always high in the sky during the year. Little variation in sun angle results in small annual temperature range.

Which climates are significantly influenced by mountain systems?

Answer

The moist climate of the marine west coast climate in North America is due to orographic uplift of marine air masses along windward slopes. The dry conditions of many deserts and steppes result from their leeward location in the rain shadow of the mountains.

What is continentality and what affect does it have on the climate of a place?

Answer

Continentality is the effect of continental location on weather and climate. Places located in the interior of a continent tend to have lower humidity, less precipitation, and a larger annual temperature range than coastal locations (exceptions do occur!)

Which climates are significantly influenced by cold ocean currents?

Answer

The dry summer subtropical climate, especially in North America is influenced by a cold ocean current. The coastal portion of the humid subtropical climate is affected by a warm ocean current. The marine west coast climate of Europe is mild due to the influence of the warm North Atlantic Current.

Why do physical geographers sometimes refer to the Ice cap climate as a "polar desert"?

Answer

The air is extremely cold and thus has a very low saturation point resulting in meager precipitation.

When does the Wet/Dry tropical (Savanna) climate experience its highest temperatures and highest rainfall?

Answer

Highest temperatures are generally prior to the wet season. Most rain falls during the high sun season.

How do the position of the ITCZ and Subtropical Highs affect the climate of the tropics?

Answer

The uplift of air by convection and convergence in the ITCZ promotes precipitation while the subsidence of air associated with the subtropical high suppresses precipitation.

? Self-Assessment Quiz 9.9.1

1. The largest temperature range is found in the
   A. Subarctic climate
   B. Ice cap climate
   C. Tundra Climate
   D. none of the above
2. Which of the following climates is dominated by mTu through much of the year?
   A. Humid subtropical
   B. Humid continental
   C. Dry summer subtropical
   D. Tropical steppe
3. If location's annual potential evapotranspiration is greater than half the annual precipitation you would classify the climate as a
   A. dry summer subtropical
   B. tropical desert
   C. tropical steppe
   D. tropical monsoon
4. Desert climates
   A. are typically found in rain shadow locations
   B. dominated by high pressure
   C. have large daily temperature ranges
   D. all the above
5. The highest monthly temperature occurs ______ in the tropical monsoon climate.
   A. just before the wet season
   B. just after the wet season
   C. during the low sun season
   D. none of the above
6. The polar front dominates the _____ climate during most of the year.
   A. dry summer subtropical
   B. humid continental
   C. humid subtropical
   D. tundra

7. Which of the following climates lacks seasonal precipitation?
   A. Tropical rain forest
   B. Monsoon
   C. Tropical Wet/Dry
   D. Tropical Steppe
8. The precipitation that falls in the marine west coast climate of North America is primarily caused by
   A. convection
   B. cyclones and orographic uplift
   C. convection and orographic uplift
   D. convection and cyclones
9. Which climate borders the Mediterranean Sea?
   A. Humid Continental
   B. Humid Subtropical
   C. Tropical Monsoon
   D. Dry Summer Subtropical
10. The precipitation along the equatorward margins of the humid subtropical climate
   A. tends to be evenly distributed throughout the year
   B. tends to fall mostly in the summer
   C. tends to fall mostly in the winter
   D. none of the above

Answer

1. A
2. A
3. B
4. D
5. A
6. B
7. A
8. B
9. D
10. A

Additional Resources

Use these resources to further explore the world of geography

Multimedia

"The Climate System" (*Met Office*)

"USGS Public Lecture Series: Climate Change 101 (August 2009)

Climate Connections: NPR series on global warming

"Polar Warming" (PBS) *News Hour with Jim Lehrer*. November 11, 2004 report on the impact of global climate change on the Arctic.

Climate Change Series - (WGBH Forum Network). Six part series includes topics of global climate change and the Arctic, The Southern Ocean, The Media, Ask the Experts, Northern Forests, The Ross Ice Shelf

"Global Warming" (NPR) *All things Considered* Sept 11, 2003 segment about puzzling climate change data that suggests "global warming isn't following the rules". (5:07)

"Climate Change" (NPR) May 2004 three-part series on climate change issues facing New York City.

"What's Happening to Alaska's Glaciers? Their Dynamic Response to Changing Climate and Other Factors" Dr. Bruce Molina (USGS) Descriptive Flyer pdf.

Visualization

- Interactive Climate Map - M. Ritter
- Global Warming: Early Warning Signs

Readings

- Paleoclimatology: An Introduction (NASA EOS)
- Global Warming and Global Climate Change (Carnegie Mellon University)
- Climate Clues in the Ice (NASA EOS)
- The Warming of the Earth: A beginner's guide to global warming. (Woods Hole Research Center)

Web Sites

- National Climatic Data Center
- World Climate Data Centers

CHAPTER OVERVIEW

10: The Hydrosphere

Figure 10.1: A rain shaft pierces a tropical sunset as seen from Man-of-War Bay, Tobago, Caribbean Sea . Most of the water evaporated from the ocean is directly returned by precipitation. (Courtesy NOAA)

Water is a critical element that sustains life and drives a variety of environmental processes acting within the Earth system. Though the hydrosphere includes all the water in the earth system, water flows between all the other subsystems of the Earth. In this chapter we'll explore how water is cycled through and its impact on the Earth system.

Learning Objectives

By the end of the chapter you should be able to:

- List the major "stores" of water in the Earth system.
- Construct a simple diagram of the hydrologic cycle and describe each of the element.
- Describe the nature of subsurface water.
- Describe the nature of surface water.
- Draw and label a diagram that illustrates the conditions that create aquifers and springs.
- Draw and label the elements of a stream hydrograph.
- Construct a diagram of, and calculate a soil water budget

10.1: The Hydrosphere
10.2: The Hydrologic Cycle
10.3: The Water Balance
10.3.1: Computing a Soil - Moisture Budget
10.3.2: Soil Moisture Seasons
10.4: Future Geographies - Water Resources and Climate Change
10.5: Review and Additional Resources

10.1: The Hydrosphere

The **hydrosphere** is often called the "water sphere" as it includes all the earth's water found in the oceans, glaciers, streams, lakes, the soil, groundwater, and in the air. The hydrosphere interacts with, and is influenced by, all the other earth spheres. The water of the hydrosphere is distributed among several different stores found in the other spheres. Water is held in oceans, lakes and streams at the surface of the earth. Water is found in vapor, liquid and solid states in the atmosphere. The biosphere serves as an interface between the spheres enabling water to move between the hydrosphere, lithosphere and atmosphere as is accomplished by plant transpiration. The hydrologic cycle traces the movement of water and energy between these various stores and spheres.

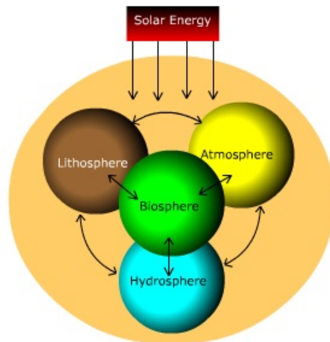


Figure 10.1.1: Earth Spheres/Systems

The **cryosphere** is the part of Earth's hydrosphere comprised of frozen water. It plays a integral role in the global climate system through its influence on surface energy budgets, atmospheric moisture, hydrology, and atmospheric and oceanic circulation. The cyrosphere is a sensitive element of the climate system providing a key indicator of climate change. The increasing loss of Arctic sea ice and breakup of Antarctic ice shelves are two harbingers of changes to the future physical geography of Earth.

Video: Tour of the Cryosphere (Courtesy NASA)

Distribution of water

The world's oceans contain 97% of the water in the hydrosphere, most of which is salt water. Ice caps, like that found covering Antarctica, and glaciers that occupy high alpine locations, compose a little more than 2% of all water found on earth. Seemingly a small amount, the water stored as ice in glaciers would have a great impact on the environment if it were to melt into a liquid. . Rising sea levels from melting ice sheets and glaciers due to global warming could devastate coastal cities, displace millions of people, and wreak havoc on freshwater systems and habitats.

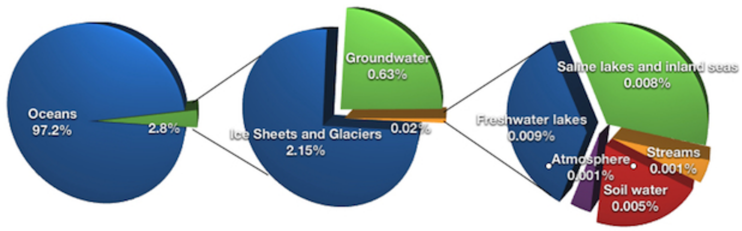


Figure 10.1.2: Various stores of water in the hydrosphere

Water beneath the surface comprises the next largest store. Groundwater and soil water make up about .63% and 0.005% of all water (by volume). **Soil water** is the water held in pore spaces between soil particles. Soil pore spaces usually are partially void of water most of the time but fill with water after a rain storm. **Groundwater** is found where earth materials are saturated throughout the year. That is, the pore spaces are always occupied with water. Both soil and groundwater are very important sources of water. Soil water is available for plants to extract and use. Groundwater is an important source of water for irrigation and drinking water supplies.

Above the surface water is found stored in streams, rivers and lakes. One might expect that given the large rivers that flow across the earth and the huge numbers of lakes that this store would be rather large. Instead, freshwater streams, rivers and lakes, and saline lakes and inlands seas comprise just under .03% of all water in the earth system. In the atmosphere, only about .0001 % of the water in the hydrosphere is found.

10.2: The Hydrologic Cycle

The ***hydrologic cycle***, or water cycle, is the cycling of water through the earth system. Not only is the hydrologic cycle a cycle of water, it is a cycle of energy as well. Over the next several pages we'll trace water as it passes through the earth system and the energy that accompanies it.

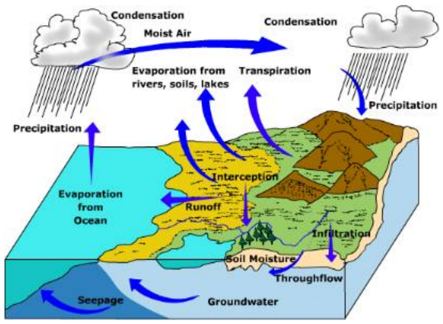


Figure 10.2.1: The Hydrologic cycle

Evaporation and Condensation

Evaporation is the phase change of liquid water into a vapor (gas). Evaporation is an important means of transferring energy between the surface and the air above. The energy used to evaporate water is called "latent energy". ***Latent energy*** is "locked up" in the water molecule when water undergoes the phase change from a liquid to a gas. Eighty-eight percent of all water entering the atmosphere originates from the ocean between 60º north and 60º south latitude. Most of the water evaporated from the ocean returns directly back to the ocean. Some water is transported over land before it is precipitated out. When water vapor condenses back into a liquid it releases latent heat, which is converted into sensible heat warming the surrounding air. The warming of the surrounding air fuels uplift to help promote adiabatic cooling and further condensation. As droplets of water coalesce into larger droplets they attain a size big enough to fall towards the earth as precipitation. Located high in the troposphere, rain drops possess a high degree of potential energy that is converted into kinetic energy once they begin to fall toward the surface. Impacting the surface they convert this kinetic energy into work done on the surface (erosion for example).

Interception and Infiltration

As water reaches the surface in various forms of precipitation, it is intercepted by plants or falls directly to the surface. Precipitation that collects on the leaves or stems of plants is known as ***interception***. The amount of water intercepted by a plant largely depends on plant form. Water is held on the leaf surface until it either drips off as ***through fall*** or trickles down the leaf stem finally reaching the ground as ***stem flow***. Interception of falling rain buffers the surface against erosion. Coniferous trees tend to intercept more water than deciduous trees on an annual basis because deciduous trees drop their leaves for a period of time.

Figure 10.2.2: Droplets of water intercepted by tree leaf. (Source: M. Marzot FAO. Used with permission)

Upon reaching the ground, some water infiltrates into the soil, possibly percolating down to the groundwater zone or it may run across the surface as ***runoff***. ***Infiltration*** refers to water that penetrates into the surface of soil. Infiltration is controlled by soil texture, soil structure, vegetation and soil moisture status. High infiltration rates occur in dry soils, with infiltration slowing as the soil becomes wet. Coarse textured soils with large well-connected pore spaces tend to have higher infiltration rates than fine textured soils. However, coarse textured soils fill more quickly than fine textured soils due to a smaller amount of total pore space in a unit volume of soil. Runoff is generated quicker than one might have with a finer textured soil.

Vegetation also affects infiltration. For instance, infiltration is higher for soils under forest vegetation than bare soils. Tree roots loosen and provide conduits through which water can enter the soil. Foliage and surface litter reduce the impact of falling rain keeping soil passages from becoming sealed.

Subsurface water

Groundwater and soil water together comprise approximately .5% of all water in the hydrosphere. Water beneath the surface can essentially be divided into two zones (Figure 10.2.3), the unsaturated zone (also known as the "zone of aeration") which includes soil water zone, and zone of saturation which includes ground water. Air and water occupies the pore spaces between earth materials in the zone of aeration. Sometimes, especially during times of high rainfall, these pore spaces are filled with water. The water table divides the zone of aeration from the zone of saturation. The height of the water table will fluctuate with precipitation, increasing in elevation during wet periods and decreasing during dry. Note how the water table intersects the level of the stream surface in Figure 10.2.3. Seepage of groundwater into a stream provides a base flow of water for perennial streams.

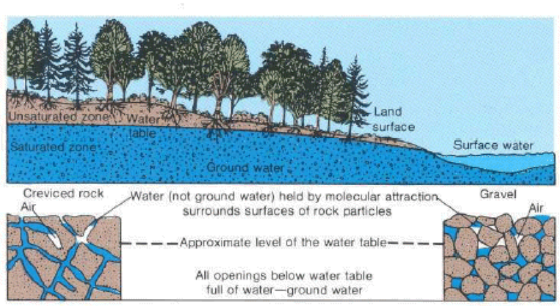


Figure 10.2.3: Zones of water beneath the surface (Courtesy USGS; Source)

Soil Water

Soil water is held in the pore spaces between particles of soil. Soil water is the water that is immediately available to plants. Soil water can be further sub-divided into three categories, 1) hygroscopic water, 2) capillary water, and 3) gravitational water. ***Hygroscopic water*** is found as a microscopic film of water surrounding soil particles. This water is tightly bound to a soil particle by molecular attraction so powerful that it cannot be removed by natural forces. Hygroscopic water is bound to soil particles by adhesive forces that exceed 31 bars and may be as great as 10,000 bars (Recall that sea level pressure is equal to 1013.2 millibars which is just about 1 bar!). ***Capillary water*** is held by cohesive forces between the films of hygroscopic water. The binding pressure for capillary water is much less than hygroscopic water. This water can be removed by air drying or by plant absorption, but cannot be removed by gravity. Plants extract this water through their roots until the soil capillary force (force holding water to the particle) is equal to the extractive force of the plant root. At this point the plant cannot pull water from the plant-rooting zone and it wilts (called the ***wilting point***). ***Gravity water*** is water moved through the soil by the force of gravity. The amount of water held in the soil after excess water has drained is called the ***field capacity*** of the soil. The amount of water in the soil is controlled by the soil texture. Soils dominated by clay-sized particles have more total pore space in a unit volume than soils dominated by sand. As a result, fine grained soils have higher field capacities than coarse-grained soils.

Representative Porosity Ranges for Sedimentary Materials

Material	% Porosity
Soils	50 - 60
Clay	45 - 55
Silt	40 - 50
Uniform Sand	30 - 40
Gravel	30 - 40
Sandstone	10 - 20
Shale	1 - 10

Figure 10.2.4: Representative Porosity Ranges for Sedimentary Materials

The diagram below shows the relationship between soil texture, wilting point, field capacity, and available water. The difference between the wilting point and the field capacity is the ***available water***.

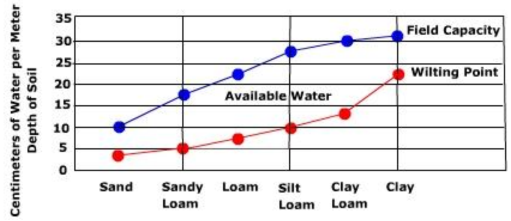


Figure 10.2.5: Relationship Between Available Water and Soil Texture

Note that the smallest amount of available water is associated with the coarsest soil texture, sand. The amount of available water increases toward the center of the graph where soils with a mixture of different sized particles (loamy soils) are found. The available water then drops off toward the fine textured soils on the right. How does one explain the relationship between available water and soil texture? Coarse soil does not have much available water because it doesn't hold much water to begin with. At the other end of the spectrum, low available water in fine soils is due to strong bond between soil particles and water. Plants have a harder time pulling water away from the soil particle under these conditions.

Groundwater

Groundwater occupies the zone of saturation. As depicted in the hydrologic cycle diagram, ground water moves downward through the soil by ***percolation*** and then toward a stream channel or large body of water as ***seepage***. The water table separates the zone of saturation from the zone of aeration. The water table fluctuates with moisture conditions, during wet times the water table will rise as more pore spaces are occupied with water. Groundwater is found in ***aquifers***, bodies of earth material that have the ability to hold and transmit water. Aquifers can be either unconfined or confined. Unconfined (open) aquifers are "connected" to the surface above. Confined (closed) aquifers are sandwiched in between dense impermeable layers of earth material called an ***aquiclude***. Ground water is replenished by percolation of water from the zone of aeration downward to the zone of saturation, or in the recharge zone of a confined aquifer. The recharge zone is where the confined aquifer is exposed at the surface and water can enter it.

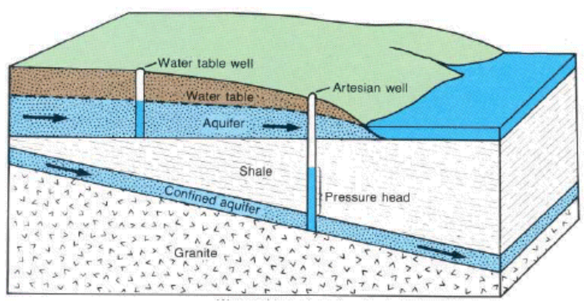


Figure 10.2.6: Unconfined and confined aquifers. (Courtesy USGS; Source)

Aquifers replenish their supply of water very slowly. The rate of groundwater flow depends on the permeability of the aquifer and the hydraulic gradient. Permeability is affected by the size and connectivity of pore spaces. Larger, better connected pore spaces creates highly permeable earth material. The ***hydraulic gradient*** is the difference in elevation between two points on the water table divided by the horizontal distance between them. The rate of ground water flow is expressed by the equation:

Ground water flow rate = permeability X hydraulic gradient

Groundwater flow rates are usually quite slow. Average ground water flow rate of 15 m per day is common. Highly permeable materials like gravels can have flow velocities of 125 m per day.

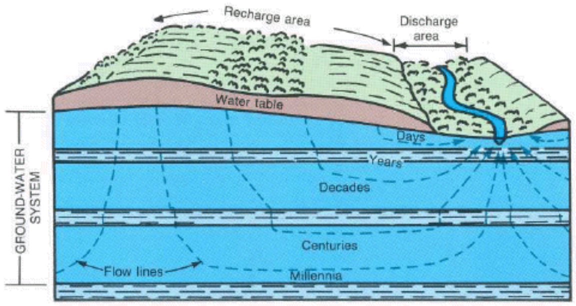


Figure 10.2.7: Ground water movement (Courtesy USGS; Source)

Groundwater in an aquifer is under pressure called *hydrostatic pressure*. Hydrostatic pressure in a confined aquifer pushes water upward when a well is drilled into the aquifer. The height to which the water rises is called the *peizometeric surface*. If the hydrostatic pressure is great enough to push the peizometeric surface above the elevation of the surface, water readily flows out as an *artesian well*.

Figure 10.2.8: Pivot irrigation on a barley field in Saudi Arabia. The barley is used as fodder for milk cows. (Source: F. Mattioli, FAO Used with permission)

Groundwater and Human Activities

Groundwater is an important source of water for human activities such as agriculture and domestic drinking water. In 2000, 68% of fresh ground water was used for irrigation while another 19% was extracted for public-supply purposes, mostly drinking water. For those who supply their own water for domestic use, over 98 percent is from ground water.

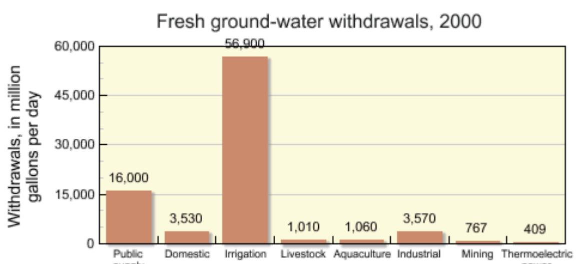


Figure 10.2.9: United States groundwater withdrawals (2000) (Courtesy USGs)

In dry regions and in places where soils are highly permeable, agriculture uses large amounts of ground water for irrigation. The high rate of water use for agriculture has fueled tensions between urban and rural interests. A Dec. 4, 1998 "Talk of the Nation - Science Friday" segment, "San Antonio: Water Rights", discusses the competing demands of urban and rural populations using the Edwards Aquifer in south Texas.

Figure 10.2.10: Outcrop of the Ogallala (sandstone) Formation, the main water-bearing unit of the High Plains aquifer, near the Canadian River in Texas. (Courtesy USGS.)

However, the rate of groundwater removal by humans sometimes exceeds the recharge of the aquifer. Such is the case of the High Plains Aquifer of Arizona, Colorado, New Mexico, and Utah. Over pumping of ground water reserves can lead to compaction and degradation of the aquifer. As the water is removed, the aquifer often collapses causing the surface to subside. Aquifer compaction reduces pore space, making recharge more difficult. One of the most striking examples is that which has occurs in the San Joaquin Valley of California. An August 6, 2013 NPR *All Things Considered* segment An NPR Morning Edition segment from July 2, 2013 "Wells Are Running Dry in Parts of Kansas" describes the plight of farmers and ranchers in Kansas where groundwater supplies are getting scarce.

Figure 10.2.11: Land subsidence in California. Joe Poland, USGS scientist shows subsidence from 1925 and 1977 10 miles southwest of Mendota, CA. Sign reads "San Joaquin Valley California, BM S661, Subsidence 9M, 1925-1977" (From USGS Professional Paper 1401-A, "Ground water in the Central Valley, California- A summary report"; Photo by Dick Ireland, USGS, 1977)

Surface Water

Once precipitation reaches the surface, water can infiltrate into the soil or move across the surface as **runoff**. Surface runoff generally occurs when the rainfall intensity exceeds the rate of infiltration, or if the soil is at its water holding capacity. Infiltration and water holding capacity are both a function of soil texture and structure. Soil composed of a high percentage of sand allows water to infiltrate through it quite rapidly because it has large, well-connected pore spaces. Soils dominated by clay have low infiltration rates due to their smaller sized pore spaces. However, there's actually less total pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and commonly generate runoff sooner than clay soils.

Figure 10.2.12: Meandering stream (Source: Geological Survey of Canada Used with Permission)

If the rainfall intensity exceeds the infiltration capacity of the soil, or if the soil has reached its field capacity, surface runoff occurs. Water runs across the surface as either confined or unconfined flow. ***Unconfined flow*** moves across the surface in broad sheets of water often creating sheet erosion. ***Confined flow*** refers to water confined to channels. Stream flow is a form of confined flow.

Water that runs along the surface may become trapped in depressions and held as ***depression storage.*** Here water may either evaporate back into the air, infiltrate into the ground or, spill out of the depression as it fills.

Stream flow is measured in a variety of ways, one of which is stream discharge. ***Stream discharge*** is the volume of water passing through a particular cross-section of a stream in a unit of time. Stream discharge is measure in cubic feet per second or cubic meters per second. The "normal" or base flow a stream is provided by seepage of groundwater into the stream channel. This seepage is what keeps perennial flowing streams going all year. When precipitation from a storm occurs, the stream discharge increases as water is added to the stream, either from direct precipitation into the channel or runoff.

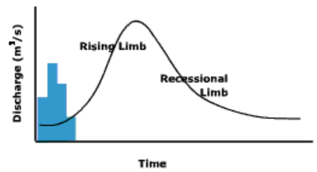


Figure 10.2.13: A stream hydrograph

A ***stream hydrograph*** (right) illustrates the relationship between discharge and runoff. The blue bar graph is precipitation and the line graph represents discharge. As time passes (measured along the x-axis) discharge increases as precipitation falls. Notice that the time of peak precipitation occurs before peak discharge. This is because it takes time for the water to flow across the surface and enter the stream.

The size, shape, land use, vegetation, and geology of the watershed all determine runoff and the shape of the discharge graph.

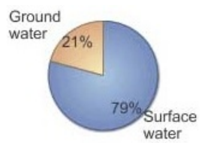


Figure 10.2.14: Total United States Water Withdrawals, 2000 (Courtesy USGS)

Surface water is an important source of water supplies, especially in the southwestern United States. Ever increasing population and development is straining regional water resources. As the Colorado River winds its way through the desert it loses half its flow to evaporation and the rest to irrigation and municipal water supplies. Recent drought and warmer temperatures predicted in the future will put a greater demand on this precious commodity. The lower course rarely reaches the Gulf of California as it did in times past. Now this once might river usually ends as a small stream or dry channel.

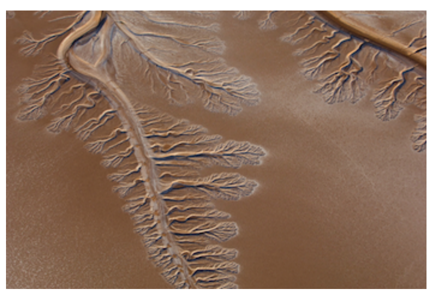


Figure 10.2.15: The now-dry Colorado River delta lies in the Baja/Sonoran Desert 5 miles north of the Sea of Cortex, Mexico (Courtesy USGS)

Some feel that we have reached maximum extraction rate for oil. In other words, we have reaches "peak" in our ability to extract oil and the rate of production will continue to decline. Can the same be said for our use of water? View the video below to explore the answer to this question.

10.3: The Water Balance

The water balance is an accounting of the inputs and outputs of water. The water balance of a place, whether it be an agricultural field, watershed, or continent, can be determined by calculating the input, output, and storage changes of water at the Earth's surface. The major input of water is from precipitation and output is evapotranspiration. The geographer C. W. Thornthwaite (1899-1963) pioneered the water balance approach to water resource analysis. He and his team used the water-balance methodology to assess water needs for irrigation and other water-related issues.

The Water Balance

To understand water-balance concept, we need to start with its various components:

Precipitation (P). Precipitation in the form of rain, snow, sleet, hail, etc. makes up the primarily supply of water to the surface. In some very dry locations, water can be supplied by dew and fog.

Actual evapotranspiration (AE). ***Evaporation*** is the phase change from a liquid to a gas releasing water from a wet surface into the air above. Similarly, ***transpiration*** is represents a phase change when water is released into the air by plants. ***Evapotranspiration*** is the combined transfer of water into the air by evaporation and transpiration. *Actual evapotranspiration* is the amount of water delivered to the air from these two processes. Actual evapotranspiration is an output of water that is dependent on moisture availability, temperature and humidity. Think of actual evapotranspiration as "water use", that is, water that is actually evaporating and transpiring given the environmental conditions of a place. Actual evapotranspiration increases as temperature increases, so long as there is water to evaporate and for plants to transpire. The amount of evapotranspiration also depends on how much water is available, which depends on the field capacity of soils. In other words, if there is no water, no evaporation or transpiration can occur.

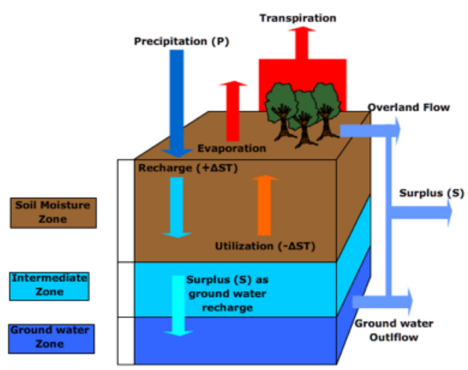


Figure 10.3.1: The soil water balance (After Strahler & Strahler, 2006)

Potential evapotranspiration (PE). The environmental conditions at a place creates a demand for water. Especially in the case for plants, as as energy input increases, so does the demand for water to maintain life processes. If this demand is not met, serious consequences can occur. If the demand for water far exceeds that which is actual present, dry soil moisture conditions prevail. Natural ecosystems have adapted to the demands placed on water.

Potential evapotranspiration is the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water. Think of potential evapotranspiration of "water need". In other words, it would be the water needed for evaporation and transpiration given the local environmental conditions. One of the most important factors that determines water demand is solar radiation. As energy input increases the demand for water, especially from plants increases. Regardless if there is, or isn't, any water in the soil, a plant still demands water. If it doesn't have access to water, the plant will likely wither and die.

Soil Moisture Storage (ST). Soil moisture storage refers to the amount of water held in the soil at any particular time. The amount of water in the soil depends soil properties like soil texture and organic matter content. The maximum amount of water the soil can hold is called the ***field capacity***. Fine grain soils have larger field capacities than coarse grain (sandy) soils. Thus, more water is available for actual evapotranspiration from fine soils than coarse soils. The upper limit of soil moisture storage is the field capacity, the lower limit is 0 when the soil has dried out.

Change in Soil Moisture Storage (ΔST). The change in soil moisture storage is the amount of water that is being added to or removed from what is stored. The change in soil moisture storage falls between 0 and the field capacity.

Deficit (D) A soil moisture deficit occurs when the demand for water exceeds that which is actually available . In other words, deficits occur when potential evapotranspiration exceeds actual evapotranspiration (PE>AE). Recalling that PE is water demand and AE is actual water use (which depends on how much water is really available), if we demand more than we have available we will experience a deficit. But, *deficits only occur when the soil is completely dried out*. That is, soil moisture storage (ST) must be 0. By knowing the amount of deficit, one can determine how much water is needed from irrigation sources.

Surplus (S) Surplus water occurs when P exceeds PE and the soil is at its field capacity (saturated). That is, we have more water than we actually need to use given the environmental conditions at a place. The surplus water cannot be added to the soil because the soil is at its field capacity so it runs off the surface. Surplus runoff often ends up in nearby streams causing stream discharge to increase. A knowledge of surplus runoff can help forecast potential flooding of nearby streams.

10.3.1: Computing a Soil - Moisture Budget

10.3.2: Soil Moisture Seasons

10.3.1: Computing a Soil - Moisture Budget

The best way to understand how the water balance works is to actually calculate a soil water budget. We'll use Rockford, Illinois which is located in the humid continental climate of northern Illinois. Rockford lies on the northern edge of the prairie and mixes with deciduous forest. This vegetation has been nearly completely replaced with agriculture. A knowledge of soil moisture status is important to the agricultural economy of this region that produces mostly corn and soy beans.

To work through the budget, we'll take each month (column) one at a time. It's important to work column by column as we're assessing the moisture status in a given month and one month's value may be determined by what happened in the previous month.

Table 10.3.1.1: Water Budget - Rockford, IL Field Capacity = 90 mm

	J	F	M	A	M	J	J	A	S	O	N	D	Year
P	50	49	66	78	100	106	88	84	86	73	56	45	881
PE	0	0	5	40	84	123	145	126	85	44	8	0	531
P-PE	50	49	61	38	16	-17	-57	-42	1	29	48	45	
ΔST	0	0	0	0	0	17	57	16	1	29	48	12	
ST	90	90	90	90	90	73	16	0	1	30	78	90	
AE	0	0	5	40	84	123	145	100	85	44	8	0	634
D	0	0	0	0	0	0	0	26	0	0	0	0	26
S	50	49	61	38	16	0	0	0	0	0	0	33	258

Soil Moisture Recharge

We'll start the budget process at the end of the dry season when precipitation begins to replenish the soil moisture, called ***soil moisture recharge***, in September. At the beginning of the month the soil is considered dry as the storage in August is equal to zero. During September, 86 mm of water falls on the surface as precipitation. Potential evapotranspiration requires 85 mm. Precipitation therefore satisfies the need for water with one millimeter of water left over (P-PE=1). The excess one millimeter of water is put into storage (ΔST=1) bringing the amount in storage to one millimeter (August ST =0 so 0 plus the one millimeter in September equals one millimeter). Actual evapotranspiration is equal to potential evapotranspiration as September is a wet month (P>PE). There is no deficit during this month as the soil now has some water in it and no surplus as it has not reached its water holding capacity.

During the month of October, precipitation far exceeds potential evapotranspiration (P-PE=29). All of the excess water is added to the existing soil moisture (ST (September) + 29 mm = 30 mm). Being a wet month, AE is again equal to PE.

Calculating the budget for November is very similar to that of September and October. The difference between P and PE is all allocated to storage (ST now equal to 78 mm) and AE is equal to PE.

Soil Moisture Surplus

During December, Rockford is deep in the grip of winter. Potential evapotranspiration has dropped to zero as plants have gone into a dormant period thus reducing their need for water and cold temperatures inhibit evaporation. Notice that P-PE is equal to 45 but not all is placed into storage. Why? At the end of November the soil is within 12 mm of being at its field capacity. Therefore, only 12 millimeters of the 45 available is put in the soil and the remainder runs off as surplus (S=33).

Given that the soil has reached its field capacity in December, any excess water that falls on the surface in January will likely generate surplus runoff. According to the water budget table this is indeed true. Note that P-PE is 50 mm and ΔST is 0 mm. What this indicates is that we cannot change the amount in storage as the soil is at its capacity to hold water. As a result the amount is storage (ST) remains at 90 mm. Being a wet month (P>PE) actual evapotranspiration is equal to potential evapotranspiration. Note that all excess water (P-PE) shows up as surplus (S=50 mm).

Similar conditions occur for the months of February, March, April, and May. These are all wet months and the soil remains at its field capacity so all excess water becomes surplus. Note too that the values of PE are increasing through these months. This indicates that plants are springing to life and transpiring water. Evaporation is also increasing as insolation and air temperatures are increasing. Notice how the difference between precipitation and potential evapotranspiration decreases through these months. As the demand on water increases, precipitation is having a harder time satisfying it. As a result, there is a smaller amount of surplus water for the month.

Surplus runoff can increase stream discharge to the point where flooding occurs. The flood duration period lasts from December to May (6 months), with the most intense flooding is likely to occur in March when surplus is the highest (61 mm).

Self Assessment 10.3.1.1

If the field capacity of this soil was larger, will the monthly surplus be larger or smaller than it is under its present field capacity?

Answer

Smaller - If the field capacity is larger, the soil will take longer to become saturated and retain more water resulting in less surplus runoff.

Soil Moisture Utilization

By the time June rolls around, temperatures have increased to the point where evaporation is proceeding quite rapidly and plants are requiring more water to keep them healthy. As potential evapotranspiration is approaching its maximum value during these warmer months, precipitation is falling off. During June P-PE is -17 mm. What this means is precipitation no longer is able to meet the demands of potential evapotranspiration. In order to meet their needs, plants must extract water that is stored in the soil from the previous months. This is shown in the table by a value of 17 in the cell for ΔST (change in soil storage). Once the 17 m is taken out of storage (ST) it reduces its value to 73.

The month of June is considered a dry month (P<PE) so AE is equal to precipitation plus the absolute value of ΔST (P + |ΔST|). When we complete this calculation (106 mm + 17 mm = 123 mm) we see that AE is equal to PE. What this means is precipitation and what was extracted from storage was able to meet the needs demanded by potential evapotranspiration. Note that there is no surplus in June as the soil moisture storage has dropped below its field capacity. There is still no deficit as water remains in storage. The calculations for July is similar to June, just different values. Note that by the time July ends, water held in storage is down to a mere 16 mm.

Soil Moisture Deficit

August, like June and July, is a dry month. Potential evapotranspiration still exceeds precipitation and the difference is a -42 mm. Up until this month there has been enough water from precipitation and what is in storage to meet the demands of potential evapotranspiration. However, August begins with only 16 mm of water in storage (ST of July). Thus we'll only be able to extract 16 mm of the 42 mm of water needed to meet the demands of potential evapotranspiration So, of the 42 mm of water we would need (P-PE) to extract from the soil. In so doing, the amount in storage (ST) falls to zero and the soil is dried out. What happens to the remaining 26 mm of the original P-PE of 42? The unmet need for water shows up as soil moisture deficit. In other words, we have not been able to meet our need for water from both precipitation and what we can extract from storage. AE is therefore equal to 100 mm (84 mm of precipitation plus 16 mm of ΔST).

So what is a farmer to do if their crops cannot obtain needed water from precipitation or soil moisture storage....they irrigate. Irrigation water usually is pumped from groundwater supplies held in aquifers deep below the surface or from nearby streams (if stream flow is sufficient to provide needed water). The amount of irrigation water required is the amount of the soil moisture deficit.

10.3.2: Soil Moisture Seasons

Four soil moisture seasons can be defined by the soil moisture conditions.

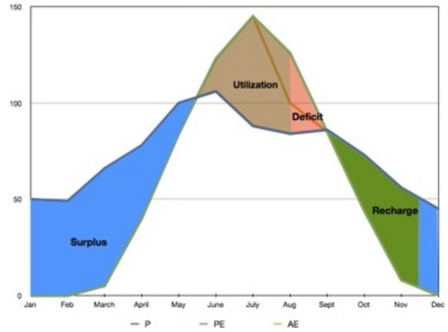


Figure 10.3.2.1: Soil Moisture Seasons for Rockford, Illinois

Recharge

The recharge season is a time when water is added to soil moisture storage (+ΔST). The recharge period occurs when precipitation exceeds potential evapotranspiration but the soil has yet to reach its field capacity.

Surplus

The surplus season occurs when precipitation exceeds potential evapotranspiration and the soil has reached its field capacity. Any additional water applied to the soil runs off. If this water runs off into nearby streams and rivers it could cause flooding. Thus, the intensity (amount) and duration (length of season) of surplus can be used to predict the severity of potential flooding.

Utilization

The utilization season is a time when water is withdrawn from soil moisture storage (-ΔST). The utilization period occurs when potential evapotranspiration exceeds precipitation but soil storage has yet to reach 0 (dry soil).

Deficit

The deficit season occurs when occurs when potential evapotranspiration exceeds precipitation and soil storage has reached 0. This is a time when there is essentially no water for plants. Farmers then tap ground water reserves or water in nearby streams and lakes to irrigate their crops. Thus, the intensity (amount) and duration (length of season) of deficit can be used to predict the need for irrigation water.

Whether a place experiences all four seasons depends on the climate and soil properties. Wet climate and those places with soils having high field capacities are less likely to experience a deficit period. Likewise the duration and intensity of any season will be determined by the climate and soil properties. Given equal amounts of precipitation, coarse textured soils will generate runoff faster than fine textured soils and may experience more intense surplus

10.4: Future Geographies - Water Resources and Climate Change

Changes to the patterns of current precipitation and those projected for the future on account of climate change are discussed in Chapter 6, "Future Geographies: Global Precipitation Patterns". The kind of precipitation is already changing, as northern regions are experiencing more rain than snow. Total snow cover has on average decreased in both hemispheres.The variability of precipitation is changing as well. Many subtropical regions have been or are gripped in devastating droughts. Precipitation is but one element of the hydrologic cycle, that will be affected by climate. The impact of climate change on water resources will have profound effects on ecosystems and humans.

Evapotranspiration

As noted earlier in this chapter, potential evapotranspiration is a measure of water need based primarily on the energy input. Potential evapotranspiration is expected to increase in nearly all regions. As temperature rises the saturation point of air increases, but relative humidity is not expected to change significantly. As a result, the evaporation of water increases yielding a larger amount of water vapor in the air. The increase evaporation of water from the soil places a greater strain on plants as their need for water to maintain growth processes increases. Actual evaporation is projected to increase over most bodies of water, the amount depending on the geographic variation in surface warming.

Plants take in carbon dioxide and release water vapor through their stomata. The increase in atmospheric carbon dioxide has competing roles in the affect of evapotranspiration from vegetation. At higher CO_2 concentrations, stomata need to open less to take in the same amount of carbon dioxide for photosynthesis. However, increased carbon dioxide can act a gaseous fertilizer to spur plant growth and leaf area. Increased leaf area results in more transpiration. The degree to which higher CO_2 concentration have depend on the type of vegetation, nutrient availability, temperature changes, and water availability

Surface water and Runoff

The impact of climate change on river flows and lake levels resulting depend on changes in the amount, type, and timing of precipitation. Changes in evaporation rates also affect river and lake levels. Global scale climate and hydrological models project runoff increases in the wet tropics and high latitudes, and decreases in the mid-latitudes and some parts of the dry tropics. Most studies show that rising temperatures lead to changes in the seasonality of river flow due to changes in the type of precipitation. Higher winter flows occurring in the European Alps, Scandinavia, the Himalayas, western, central, and eastern North America will result from more precipitation falling as rain and earlier snow melt. The frequency of heavy precipitation events are expected to increase in an ever warming world for most regions. This will likely increase the threat for flash flooding and urban flooding.

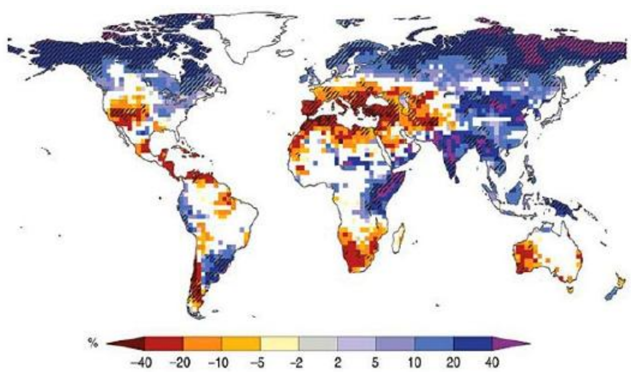


Figure 10.4.1: Runoff model projections of large-scale relative changes in annual runoff for the period 2090-2099 relative to 1980-1999. (Courtesy IPCC)

Ground water

Ground water levels are maintained when aquifers are adequately recharged. How this occurs varies with soil conditions, vegetation and precipitation intensity and timing. Generally speaking, if precipitation intensity is greater than the infiltration capacity of the soil, most water will runoff and not percolate down into the ground water zone. However, more frequent and larger precipitation events projected for some humid region may result in decreased groundwater recharge as the infiltration capacity of the soil is exceeded more often. In semi-arid and arid regions, groundwater level may rise with high-intensity storms as rainfall is ability to infiltrate downward before evaporating.

Soil moisture

The amount of moisture held in the soil depends on when and how much precipitation and evaporation occurs at a place. The resulting changes to the spatial patterns of soil moisture is expected to be quite similar to that of changes in precipitation. Though the amount of change is not well established, projections generally agree on the kind of change that will occur. A reduction in soil moisture in the subtropics and Mediterranean regions will accompany a decrease in precipitation. Projected decreases in snow cover at high latitudes will also result in less soil moisture. Soil moisture will likely increase in East Africa and central Asia where increases precipitation is expected to occur.

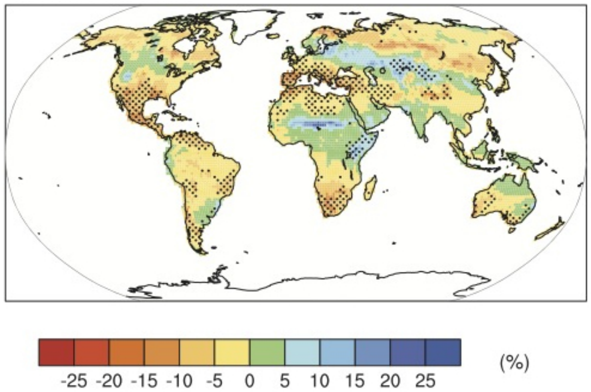


Figure 10.4.2: Fifteen-model mean changes in soil moisture. Stippled areas are those where 80% of models agree on sign of change. (Source: IPCC)

Water supply

Population growth, economic development and land use change largely determine the stress put on water supplies. Climate change will be an additional factor that affects stressed water resources. Glacier meltwater provides a source of water for many living in mountainous underdeveloped countries. Recent loss of glacier ice has or will place these people at risk. Peruvian glaciers have lost more than 20% of their mass in the past 35 years, resulting in a 12 percent decrease in runoff to the country's coastal region, where 60 percent of Peru's population live.

Agriculture, industry, and urban populations across the earth depend on major river systems to transpiration, irrigation, and drinking water. Millions of acres of farmland and tens of million people rely on the Colorado River system for water. Impoundment of water behind large dams regulate the flow and delivery of water supplies. The timing of when regulated flows deliver water is based on the experience of the past 100 years. Scheduled delivery of water may be missed 60 to 90 percent of the time as human-induced climate change continues to make the Colorado River basin drier.

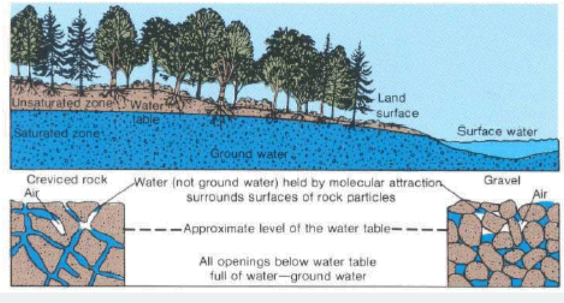
10.5: Review and Additional Resources

Review

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **hydrosphere**
  often called the "water sphere" as it includes all the earth's water found in the oceans, glaciers, streams, lakes, the soil, groundwater, and in the air.
- **hydrologic cycle**
  aka water cycle. the cycling of water through the earth system. It is a cycle of energy as well.
- **soil water**
  the water that is immediately available to plants.
- **groundwater**
  occupies the zone of saturation. Found in aquifers and replenished by percolation of water from the zone of aeration downward to the zone of saturation, or in the recharge zone of a confined aquifer.
- **evaporation**
  the phase change of liquid water into a vapor (gas)
- **latent energy**
  "locked up" in the water molecule when water undergoes the phase change from a liquid to a gas.
- **precipitation**
  droplets of water that fall from the clouds to the earth
- **interception**
  Precipitation that collects on the leaves or stems of plants
- **infiltration**
  refers to water that penetrates into the surface of soil.
- **zone of aeration**
  aka "unsaturated zone", includes soil water zone. See image under "zone of saturation"
- **zone of saturation**
  includes ground water



- **groundwater zone**

  included in zone of saturation. See image under "zone of saturation"

- **water table**

  divides the zone of aeration from the zone of saturation. The height of the water table will fluctuate with precipitation, increasing in elevation during wet periods and decreasing during dry.

- **hygroscopic water**

  a microscopic film of water surrounding soil particles

- **capillary water**

  held by cohesive forces between the films of hygroscopic water

- **wilting point**

  At this point the plant cannot pull water from the plant-rooting zone and it wilts

- **gravity water**

  water moved through the soil by the force of gravity

- **field capacity**

  The amount of water held in the soil after excess water has drained

- **available water**

  The difference between the wilting point and the field capacity

- **percolation**

  the movement of water downward through the soil

- **seepage**

  water that moves downward through the soil toward a stream channel of large body of water

- **aquifer**

  bodies of earth material that have the ability to hold and transmit water

- **aquiclude**

  dense impermeable layers of earth material

- **hydraulic gradient**

  the difference in elevation between two points on the water table divided by the horizontal distance between them

- **groundwater flow rate**

  permeability X hydraulic gradient

- **runoff**

  precipitation that moves across the surface

- **unconfined flow**

  moves across the surface in broad sheets of water often creating sheet erosion

- **confined flow**

  water confined to channels

- **depression storage**

Water that became trapped in depressions

- **stream discharge**
  the volume of water passing through a particular cross-section of a stream in a unit of time
- **stream hydrograph**
  illustrates the relationship between discharge and runoff
- **water balance**
  an accounting of the inputs and outputs of water
- **precipitation**
  makes up the primarily supply of water to the surface.
- **actual evapotranspiration**
  the amount of water delivered to the air from evaporation and transpiration
- **evaporation**
  the phase change from a liquid to a gas releasing water from a wet surface into the air above
- **transpiration**
  represents a phase change when water is released into the air by plants
- **evapotranspiration**
  combined transfer of water into the air by evaporation and transpiration
- **potential evapotranspiration**
  the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water
- **soil moisture storage**
  the amount of water held in the soil at any particular time
- **change in soil moisture storage**
  the amount of water that is being added to or removed from what is stored
- **deficit**
  demand for water exceeds that which is actually available; when potential evapotranspiration exceeds actual evapotranspiration (PE>AE)
- **surplus**
  when P exceeds PE and the soil is at its field capacity (saturated); we have more water than we actually need to use given the environmental conditions at a place
- **soil moisture recharge**
  Precipitation satisfies the need for water with water left over and begins to replenish the soil moisture
- **soil moisture utilization**
  precipitation is no longer is able to meet the demands of potential evapotranspiration. Plants must extract water that is stored in the soil from the previous months

? Review Questions 10.5.1

Briefly describe what the hydrologic cycle is.

Answer

The hydrologic cycle or water cycle is the pathway through which water moves in the Earth system. It is a cycle of energy as well as moisture.

Compare and contrast soil water and groundwater.

Answer

Soil water is held in the soil moisture zone that lies in the zone of aeration. **Groundwater** is held in the zone of saturation. Soil water is directly available for plants to use, ground water is not.

How do plants affect the hydrologic cycle?

Answer

Plants affect the water cycle though by extracting water from the soil moisture zone and passing it to the atmosphere. Water moves as through fall through plant canopy.

What impact does soil texture have on field capacity?

Answer

The **field capacity** is the maximum amount of water held in the soil after it has bee drained by gravity. Field capacity is higher in fine textured soils because there is more pore space per unit volume than for coarse textured soils.

What affects the permeability of subsurface warth materials?

Answer

Permeability is the ability for water to move through earth material. The connectivity of pore spaces largely controls permeability. Large, well-connected pore space results in greater permeability. Thus, coarse soils are more permeable than fine textured soils.

How does soil texture affect available water?

Answer

Finer textured soils hold more water and thus have more available water than coarse textured soils.

Compare and contrast an aquiclude with an aquifer.

Answer

An aquifer is a body of earth material able to hold and transmit groundwater in economical amounts. An aquiclude is far less permeable and cannot transmit water through it.

Describe the effect of urbanization on a stream hydrograph.

Answer

Urbanization can decrease the lag time between maximum precipitation and runoff, and increase and steepen the recessional limb of a hydrograph.

What is potential evapotranspiration?

Answer

Evapotranspiration is the amount of water evaporated and transpired under an unlimited supply of water. Fundamentally it is determined by energy input to the environment. Evapotranspiration can be thought of as "water need".

Under what conditions does a soil water deficit occur?

Answer

A soil water deficit occurs when potential evapotranspiration exceeds precipitation and the soil water storage is zero (dry soil).

Under what conditions does a soil water surplus occur?

Answer

A soil water surplus occurs when precipitation exceeds potential evapotranspiration and the soil is at field capacity.

? Self-Assessment Quiz 10.5.1

1. In soil moisture budgeting, potential evapotranspiration is largely dependent on
   A. soil texture
   B. energy input
   C. plant type
   D. all the above
2. The largest store of fresh water in the hydrosphere is
   A. the ocean
   B. glaciers
   C. the Great Lakes
   D. ground water
3. Over pumping of ground water could lead to
   A. lowered water tables
   B. land subsidence
   C. decreased aquifer permeability
   D. all the above
4. Infiltration of water into the soil
   A. is higher for coarse textured soil
   B. is higher when the soil is dry
   C. is higher for vegetated surfaces
   D. is affected by all the above
5. Which of the following soil texture classes would have the largest available water?
   A. sand
   B. silt
   C. clay
   D. loam
6. The water held that is "bound" the tightest to soil particles is
   A. hydroscopic water
   B. capillary water
   C. gravity water
   D. pore water
7. The process whereby water drips from leaf-to-leaf finally making it to the ground is called
   A. through flow
   B. stem flow
   C. through fall

   D. interception
8. The zoom of saturation is the
   A. soil water zone
   B. intermediate zone
   C. aeration zone
   D. ground water zone
9. The point at which plants can no longer extract water from the soil is called the
   A. field capacity point
   B. dryness point
   C. wilting point
   D. none of the above
10. If PE is greater than AE and P, and the soil is dry, then
   A. soil water recharge is likely to occur
   B. soil water surplus is likely to occur
   C. soil water utilization is likely to occur
   D. soil water deficit is likely to occur

Answer

1. B
2. B
3. D
4. D
5. D
6. A
7. A
8. D
9. C
10. D

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "The Rise and Fall of Africa's Great Lake" *NASA Earth Observatory*

Connections: "Could California's drought make residents sick?" *NewsHour* (PBS) 09/03/2016 report

Physical Geography Today: Ground Water Climate Response Network - USGS

World of Change: Evaporation of the Aral Sea (*NASA Earth Observatory*)

Multimedia

"The Desert Springs of Mexico's Cuatro Cienegas", (8:56)

Readings

"Defining Drought" National Drought Mitigation Center, University of Nebraska - Lincoln

Web Sites

Water Resources of the United States - United States Geological Survey

National Oceanic and Atmospheric Administration (NOAA)

CHAPTER OVERVIEW

11: Soil Systems

Learning Objectives

By the end of the chapter you should be able to:

- Create and label a diagram of horizon development process.
- Explain how soil color relates to soil properties.
- Define soil texture, structure and bulk density, and explain their importance to soil development.
- Use the soil texture triangle to determine soil texture class.
- Explain basic soil chemistry and relate it to soil fertility.
- Construct, label, and describe the horizons in a typical soil profile.
- Describe each of the soil development factors and how they influence properties of soils.
- Describe the soil forming (pedogenic) processes and their effects on soil properties.
- Describe the major soil orders and explain their general distribution.

Soil is crucial to the functioning of the Earth system. Soil is the foundation upon which vegetation grows and home to a diverse community of organisms. The global mosaic of world soils is a reflection of the geographic variation of climate, vegetation, and geological processes. Soil is a resource easily degraded or destroyed by misuse. Once damaged, it take hundreds of years to regenerate and become productive again.

Figure 11.1: Fertile soil dried and cracked due to a lack of rain, Morocco (Courtesy FAO)

Determining soil moisture using the wet ball method
Courtesy NRCS

Figure 11.2

11.1: Soil Development
11.2: Horizon Development Processes
11.3: Soil Properties
11.4: Soil Profiles
11.5: Factors Affecting Soil Development
11.6: Soil Forming (Pedogenic) Processes
11.7: Soil Orders

11.8: Review and Additional Resources

11.1: Soil Development

Soil forms from a complex interaction between earth materials, climate, and organisms acting over time. The brightly colored soils of the humid tropics reflect the intense chemical reactions occurring in warm climates. The fertile prairie soils of the American Midwest evolved from the nutrient-rich organic matter left by decaying grasses. Regardless of soil characteristics, the whole process starts with the breakdown of earth material.

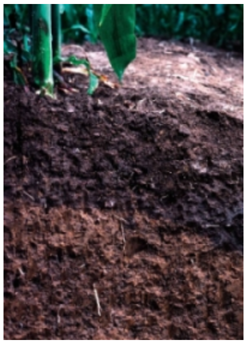


Figure 11.1.1: Soil profile in central Iowa (Image Courtesy NRCS)

Weathering

Weathering refers to processes that physically breakdown and chemically alter earth material. ***Physical weathering***, also known as mechanical weathering, is the breakdown of large pieces of earth material into smaller ones. Think of physical weathering as the *disintegration* of rock without changing its chemical composition. There are many ways earth material can be physically weathered. When water freezes in rock crevices it expands creating stress in the crevice. As the stress increases, the crevice widens ultimately breaking the rock. Plant roots wedge rocks apart as they grow into rock crevices too. The shrinking and swelling by alternating heating and cooling weakens mineral bonds causing the rock to disintegrate.

A very important result of physical weathering is its impact on the surface area of weathered material. When a block of earth material is broken into several smaller pieces, the amount of exposed surface increases. Examine the diagram below. A block with a width, depth, and height of 1 cm has a total surface area of 6 square centimeters. If we break the block in half in all directions it yields eight smaller pieces all with width, height, and depth of .5 cm. Breaking the block apart creates additional exposed surfaces such that the total surface area is now 12 square centimeters. Having more total exposed surface provides more area upon which chemical reactions can take place to further weather the material. The shape of the pieces also affects the the amount of exposed surface area. Plate-like pieces have more exposed surface area than do block-like pieces. [See "Surface Area vs. Size and Shape"]

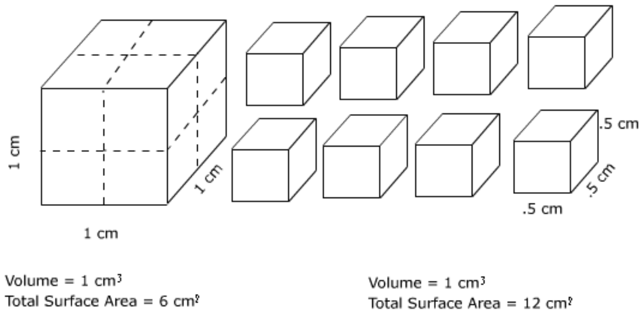


Figure 11.1.2: Effect of physical weathering on surface area

Chemical weathering breaks down earth material by chemical alteration. This usually means adding a substance like water or air to the material. For instance, when oxygen is added to iron bearing minerals, ***oxidation*** takes places and a loose mantle of iron oxide is created (rust). ***Hydrolysis*** is an exchange reaction involving minerals and water. Free hydrogen (H^+) and hydroxide $(OH)^-$ ions in water replace mineral ions and drive them into solution. As a result, the mineral's structure is changed into a new form. Hydrolysis is a common process whereby silicate minerals are weathered into a clay mineral. Think of chemical weathering as the decomposition of earth material.

The spatial variation of climate and organisms play a significant role in the weathering of earth materials. Dry locations tend to be dominated by physical weathering and moist places by chemical weathering. The type of earth material available also determines the amount of weathering that might take place. Limestone is easily broken down where abundant rainfall and high temperatures prevail. However, limestone will remain intact in dry locations.

The end result of the weathering process is the creation of a weathered mantle. The ***weathered mantle*** is not yet a soil until it undergoes further change. This involves the addition, transformation, translocation and removal of materials from the weathered mantle to form distinctive soil layers.

11.2: Horizon Development Processes

Ever dug into in the soil and noticed how it seems to change color the deeper you go? Some soils are dark brown near the surface and get lighter in color as you go deeper. Others display a sandy, light-gray layer near the surface with a reddish layer beneath. These different colored layers are known as ***horizons***. All the horizons taken together comprise the ***soil profile***. Soil horizons form as a result of the four horizon development processes, additions, transformation, translocation, and removal.

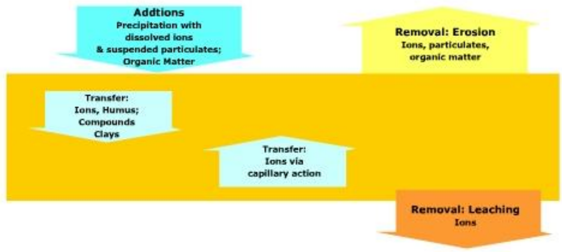


Figure 11.2.1: Horizon Development Processes

Additions

Additions can be materials that are transported into the location where a soil is forming. For instance, dust with a high calcium carbonate content could be blown on to the developing soil adding calcium to the evolving profile. This is one idea as to how soils in the Midwestern part of the United States called mollisols were enriched with $CaCO_3$. When plants die or leaves fall on to the surface they decompose adding organic matter to the soil.

Figure 11.2.2: This spodosol soil displays well-developed horizons. (Source: NRCS)

Transformation

Transformation of the materials added to the developing soil occur by chemical and biological processes acting on them. For instance, leaves falling on the surface and plant roots dying beneath may decompose into a dark brown, nutrient-rich material called ***humus***. Humus is responsible for the dark brown to black color of many soils, especially near the top of the soil profile. Iron and aluminum can be oxidized under warm, moist climates. Soil material is constantly being transformed in one way or another.

Translocation

Translocation involves the movement of soil-forming materials through the developing soil profile. Translocation occurs by water running through the soil transferring materials from upper to lower portions of the profile. Burrowing animals like earth worms, ants, etc., move soil materials within the profile. Burrowing animals create passage ways through which air and water can travel promoting soil development.

Removal

Removal of soil forming materials means that they are completely removed from the soil profile. Easily dissolved elements like calcium carbonate can be removed from the soil profile under rainy climates.

Soil horizons develop in response to the relative importance of each of the above processes. All soils are impacted by the horizon development processes to one degree or another. These processes determine the characteristics or properties of soil in each of the horizons.

11.3: Soil Properties

Soils can be enormously complex systems of organic and inorganic components. Here, we'll concentrate on a few of the most significant properties, texture, structure, color, and chemistry

Figure 11.3.1: Loamy agricultural soil (Source NRCS Used with permission)

Soil Texture

Soil texture refers to the relative proportion of sand, silt and clay size particles in a sample of soil. Clay size particles are the smallest being less than .002 mm in size. Silt is a medium size particle falling between .002 and .05 mm in size. The largest particle is sand with diameters between .05 for fine sand to 2.0 mm for very coarse sand. Soils that are dominated by clay are called fine textured soils while those dominated by larger particles are referred to as coarse textured soils. Soil scientists group soil textures into soil texture classes. A ***soil texture triangle*** is used to classify the texture class (see below).

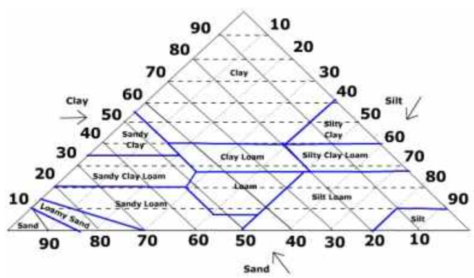


Figure 11.3.2: Soil Texture Triangle

The sides of the soil texture triangle are scaled for the percentages of sand, silt, and clay. Clay percentages on the left side of the triangle are read from left to right across the triangle (dashed lines). Silt runs from the top to the bottom along the right side and is read from the upper right to lower left (light, dotted lines). The percentage of sand increases from right to left along the base of the triangle. Sand is read from the lower right towards the upper left portion of the triangle (bold, solid lines). The boundaries of the soil texture classes are highlighted in blue. The intersection of the three sizes on the triangle give the texture class. For instance, if you have a soil with 20% clay, 60% silt, and 20% sand it falls in the "silt loam" class.

? Self-Assessment 11.3.1

What is the texture class for a soil having 45% clay, 45% silt, and 10% sand?

Slit Loam, Clay, Silty Clay, or Silty Clay Loam?

Answer

Silty Clay

Soil texture effects many other properties like structure, chemistry, and most notably, soil porosity, and permeability. ***Soil porosity*** refers to the amount of pore, or open space between soil particles. Pores are created by the contacts made between irregular shaped soil particles. Fine textured soil has more pore space than coarse textured because you can pack more small particles into a unit volume than larger ones. More particles in a unit volume creates more contacts between the irregular shaped surfaces and hence more pore space. As a result, fine textured clay soils hold more water than coarse textured sandy soils. ***Permeability*** is the degree of connectivity between soil pores. A highly permeable soil is one in which water runs through it quite readily. Coarse textured soils tend to have large, well-connected pore spaces and hence high permeability.

Soil Structure

Soil structure is the way soil particles aggregate together into what are called peds. Peds come in a variety of shapes depending on the texture, composition, and environment.

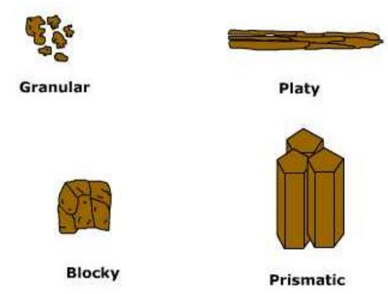


Figure 11.3.3: Common soil structure forms

Granular, or crumb structures, look like cookie crumbs. They tend to form an open structure that allows water and air to penetrate the soil. Platy structure looks like stacks of dinner plates overlaying one another. ***Platy structure*** tends to impede the downward movement of water and plant roots through the soil. Therefore, open structures tend to be better agricultural soils.

Bulk density of a soil is the mass per unit volume including the pore space. Bulk density increases with clay content and is considered a measure of the compactness of the soil. The greater the bulk density, the more compact the soil. Compact soils have low permeability, inhibiting the movement of water. The use of heavy agricultural equipment can cause compaction of soil, especially in wet clay soil. Soil compaction results in reduced infiltration and increase runoff and erosion.

Soil Chemistry

As plant material dies and decays it adds organic matter in the form of humus to the soil. Humus improves soil moisture retention while affecting soil chemistry. Cations such as calcium, magnesium, sodium, and potassium are attracted and held to humus. These cations are rather weakly held to the humus and can be replaced by metallic ions like iron and aluminum, releasing them into the soil for plants to use. Soils with the ability to absorb and retain exchangeable cations have a high cation-exchange capacity. Soils with a high cation-exchange capacity are more fertile than those with a low exchange capacity.

Hydrogen ion concentration in the soil is measured in terms of the ***pH scale***. Soil pH ranges from 3 to 10. Pure water has a pH of 7 which is considered neutral, pH values greater than seven are considered *basic* or *alkaline*, below seven *acidic*. Most good agricultural soils have a pH between 5 and 7. Though acidic soils pose a problem for agriculture due to their lack of nutrients, alkaline soils can pose a problem as well. Alkaline soils may contain appreciable amounts of sodium that exceed the tolerances of plants, contribute to high bulk density and poor soil structure. Alkaline soils are common in semiarid regions.

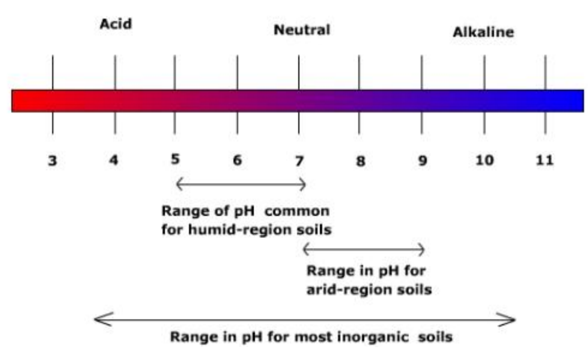


Figure 11.3.4: Soil pH

11.4: Soil Profiles

Soil formation begins first with the break down of rock into regolith. Continued weathering and soil horizon development process leads to the development of a ***soil profile***, the vertical display of soil horizons. Watch the typical progression of a soil profile then read the description below of a generic, fully developed soil.

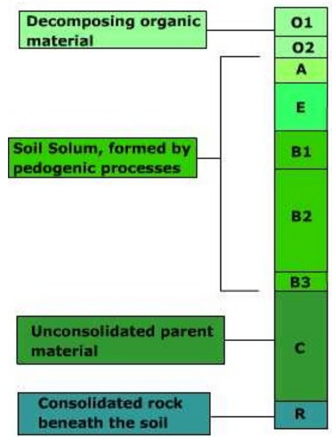


Figure 11.4.1: A Typical Soil Profile (after Oberlander & Muller, 1987)

O Horizon

At the top of the profile is the O horizon. The O horizon is primarily composed of organic matter. Fresh litter is found at the surface, while at depth all signs of vegetation structure has been destroyed by decomposition. The decomposed organic matter, or humus, enriches the soil with nutrients (nitrogen, potassium, etc.), aids soil structure (acts to bind particles), and enhances soil moisture retention.

A Horizon

Beneath the O horizon is the A horizon. The A horizon marks the beginning of the true mineral soil. In this horizon organic material mixes with inorganic products of weathering. The A horizon typically is dark colored horizon due to the presence organic matter. ***Eluviation***, the removal of inorganic and organic substances from a horizon by leaching occurs in the A horizon. Eluviation is driven by the downward movement of soil water.

E Horizon

The E horizon generally is a light-colored horizon with eluviation being the dominant process. Leaching, or the removal of clay particles, organic matter, and/or oxides of iron and aluminum is active in this horizon. Under coniferous forests, the E horizon often has a high concentration of quartz giving the horizon an ashy-gray appearance.

B Horizon

Beneath the E horizon lies the B horizon. The B horizon is a zone of ***illuviation*** where downward moving, especially fine material, is accumulated. The accumulation of fine material leads to the creation of a dense layer in the soil. In some soils the B horizon is enriched with calcium carbonate in the form of nodules or as a layer. This occurs when the carbonate precipitates out of downward moving soil water or from capillary action. The diagram below illustrates the effect of climate on eluviation and illuviation. Eluviation is significant in humid climates where ample precipitation exists and a surplus in the water balance occurs. Illuvial layers are found low in the soil profile. Illuvial zones are found closer to the surface in semiarid and arid climates where precipitation is scarce. Capillary action brings cations like calcium and sodium dissolved in soil water upwards where they precipitate from the water.

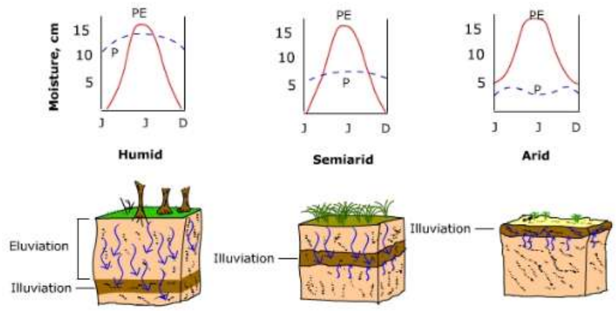


Figure 11.4.2: Eluviation and illuviation under humid, semiarid and arid conditions. (after Marsh, 1987)

C Horizon

The C horizon represents the soil parent material, either created in situ or transported into its present location. Beneath the C horizon lies bedrock.

Figure 11.4.3: Glacial till exposed in a moraine; a typical parent material for soils in the central United States. (Image Source: Agriculture Agri-Food Canada. Used with permission)

The preceding paragraphs describe a generic soil profile, yet not all soils have each one of the horizons, nor are they all the same with respect to thickness composition and structure. Newly formed "immature" soils may only have an O-A-C sequence while older more "mature" soils display the full profile of horizons as described above. The particular compositional, structural and chemical composition of the soil depends on the various factors that influence soil formation.

11.5: Factors Affecting Soil Development

Soil research has shown that soil profiles are influenced by five separate, yet interacting, factors: parent material, climate, topography, organisms, and time. Soil scientists call these the ***factors of soil formation***. These factors give soil profiles their distinctive character.

Parent Material

Soil ***parent material*** is the material that soil develops from, and may be rock that has decomposed in place, or material that has been deposited by wind, water, or ice. The character and chemical composition of the parent material plays an important role in determining soil properties, especially during the early stages of development.

Figure 11.5.1: Stabilized dunes are a form of Eolian (wind deposited) parent material (Source: Agriculture Agri-Food Canada)

Soils developed on parent material that is coarse grained and composed of minerals resistant to weathering are likely to exhibit coarse grain texture. Fine grain soil develop where the parent material is composed of unstable minerals that readily weather.

Parent material composition has a direct impact on soil chemistry and fertility. Parent materials rich in soluble ions-calcium, magnesium, potassium, and sodium, are easily dissolved in water and made available to plants. Limestone and basaltic lava both have a high content of soluble bases and produce fertile soil in humid climates. If parent materials are low in soluble ions, water moving through the soil removes the bases and substitutes them with hydrogen ions making the soil acidic and unsuitable for agriculture. Soils developed over sandstone are low in soluble bases and coarse in texture which facilitates leaching. Parent material influence on soil properties tends to decrease with time as it is altered and climate becomes more important.

Climate

Soils tend to show a strong geographical correlation with climate, especially at the global scale. Energy and precipitation strongly influence physical and chemical reactions on parent material. Climate also determines vegetation cover which in turn influences soil development. Precipitation also affects horizon development factors like the translocation of dissolved ions through the soil. As time passes, climate tends to be a prime influence on soil properties while the influence of parent material is less.

Climate, vegetation, and weathering

Climate affects both vegetative production and the activity of organisms. Hot, dry desert regions have sparse vegetation and hence limited organic material available for the soil. The lack of precipitation inhibits chemical weathering leading to coarse textured soil in arid regions. Bacterial activity is limited by the cold temperatures in the tundra causing organic matter to build up. In the warm and wet tropics, bacterial activity proceeds at a rapid rate, thoroughly decomposing leaf litter. Under the lush tropical forest vegetation, available nutrients are rapidly taken back up by the trees. The high annual precipitation also flushes some organic material from the soil. These factors combine to create soils lacking much organic matter in their upper horizons.

Climate, interacting with vegetation, also affects soil chemistry. Pine forests tend to dominate cool, humid climates. Decomposing pine needles in the presence of water creates a weak acid that strips soluble bases from the soil leaving it in an acidic state. Additionally, pine trees have low nutrient demands so few soil nutrients are taken back up by the trees to be later recycled by decaying needle litter. Broadleaf deciduous trees like oak and maple have higher nutrient demand and thus continually recycle soil nutrients keeping soils high in soluble bases.

Topography

Topography has a significant impact on soil formation as it determines runoff of water, and its orientation affects microclimate which in turn affects vegetation. For soil to form, the parent material needs to lie relatively undisturbed so soil horizon processes can proceed. Water moving across the surface strips parent material away impeding soil development. Water erosion is more effective on steeper, unvegetated slopes.

Effect on soil erosion

Slope angle and length affects runoff generated when rain falls to the surface. Examine the diagram below showing the relationship between hill slope position, runoff, and erosion.

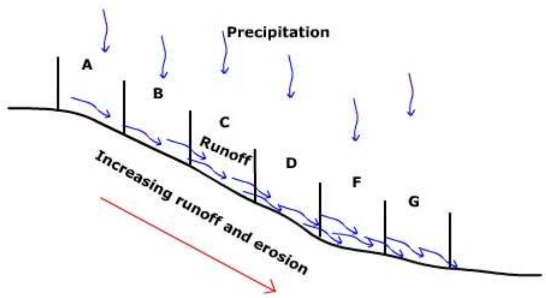


Figure 11.5.2: Hill slope position, runoff & erosion

The amount of water on a particular hill slope segment is dependent on what falls from precipitation and what runs into it from an upslope hill slope segment. The hill slope in Figure 11.5.2 has been divided into several segments and the amount of precipitation falling on each segment is the same. As water runs down slope, the water that has accumulated in segment A runs off adding to what falls into segment B by precipitation. The water in B runs into C, and C into D, and so on. The amount of water increases in the down slope direction as water is contributed of water from upslope segments. The velocity of the water increases as well as it moves towards the base of the slope. As a result, the amount and velocity of water, and hence rate of erosion increases as you near the base of the slope. Rather than infiltrating into the soil to promote weathering and soil development, water runs off. Erosion causes stripping of the soil thus preventing parent material to stay in place to develop into a soil. So we should expect to find weakly developed soil at the mid- and near the bottom of the slope.

Effect on deposition and soil texture

Water velocity not only determines the rate of erosion but the deposition of soil material in suspension too. Figure 11.5.3 shows the relationship between location and texture. Sites A, B, and C, are located progressively further from the base of a slope. A soil texture triangle is used to illustrate the variation in soil textures at the three sites.

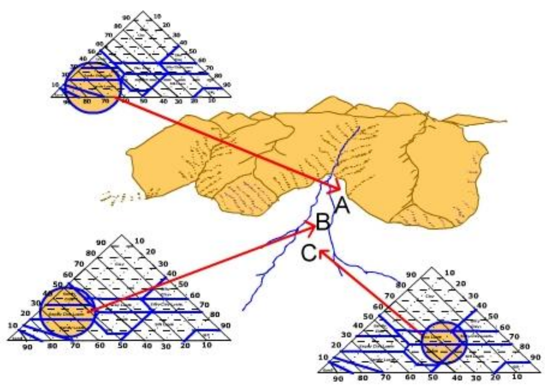


Figure 11.5.3: Location, Deposition and Soil Texture (after Marsh, 1984)

As water empties from a mountain stream, its velocity starts to decrease. The largest size particles, like sand, are the first to drop out of suspension (Site A). Fine, clay size particles can be carried further away from the base of the slope before they are deposited. As a result, coarse textured soils tend to be found near the base of the mountain and fine textured soils are located further away (Site C).

Microclimatic effects

Hill slope orientation affects the microclimate of a place. As the slope of the surface increases, so does the local sun angle, up to a point. As the local sun angle increases, the intensity of heating increases, causing warmer surface temperatures and, likely, increased evaporation. Orientation of the hill slope is certainly important too. Those slopes which face into the sun receive more insolation than those facing away. Thus inclined surfaces facing into the sun tend to be warmer and drier, than flatter surfaces facing way from the sun. The microclimate also impact vegetation type.

Organisms

Organism, both plant and animal, play an important role in the development and composition of soil. Organisms add organic matter, aid decomposition, weathering and nutrient cycling. The richness and diversity of soil organisms and plant life that grows on the surface is, of course, also tied to climate.

Nutrient cycling

Biotic elements of the environment need life-sustaining nutrients that find their origin in the soil. Upon their death, organisms return these nutrients to the soil to be taken up again by other plants and animals. Hence there is a constant cycling of nutrients between organisms and soils. This cycling refreshes and maintains the nutrient status of soils. Without it, soluble nutrients would be leached from the soil, decreasing the soil's ability to support life.

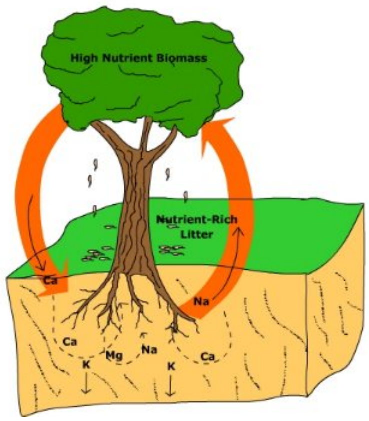


Figure 11.5.4: Nutrient Cycling under broadleaf deciduous trees. (After Oberlander & Muller, 1987)

The degree to which nutrients are cycled depends on the needs of the organism occupying a particular place. For instance, broadleaf, deciduous trees like oak and maple generally have high nutrient demand creating surface litter rich in nutrients when leaves die and fall to the forest floor. Decomposition of the litter releases the nutrients back into the soil for the tree to take back up. Thus soils under these kinds of forests tend to be high in soluble bases and nutrients.

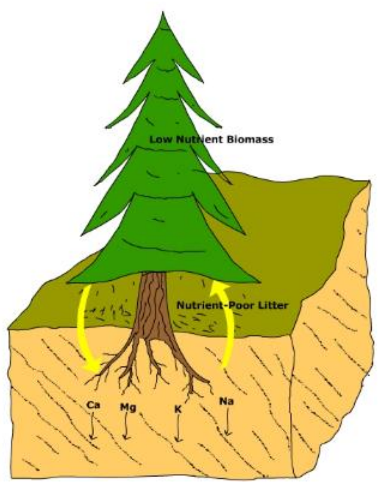


Figure 11.5.5: Nutrient cycling under pine forests (After Oberlander & Muller, 1987)

Pine trees generally have low nutrient demands. The decaying litter that falls to the forest floor is poor in nutrients. As a result, little cycling of soluble nutrients like calcium, magnesium, sodium, and potassium occurs and are thus leached creating an acidic soil environment.

Organisms and weathering

Figure 11.5.6: Soil biota such as worms are important factor in soil development (Source: A. Odoul. FAO#17449 Used with permission)

Soil organisms also affect weathering. The decomposition of pine needles creates a weak acid that can strip soluble ions from the soil. Burrowing animals create passage ways through the soil to help aerate and allow water to infiltrate into it. Burrowing animals help translocate materials and fertilize the soil at depth.

Time

As time passes, the weathering processes continue to act on soil parent material to break it down and decompose it. Horizon development processes continue to differentiate layers in the soil profile by their physical and chemical properties. As a result, older more mature soils have well-developed sequence of horizons, though some may undergo so much weathering and leaching that visually distinct layers may be hard to see. This is a notable characteristic of oxisols. Some geological processes keep soils from developing by constantly altering the surface and thus not allowing parent material to weather over a significant period of time. For instance, erosion of hillsides constantly removes material thus impeding soil development. Along the channels of rivers, new sediment is frequently deposited as the river spills out onto its floodplain during floods. The constant addition of new material restarts the soil development process.

Climate interacts with time during the soil development process. Soil development proceeds much more rapidly in warm and wet climates thus reaching a mature status sooner. In cold climates, weathering is impeded and soil development takes much longer.

Video: Watch "The Five Factors of Soil Formation" (Courtesy of UBC Virtual Soil Learning Resources)

11.6: Soil Forming (Pedogenic) Processes

The physical and chemical properties of a soil are determined by the soil forming process under which they form. Though all soils are created by the various horizon development processes of additions, transformations, translocation and removals, it is the soil forming or, pedogenic processes that determines the kind of soil that is ultimately formed.

Laterization

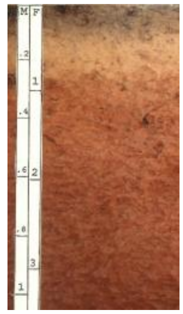


Figure 11.6.1: This ultisol displays the typical features of a soil having undergone laterization (Image source: USDA NRCS. Used with permission)

The deep red to bright orange-red soils of the tropics are a product of laterization. Laterization occurs in the hot, rainy tropics where chemical weathering proceeds at a rapid rate. Soils subject to laterization tend toward the acidic and lack much organic matter as decomposition and leaching is extreme. Exposure of the soil to the hot tropic sun by deforestation bakes the soil dry, reducing infiltration, increasing runoff, and reducing fertility.

Calcification

Figure 11.6.2: Mollisol soil enriched with calcium carbonate (Image source: Agriculture Agri-Food Canada. Used with permission)

Calcification occurs in warm, semi-arid environments, usually under grassland vegetation. Soil tends to be rich in organic matter and high in soluble bases. The B horizon of the soil is enriched with calcium carbonate precipitated from water moving downward through the soil, or upward by capillary action of water from below.

Podzolization

Podzolization occurs in cool and moist climates under pine forests. They are typical of the colder portions of the humid continental and subarctic climates. The E horizon is heavily leached and basically composed a of light colored layer of sand.

Figure 11.6.3: Typical ashy, gray layer left from leaching of sesquioxides is apparent in this podzolized soil. (Image source: Agriculture Agri-Food Canada. Used with permission)

The upper portion of the B horizon is stained reddish color from the accumulation of sesquioxides. The profile gets lighter in color as depth increases. Podzolization of sandy soils in the southern United States has been the result of planting pine plantations.

Salinization

Figure 11.6.4: Accumulation of salts is easily seen in this salinized soil (Image source: Agriculture Agri-Food Canada. Used with permission)

Salinization occurs in warm and dry locations where soluble salts precipitate from water and accumulate in the soil. Saline soils are common in desert and steppe climates. Salt may also accumulate in soils from sea spray. The rapid evaporation of salt-rich irrigation water has devastated thousands of acres of land world-wide.

Gleization

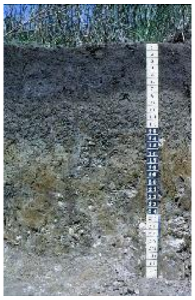


Figure 11.6.5: Cultivated gley soil in southern Canada (Image source: Agriculture Agri-Food Canada. Used with permission)

Gleization occurs in regions of high rainfall and low-lying areas that may be naturally waterlogged. Bacterial activity is slowed in the constantly wet environment thus inhibiting the decomposition of dead vegetation allowing it to accumulate in thick layers. Peat is found in the upper portion of the soil. Decaying plant matter releases organic acids that react with iron in the soil. The iron is reduced rather than oxidized giving the soil a black to bluish - gray color.

? Self-Assessment 11.6.1

Which soil forming process is active in the Amazon Basin of Brazil?

Calcification, Laterization, Podzolization, or Salinization?

Answer

Laterization

11.7: Soil Orders

The are several different ways in which soils have been classified. The brief discussion below reflects the way soils are classified in the United States. Soils are classified on the basis of **diagnostic horizons**, that are different from the O, A, B, C horizons. A diagnostic horizon has a unique feature that reflects the soil development processes acting at a site. For instance, a mollic epipedon (an epipedon is a type of diagnostic horizon) is a organic-rich horizon typical of a mollisol soil. The following material is intended to give you a basic understanding of the major categories of soils called ***soil orders*** and the environments under which they form. For a comprehensive description of how soils are classified in the United States, see the Soil Taxonomy (*only for those of you dying to learn more about soil classification than you ever wanted to know!*)

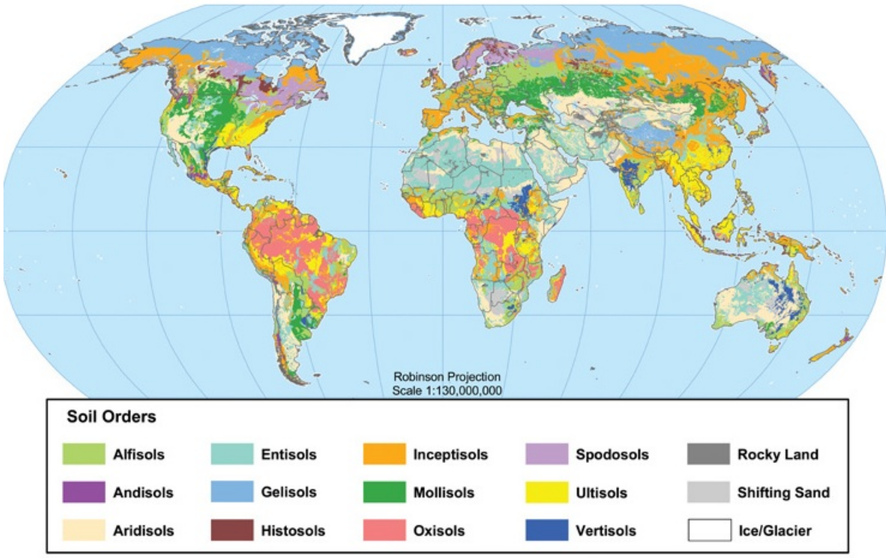


Figure 11.7.1: Global Soil Regions. Click map for high resolution map (Courtesy NRCS)

Entisols, like this one found in southwestern Wisconsin, are soils lacking horizons because their parent material has only recently accumulated. Entisols also form where the parent material is quartz sand, in which horizons do not easily form. They have a wide geographic distribution and can be found in any climate and under any vegetation. Entisols and Inceptisols are often found on floodplains, delta deposits, or steep slopes where parent material has difficulty accumulating.

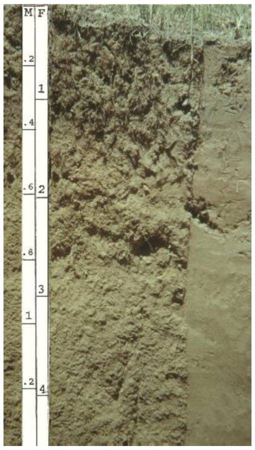


Figure 11.7.2: Entisol (Image Source: USDA NRCS Used with permission)

Inceptisol

Inceptisols are soils just starting to show horizon development because the soil is quite young. You can see the differentiation of layers in an inceptisol formed on colluvium in West Virginia on the right. Inceptisols, like Entisols, are found in any type of environment and are commonly found forming in alluvium on floodplains and delta deposits.

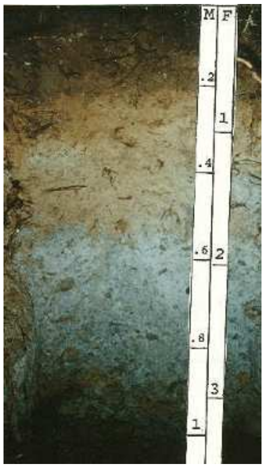


Figure 11.7.3: Inceptisol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Histosol

Histosols have a very high content of organic matter in the dark upper layer of the profile. Found in many different environments from the tundra to the tropics, Histosols form in places where organic matter is slow to decompose and thus accumulates over time such as bogs and swamps. They are often "mined" for peat which is dried and burned as fuel.

Figure 11.7.4: Histosol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Aridisol

Aridisols are soils of arid and semiarid environments where moisture is scarce. They are typically light in color as there is little vegetation to add organic matter to the soil profile. A negative moisture balance in these soils inhibits eluviation. Calcification and salinization are important soil forming processes acting in these soils. Soil horizons are weakly developed and sodium is often high in concentration making them alkaline. The coarse texture of aridisols makes it difficult to retain much moisture. Aridisols can be quite fertile soil if irrigation is properly used. Used improperly, a salt crust can form on the soil. Most aridisols are used for grazing.

Figure 11.7.5: Aridisol Soil. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Video: Desert Soil & Erosion Courtesy BBC

Andisol

Andisols are soils developing in parent material containing at least fifty percent volcanic ash. The layers of ash can be seen in this Andisol from Hawaii. Naturally fertile soils, they support a dense natural cover in moist climates. Andisols occur around individual volcanoes created from andesite-rich magma. They are common on the volcanic islands and mountains of "The Ring of Fire", that encircles the Pacific Ocean from North America through Japan.

Figure 11.7.6: Andisol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Vertisol

Vertisols are dark black soils rich in expandable clay minerals. The clay readily swells upon wetting and shrinks when dried. Though found in every type of climate, they are often found in steppe and wet/dry tropical climates where the soil develops deep cracks as it dries. Surface fragments fall into the cracks and are "swallowed" when the soil swells upon wetting. The soil then develops an "inverted profile" with organic material that is typically located near the surface of the profile is now found at depth.

Figure 11.7.7: Vertisol. Click image to enlarge (Image Source: Soil Science Division at the University of Idaho; Used with permission)

Mollisol

Mollisols are among the most fertile soils on the Earth. Born under grassland vegetation, these soils are well-known for their dark brown to black organic rich surface layers. These soils have a granular structure and soft consistency when dry. Mollisols are rich in calcium and others nutrients, and generally posses high moisture retention. Calcium nodules are found near the base of the soil as calcium carbonate precipitates out of soil water. Mollisols are found in the drier portions of the humid continental climate through the steppe climate.

Figure 11.7.8: Mollisol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Spodosol

Spodosol soil is commonly found in cool, moist environments under coniferous forest vegetation. Surface litter composed of pine needles breaks down in the presence of water to form a weak organic acid. Acidic soil water removes base ions in solution to create an acidic soil. Easily dissolved materials are leached from surface layers leaving behind the most resistant material like quartz, creating an ashy-gray near-surface layer. Layers at depth are stained with iron and aluminum oxides.

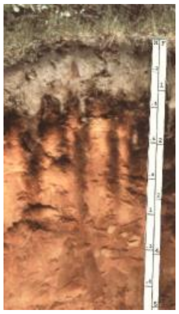


Figure 11.7.9: Spodosol. Click image to enlarge (Image Source: USDA NRCS; Used with permission)

Alfisol

Alfisols are soils developed under temperate forests of the humid midlatitudes. Eluviation is moderate and base status is fairly high in these soils. Common to the humid continental (like the one in Michigan on the left) and humid subtropical climates, these soils are well-developed and contain a subsurface layer of clay called an argillic horizon. Some alfisols are found in the wet/dry tropical climate of Africa, South America, Australia, and Southeast Asia. Having a favorable moisture balance and good fertility, they are very productive soils for agriculture. In fact, they have been successfully used for farming in China and Europe for thousands of years. Alfisols are abundant on older glacial deposits in the United States, and loess deposits in and near the Mississippi embayment.

Figure 11.7.10: Alfisol. Click image to enlarge (Image Source: USDA NRCS; Used with permission)

Ultisol

Ultisols share many of the same properties as Oxisols. Highly weathered soils, they are often red/yellow in color reflecting the oxidation of iron and aluminum. Found in the moister portions of the Humid Subtropical climate, they have a illuvial clay layer which distinguishes them from Oxisols which do not.

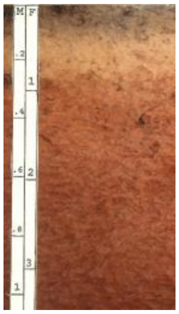


Figure 11.7.11: Ultisol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

Oxisol

Oxisol soil is found in warm, rainy climates under broadleaf, evergreen vegetation like that found in the rain forest. Chemical weathering (especially oxidation) in the presence of warm temperatures combined with heavy rainfall creates a soil rich in iron and aluminum oxides called "sesquioxides". A rich diversity of decomposers, rapid uptake by vegetation, and heavy precipitation quickly removes nutrients from the soil. What is left is a nutrient poor soil, not well-suited for agriculture. Cleared of vegetation, the exposed surface is easily eroded.

Figure 11.7.12: Oxisol. Click image to enlarge (Image Source: USDA NRCS Used with permission)

? Self-Assessment 11.7.1

Which of the following soil forming processes created this oxisol?

Laterization, Podzolization, or Calcification?

Answer

Laterization

Gelisol

Gelisol soil develops on permafrost and common to the tundra. These soils consist of mineral or organic material, or both and have experienced cryoturbation (frost churning) due to annual freeze-thaw cycles.

Figure 11.7.13: Gelisol. Click image to enlarge (Image Source: USDA NRCS; Used with permission)

11.8: Review and Additional Resources

Review

Determining soil color. Courtesy NRCS

Figure 11.8.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **Parent material**
  the material that soil develops from, and may be rock that has decomposed in place, or material that has been deposited by wind, water, or ice
- **Soil forming factors**
  parent material, climate, topography, organisms, and time
- **Soil horizon**
  different colored layers; form as a result of the four horizon development processes, additions, transformation, translocation, and removal
- **O horizon**
  primarily composed of organic matter; filled with nutrients and has strong soil moisture retention
- **A horizon**
  the beginning of the true mineral soil; organic material mixed with inorganic products of weathering; typically dark colored due to the presence organic matter
- **E horizon**
  generally light-colored with eluviation being the dominant process; Leaching is active in this horizon
- **B horizon**
  accumulation of fine material leads to the creation of a dense layer
- **C horizon**
  the soil parent material, either created in situ or transported into its present location
- **Soil profile**
  All the horizons taken together
- **Humus**

dark brown, nutrient-rich material made from decomposed leaves and plant roots.

- **Material addition**
  materials that are transported into the location where a soil is forming
- **Material transformation**
  occur by chemical and biological processes acting on them
- **Material translocation**
  involves the movement of soil-forming materials through the developing soil profile
- **Material removal**
  the materials are completely removed from the soil profile
- **pH scale**
  how hydrogen ion concentration in the soil is measured
- **Bulk density**
  the mass per unit volume including the pore space
- **Soil structure**
  the way soil particles aggregate together into peds.
- **Soil texture**
  refers to the relative proportion of sand, silt and clay size particles in a sample of soil
- **Ped**
  soil structure forms; come in a variety of shapes depending on the texture, composition, and environment
- **Granular structure**
  crumb structures, look like cookie crumbs. They tend to form an open structure that allows water and air to penetrate the soil
- **Platy structure**
  looks like stacks of dinner plates overlaying one another. Platy structure tends to impede the downward movement of water and plant roots through the soil
- **Physical weathering**
  aka *mechanical weathering;* the breakdown of large pieces of earth material into smaller ones
- **Chemical weathering**
  breaks down earth material by chemical alteration
- **Laterization**
  occurs in the hot, rainy tropics where chemical weathering proceeds rapidly
- **Podzolization**
  The E horizon is heavily leached and basically composed a of light colored layer of sand. The upper portion of the B horizon is stained reddish color from the accumulation of sesquioxides. The profile gets lighter in color as depth increases.
- **Calcification**

Soil tends to be rich in organic matter and high in soluble bases. The B horizon of the soil is enriched with calcium carbonate

- **Gleization**

  occurs in regions of high rainfall and low-lying areas that may be naturally waterlogged. Bacterial activity is slowed, inhibiting the decomposition of dead vegetation. Peat is found in the upper portion of the soil. the soil has a black to bluish - gray color.

- **Salinization**

  occurs in warm and dry locations where soluble salts precipitate from water and accumulate in the soil. Salt may also accumulate in soils from sea spray.

- **Oxisol**

  Chemical weathering in the presence of warm temperatures combined with heavy rainfall creates a soil rich in iron and aluminum oxides. A rich diversity of decomposers, rapid uptake by vegetation, and heavy precipitation quickly removes nutrients from the soil. What is left is a nutrient poor soil, not well-suited for agriculture. Cleared of vegetation, the exposed surface is easily eroded.

- **Ultisol**

  Highly weathered soils, they are often red/yellow in color. Found in the moister portions of the Humid Subtropical climate, they have a illuvial clay layer

- **Alfisol**

  Eluviation is moderate and base status is fairly high; well-developed and contain a subsurface layer of clay. Having a favorable moisture balance and good fertility, they are very productive soils for agriculture.

- **Spodosol**

  Surface litter breaks down in the presence of water to form a weak organic acid. Acidic soil water removes base ions in solution to create an acidic soil. Easily dissolved materials are leached from surface layers leaving behind the most resistant material creating an ashy-gray near-surface layer. Layers at depth are stained with iron and aluminum oxides.

- **Mollisol**

  well-known for their dark brown to black organic rich surface layers; have a granular structure and soft consistency when dry. Rich in calcium and others nutrients, and generally posses high moisture retention. Calcium nodules are found near the base of the soil as calcium carbonate precipitates out of soil water.

- **Entisol**

  soils lacking horizons because their parent material has only recently accumulated. Also form where the parent material is quartz sand, in which horizons do not easily form.

- **Inceptisol**

  soils just starting to show horizon development

- **Histosol**

  have a very high content of organic matter in the dark upper layer of the profile. Form in places where organic matter is slow to decompose and thus accumulates over time such as bogs and swamps.

- **Aridisol**

  typically light in color as there is little organic matter. A negative moisture balance in these soils inhibits eluviation. Calcification and salinization are acting in these soils. Soil horizons are weakly developed and sodium is often high in concentration.

- **Andisol**

Soils developing in parent material containing at least fifty percent volcanic ash; support a dense natural cover in moist climates.

- **Vertisol**

  Dark black soils rich in expandable clay minerals. The clay readily swells upon wetting and shrinks when dried. Surface fragments fall into the cracks and are "swallowed" when the soil swells upon wetting. The soil then develops an "inverted profile" with organic material that is typically located near the surface of the profile is now found at depth.

Review Questions 11.8.1

Which soil orders lack noticeable horizons?

Answer

Entisols lack noticeable horizons as parent material has not undergone significant weathering processes. On the other hand, oxisols may be so strongly weathered that visually distinguishing horizons can be difficult.

Which soil order has the highest organic content?

Answer

Histosols are noted for high organic content. Peat can be mined from histosols.

Describe the various soil forming processes.

Answer

Soil forming processes are what determine the type of soil that forms. **Podzolization** - Cool, humid environments; needle leaf forest cover common. Leads to the development of soils that are acidic, have an ash-grey E-horizon. Spodosols. **Laterization** - warm, humid environments; broadleaf evergreen forest cover. Creates highly oxidized soils that are red/yellow in color. Oxisols; Ultisols. **Calcification** - warm, dry environments; grass cover. Creates soils rich in calcium carbonate; high base status. **Salinization** - warm, dry environments. Creates soils containing soluble salts.

Which vegetation biome is associated with mollisols?

Answer

Grassland

In which soil order might you find a subsurface layer of calcium carbonate?

Answer

Mollisol

Which soil order forms an "inverted soil profile"?

Answer

Vertisol

Which soil orders are associated with midlatitude temperate forests?

Answer

Alfisol

What impact do broadleaf deciduous trees have on the nutrient status of soils?

Answer

Broadleaf deciduous forest increase the nutrient base status of soil. A constant cycling of nutrients between the soil and tree occurs through decomposition of leaf litter and root uptake.

How does soil particle size influence field capacity, infiltration, and permeability?

Answer

Fine textured soils (small particle size) have more total pore space per unit volume than does coarse textured soils (large particle size). Fine textured soils have high field capacity than coarse textured soils. Coarse textured soil has larger, better connected pore space yielding greater infiltration and permeability compared to fine textured soil.

What is soil texture and why is it important?

Answer

Soil texture is the relative proportions of sand, silt, and clay size particles. Soil texture effects such processes as infiltration, permeability, and field capacity.

? Self-Assessment Quiz 11.8.1

1. The zone of illuviation is commonly the
   A. O horizon
   B. A horizon
   C. B horizon
   D. C horizon
2. A soil texture with 30% Clay, 30 % silt, and 40% Sand is classified as a
   A. loam
   B. clay loam
   C. silty clay loam
   D. sandy clay
3. Which of the following soil structures would impede the infiltration of water the most?
   A. Platy
   B. Blocky
   C. Crumb
   D. Columnar
4. Which of the following soil orders is most associated with broadleaf deciduous temperate forests?
   A. Spodosol
   B. Aridisol
   C. Mollisol
   D. Alfisol
5. Soil profiles are likely to be the least developed
   A. at the top of a hill
   B. at the middle of a hill slope
   C. a slight distance ahead of a hill slope
   D. none of the above as hill slope site has nothing to do with soil development
6. Which of the following soil horizon processes creates the acidification of soils by the break down of organic matter?
   A. Additions
   B. Removals
   C. Transformation
   D. Transfer
7. Which of the following is not a soil forming factor?
   A. Time

B. Organisms
C. Parent material
D. Season

climate map

8. Which of the following soil forming processes is likely occurring at letter L
   A. Calcification
   B. Laterization
   C. Podzolization
   D. Acidification
9. Which soil would I most likely find at location E
   A. Spodosol
   B. Ultisol
   C. Mollisol
   D. Aridisol
10. Which soil would I most likely find at location C
    A. Spodosol
    B. Ultisol
    C. Mollisol
    D. Aridisol

Answer

1. C
2. B
3. A
4. D
5. B
6. C
7. D
8. A
9. B
10. A

Additional Resources

Use these resources to further explore the world of geography

Connections: "How to green the world's deserts and reverse climate change | Allan Savory" TED Talk

Web Sites

Natural Resources Conservation Service

States Soils - NRCS

CHAPTER OVERVIEW

12: Biogeography of the Earth

Learning Objectives

By the end of the chapter you should be able to:

- Compare and contrast ecology and biogeography
- Describe habitat and niche and how they relate to one another.
- Explain how habitats are occupied by plants and animals.
- Describe the processes of photosynthesis, transpiration, and respiration.
- Define net biomass productivity and how it relates to climate, soils and nutrient availability.
- Define succession and describe how succession occurs in terrestrial ecosystems.
- Describe the first and second laws of thermodynamics and how they relate to trophic levels and food chains.
- Explain how plants have adapted to light and moisture availability

The distribution of biotic systems is related to the variation in climate, soils, and topography on Earth. Over eons of time, plants and animals have occupied and adapted to the particular environmental conditions in which they live. The giant saguaro cactus stores water in fleshy stems to nourish itself in the hot desert, while the heavy, shaggy coat of the musk oxen helps protect it from the cold arctic wind. In this chapter you will become familiar with what affects the geographic distribution of plant and animal species.

The animation of net primary productivity below shows the net gain in chemical energy from atmospheric or aquatic carbon dioxide. Highly productive regions are dark green, less productive light brown. Watch the animation by clicking the play button and describe what you see.

Seasonal Changes in Net Primary Productivity (Courtesy: NASA Earth Observatory)

The most productive regions appear through the tropics, while the subtropics show very low productivity. The region of high net productivity shifts north and south through the year. Why does this spatial and temporal pattern in net primary productivity occur and what are the implications? Will this pattern change in the future?

12.1: Fundamentals of Biogeography and Ecology

12.1.1: Biogeography and ecological systems

12.1.2: Habitat Occupation

12.1.3: Principle of Limiting Factors

12.2: Ecology of Vegetation and Plant Succession

12.3: Energy Flow Through Ecosystems

12.4: Review and Additional Resources

SECTION OVERVIEW

12.1: Fundamentals of Biogeography and Ecology

12.1.1: Biogeography and ecological systems

12.1.2: Habitat Occupation

12.1.3: Principle of Limiting Factors

12.1.1: Biogeography and ecological systems

Biogeography is the study of the geographical patterns of plant and animal species. To understand the distribution of plant and animal species on Earth, a fundamental knowledge of ecology and ecosystem dynamics is required. **Ecology** is the study of the interactions among organisms. An **ecosystem** is a functioning entity of all the organisms in a biological system generally in equilibrium with the inputs and outputs of energy and materials in a particular environment. It is the basic ecological unit of study. There are two kinds of ecosystems, aquatic and terrestrial. An ecosystem is comprised of habitats, biological communities, and ecotones.

A **biome** is often referred to as a global-scale community of plants and animals and is the largest subdivision of the biosphere. A biome may contain many different kinds of smaller ecosystems. Biomes are typically distinguished on the basis of the characteristics of their vegetation because it makes up the largest portion of biomass. Biomes are subdivided by **formation class**, vegetation units of a dominant species.

Video: Biomes (Courtesy of Great Pacific Media)

A **habitat** is the natural environment in which an organism lives. Most African elephants live on savannas and in dry woodlands. Bass prefer a habitat of warm, calm, clear water and are usually found in slow-moving streams, ponds, lakes, and reservoirs. Habitats can be identified at different spatial scales. **Macrohabitats** are delineated by climate and subdivided on the basis of their vegetation. **Microhabitats** are smaller in size, such as the habitat along a stream channel or a layer within the canopy of a rain forest. Each species has specific habitat parameters (temperature, moisture, and nutrient availability).

Figure 12.1.1.1: Beaver habitat. Beaver are known for how they create their own habitats by constructing dams on streams to impound water, then build their "lodges" in the resulting pond. (Source: United States Fish and Wildlife Service)

Within a habitat, organisms "occupy" a **niche**. A **niche** is the function or occupation, of a life-form within a community. An organism's niche incorporates the physical (habitat), chemical, and biological factors that maintains the health and vitality of the organism. An organism's interaction with the abiotic factors of its environment (heat and moisture) defines its niche. The food requirements, and those that prey on it, are part of the organism's niche. A niche, therefore, is the sum of an organism's physiological adaptation to, and interaction with, its physical environment.

The variation of life determines the **biodiverisity** of an ecosystem. The biodiversity of an ecosystem reflects the variety and abundance of plant and animal species within it. It includes the variety of habitat types with a landscape that support life. Watch the video "*Why Biodiversity Matters*" to appreciate our dependence of biodiversty.

Video: Why Biodiversity Matters. (Courtesy of the David Suzuki Foundation)

12.1.2: Habitat Occupation

The effectiveness of an organism to occupy a habitat depends in part on its means of transportation. Animals must use their own locomotion, while plants disperse by wind, running water, ocean currents, and animals. Thus, climate and topographic barriers are more of an impediment to animals than plants. For either, continental drift poses a significant barrier to diffusion. The separation of continents has isolated plants and animals in the past thus preventing their complete occupation of a suitable habitat. Continental collisions have opened land bridges for habitat occupation. Sea level changes have similarly affected plant and animal distributions. Lowered sea level, as what occurred during the last ice ages, resulted in chains of islands being connected opening migration routes for animal and plant species. Sea level rise during post-glacial times isolated habitats. Isolation thus prevented plant and animal migration. Presently, trends in global warming are affecting the distribution of parasites carrying infectious diseases. In a June 2002 All Things Considered report it was noted that malaria-bearing mosquitoes from lower elevations are invading mountain ecosystems at higher elevations as temperatures rise, affecting Hawaiian bird populations. (4:41)

Figure 12.1.2.1: Influence of sea-level fluctuation on dispersal of species

Sometimes humans aid in the dispersal of plants and animals. Humans have intentionally or unintentionally introduced species into habitats that they would otherwise not have been able to on their own, sometimes with disastrous effects. The inadvertent introduction of the African Honey Bee in South America is a notable example. Imported to spur production of honey by mating with other native species, this aggressive bee was accidentally released. With few natural predators, populations exploded and has migrated to the southern United States. People have been attacked by swarms of these "killer bees" when disturbing them. Hawaii's biota evolved in relative isolation. But after its discovery by white culture, the inadvertent, and the sometimes purposeful introduction of alien plant and animal species, have endangered Hawaii's native organisms. *All Things Considered* (NPR) segment from March 21, 2000 "Hawaii Extinction" reports on how Hawaii's geographical isolation makes its native organisms especially vulnerable to extinction by alien plant and animal introductions. (12:07)

Human activities have profound effects on habitats. To find out more continue "Digging Deeper: Habitat Degradation and Human Activity" or skip and keep reading.

Digging Deeper: Habitat Degradation and Human Activity

Habitat encroachment, fragmentation, and destruction has produced a plethora of problems. Habitat destruction is a leading cause of species endangerment. Habitat encroachment increases the contact between human populations and animal populations. Shrinking habitat and accessible sources of food from expanding urban and suburban land use have brought animals and humans into conflict. The loss of tiger prey and presence of livestock have increased attacks on villagers living near tiger habitat in India. Alligators in homeowners backyards is becoming a more frequent site in Florida as urban sprawl invades the state's wetlands. Deer are a nuisance in many suburban areas, destroying gardens and posing a threat to motorists.

Habitat encroachment is responsible for the recent emergence of diseases like Ebola as a threat to humans. Intact habitats tend to inhibit the spread of infectious agents. Damaged, altered, and degraded habitats trigger the spread of new and existing diseases to humans. A 2005 United Nations Global Environment Outlook Year Book 2004/5 reported that the deadly Nipah virus, normally found in Asian fruit bats, is believed to have passed over to humans. Land clearance for palm plantations brought bats in contact with swine, and then humans as their habitat shrunk. The geographic range and seasonality of mosquito-borne diseases like malaria and dengue fever, are very sensitive to changes in climate.

Illegal logging is the greatest threat to the survival of the orangutan. Native to the Indian Ocean islands of Sumatra, it is estimated that no more that 60,000 wild orangutans are left worldwide, half the population that existed a mere 10 years ago. Forest fires, poaching and conversion of jungles to palm plantations have also decimated their populations. Living in trees, the great apes feed on insects and fruits, and in turn, disperse seeds that regenerate the tropical forests. In spite of government declarations to curb illegal logging, environmental activists blame political corruption, and of will and insufficient resources to halt the multibillion dollar illegal logging activity.

Human conflict has deviated habitats and threatened biodiversity in many regions, especially Africa. But remarkably, some have managed to survive. Listen to NPR's report "After Sudan's Civil War, Where The Wild Things Are" and learn the region is hoping to capitalize on eco-tourism.

Miguel Juarez for NPR

npr

Share

Africa

After Sudan's Civil War, Where The Wild Things Are

Listen 7:51

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Wildlife Corridors

Wildlife require large areas to seek out food, mates, and nesting sites. Habitat fragmentation restricts wildlife movement resulting in overcrowding, over exploitation of resources and species endangerment. Scientists are attempting to preserve wildlife by creating corridors between fragmented portions of habitat. Wildlife corridors allow young animals to seek new territory and maintain gene flow between individual habitats thus improving species fitness. Only recently have scientists been able to show that wildlife corridors work.

Figure 12.1.2.2: Wildlife corridors connect critical habitats in the agricultural heartland of Iowa. (Courtesy NRCS)

Wildlife corridors like those seen here in Iowa permit animals to exploit a variety of resources without having to cross unfriendly terrain like roads, lawns, or barren farm fields.

The Terai Arc is a fifty year effort to reconnect 11 national parks in India and Nepal with one continuous corridor of protected areas. Preliminary data from the Khata corridor between Nepal's Royal Bardia National Park and the Katarniaghat Wildlife Sanctuary of India show use by tigers and elephants. The presence of Spotted Deer and Wild Boar hoof prints provide additional evidence of corridor use.

12.1.3: Principle of Limiting Factors

The plants and animals that succeed in occupying a particular niche are those that can easily adapt to the unique environmental conditions of a site. Each plant and animal in the community has a specific range of tolerance for particular environmental conditions. Climate factors are the most important influence over the successful establishment of plant and animal communities. Two climatic factors are important, sunlight and moisture.

Not only is the *amount* of sunlight available important but the *duration and quality* of light are important too. For instance, at high altitudes the intense ultra violet light may inhibit the growth of particular plants. The *intensity* of light affects photosynthesis and rate of primary productivity. The duration of sunlight affects the flowering of plants and the activity patterns of animals. The availability of water is important for the survival of most life forms. But plants require water for a number of life processes like germination, growth and reproduction too. The **principle of limiting factors** says that the maximum obtainable rate of photosynthesis is limited by whichever basic resource of plant growth is in least supply. The availability of energy and moisture varies geographically. At high latitudes the limiting factor is generally energy availability while in low latitudes moisture is the limiting factor to growth. The diagram below shows the relationship between potential evapotranspiration, a moisture index, climate and vegetation.

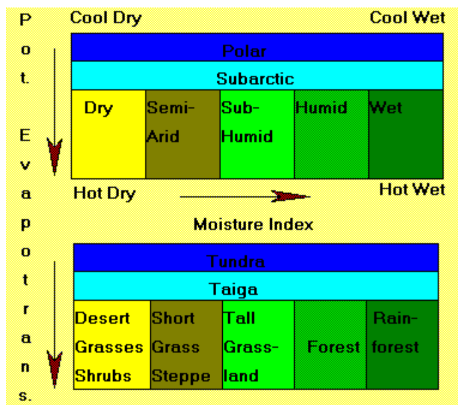


Figure 12.1.3.1: Relationship between climate, vegetation potential evapotranspiration and the moisture index.

The figure on the left shows the relationship between potential evapotranspiration (PE), a moisture index (MI), climate and vegetation. Potential evapotranspiration is the optimal amount of water entering the atmosphere as a result of evaporation and plant transpiration when there is an unlimited amount of moisture. Because evaporation and transpiration depend on energy availability, potential evapotranspiration is a measure of energy input. High values of potential evapotranspiration relate to warm climates while low values to cool climates. The moisture index is a measure of moisture availability. High values of the moisture index means that plenty of water is available. Combining the two variables, potential evapotranspiration and moisture index we have a notion of what the climate is like in any part of the diagrams. For instance, high PE and large values of MI are indicative of warm and moist climates. Note that tundra and taiga (mostly conifers) are successfully established over a wide range of moisture conditions, from dry to moist, but always in cool environments. Other vegetation systems have more narrowly defined moisture and temperature requirements.

Plants of a particular region have adapted to the temperature and moisture conditions in which they live. Most gardeners are familiar with plant hardiness (growing) zone maps. The zones are based on the minimum temperature experienced and thus tolerated by different species of plants. There have been recent signs that these zones are starting to shift due to global warming.

12.2: Ecology of Vegetation and Plant Succession

Principal Adaptive Strategies of Vegetation

Plants evolve a variety of adaptations to the light and moisture availability within a particular environment in order to flourish. Plants adaptations include those of leaf form and canopy structure (the roof of foliage formed by the crowns of trees). For instance, a hard, needle leaf structure is an adaptation to extreme temperatures and low moisture status in winter. The leaves of some rain forest trees have a special joint at the bottom of their stalk that enables them to twist and turn to follow the light as the sun passes from east to west over head. Deciduous trees drop their leaves to cut transpiration loss during dry periods and when temperatures are very cold.

Conifer needles are an important adaptation to the extreme conditions present in the climate of the boreal forest. Pine needles contain very little sap, so freezing is not much of a problem. Conifer needles have a unique structure which limits the loss of water, a precious commodity in this environment. Pine needles have fewer stomata than broadleaf tree leaves. The stomata are recessed into pits on the needle and aligned in a groove on its underside. The groove in the needle creates a small layer of still air which slows the loss of water vapor by diffusion. Water loss is further reduced by the thick waxy coating common to pine needles. Water is "shut off" from the tree when the ground completely freezes. Under these circumstances the stomata close-up to prevent loss of water from the tree.

Figure 12.2.1: A Baobab tree, with its thick trunk and large edible fruit, Dakar, Senegal. (UN/DPI Photo #187250C by Evan Schneider Used with permission)

Figure 12.2.2: Semidesert vegetation of Arizona (Photo Credit: U.S. G.S. DDS21)

Fleshy "leaves", like those of desert succulents or thick skin like that of the giant Saguaro cactus helps retain moisture. The Baobab tree, found in the wet/dry tropical (savanna) climate stores water in its trunk to combat the long drought period experienced in that climate.

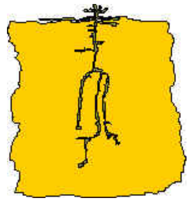


Figure 12.2.3: Rooting system adaptation. Grasses which can't store much water must rely on deep root systems to extract water held far below the surface

Figure 12.2.4: Curled leaf of desert grass

Plants have adapted particular root structures to live in arid regions. Deep tap roots draw moisture hidden deep below the surface while extensive near - surface root systems catch moisture as it infiltrates into soil. The Havard Oak (Figure 12.*) is a shrub found in the semi-arid southwestern United States. It is well adapted to the dry conditions having an extensive root system and tap roots that extend 15 to 20 feet deep. Tap roots "equal to a man's thigh" are not uncommon. Above ground, thick waxy leaves reduce water loss through transpiration.Some desert grasses have rolled surfaces to reduce water loss from the inner surface and hairs which reduce air movement.

Figure 12.2.5: Havard Oak *Q. havardii* (Photograph courtesy Michael Ritter)

Canopy structures reflect the environmental conditions vegetation grows in. The conical canopies of conifers help shed snow and catch low angle sun rays during the long winters where they grow. The rain forest displays a multi-layered canopy. Each layer possesses organisms adapted to the environmental conditions found in it. A canopy can be so thick and dense, like that found in the rain forest, that little light penetrates to the surface. The lack of light for understory growth creates an **open forest structure** that you can see into for some distance. Where canopy density is low, more light filters to the surface creating a thick ground cover and a **closed forest structure**. Standing on the floor of a closed forest, it's nearly impossible to see more than a few meters into it.

Plant Communities

Rarely is any location dominated by a single specie of plant. A **plant community** refers to the associated plant species that form the natural vegetation of any place. For instance, a midlatitude forest is comprised of a community of trees, shrubs, ferns, grasses, and flowering herbs. Plant communities provide a habitat for animals and significantly modify the local environment. Plant communities affect soil type when organic material decomposes into the soil altering soil moisture retention, infiltration capacity, soil structure and soil chemistry. Trees shade the forest floor, reducing incident solar radiation and lowering temperatures of both the soil and the air. Reduced incident light decreases evaporation keeping soils moister beneath the forest canopy. These impacts affect animal habitats and the diversity of animal species which are associated with these plant communities.

Figure 12.2.6: Mixed deciduous - evergreen forest community is a transitional community between needleleaf forest and deciduous forest (Wisconsin, U.S.A.) (Photo credit: U.S. Conservation Service)

An **ecotone** is a plant community in a distinct zone of transition between other more extensive communities. Ecotones vary in scale, from local (between forest and field) to global (savannas). Within an ecotone plants of different environmental tolerances often intermingle. For instance, grasses adapted to low moisture conditions intermingle with deciduous trees within a prairie - forest ecotone.

Plant Succession

Figure 12.2.7: Fireweed reestablishing on the devastated slopes of Mt. St. Helens. (Courtesy USGS CVO)

Natural vegetation of a particular location evolves in a sequence of steps involving different plant communities. The evolutionary process is known as **plant succession**. Plant succession usually begins with a fairly simple community known as a **pioneer community**. The pioneer community, and each successive community alters the environment in such a way to permit new communities to occupy a site. These alterations of the environment include changes in site microclimate and soil conditions.

A **climax community** is the result of a long period of plant succession. Climax communities usually exhibit a good deal of species diversity and thus are relatively stable systems. Disturbance renews a successional sequence. Plant succession was renewed after the explosion of Mt. St. Helens with the subsequent disruption of biotic communities that inhabited the region. Human disturbance related to tropical deforestation has renewed the successional sequence of plant communities in the tropical rain forest.

Video: "Climax Communities Are Largely Stable" (Courtesy of Great Pacific Media)

12.3: Energy Flow Through Ecosystems

Energy capture and use

Photosynthesis

At the base of an ecosystem, primary producers are actively converting solar energy into stored chemical energy. **Photosynthesis** is the process of converting solar energy, water, and carbon dioxide into carbohydrates and oxygen. The process occurs in two steps: first light energy is absorbed by chlorophyll to split a molecule of water releasing hydrogen and oxygen. The second step uses the energy to convert carbon dioxide to carbohydrates.

$$6CO_2 + 12H_2O \xrightarrow[\text{(chlorophyll)}]{\text{Solar Energy}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$

The carbohydrate ($C_6H_{12}O_6$) can be converted into starch and stored by the plant. Carbohydrate can be combined with other sugar molecules to make cellulose, the basic structural material of a plant.

Video: "Photosynthesis". (Courtesy of Britannica)

Oddly enough, of all the solar radiation striking a plant, only about 1% is used in photosynthesis. The rate of photosynthesis is dependent on several things, especially the amount of light received ... up to a point. As solar radiation increases the rate of photosynthesis increases. For many plants there is an upper limit to the rate of photosynthesis. In some plants as incident solar radiation increases the rate of photosynthesis levels off, or may decrease. The increasing solar energy load causes the plant to be too hot and the need to cool the plant increases. As a result, transpiration takes over as the dominate plant process. **Transpiration**, the loss of water from plants, acts to cool the plant by releasing latent energy. Adequate supplies of water, carbon dioxide and the availability of nutrients in the soil affect photosynthesis.

Respiration

While photosynthesis builds stored chemical energy in a plant, respiration is the process of "burning" stored chemical energy, basically through oxidation, for maintaining plant metabolism. During plant respiration, carbohydrates combine with oxygen and is reduced to carbon dioxide, water, and heat.

$$C_6H_{12}O_6 + 6O_2 \text{ ---> } 6CO_2 + 6H_2O + 2830 \text{ kj}$$

While photosynthesis operates only during day when sunshine is available, respiration goes on both night and day. Plant growth occurs so long as photosynthesis exceeds respiration.

Transpiration

Transpiration is the loss of water from plant leaves. Water exits the leaf through **stomata**, which are tiny pore spaces in the leaf. The rate of transpiration depends on air temperature and solar radiation. As pointed out earlier, transpiration is a cooing process for plants when temperatures or incident light rise too high and cause heating of the plant. Low humidity, often aided by windy conditions, creates a vapor gradient between the plant and the air. This too induces transpiration. Soil factors are important control over transpiration. If the pore space between soil particles are too large the soil will have poor or low soil capillary. That is, the rate of water rise is too low for plants to extract water from the soil and maintain proper moisture supply. Low soil capillary results from soil drying too. During the moist season, ample soil water is available to line soil particles to aid the movement of soil water upwards to the root zone.

However, during the dry season, a dry layer of soil develops beneath the root zone inhibiting the upward movement of capillary water causing a ***capillary lag***. The plant ultimately wilts as it cannot extract enough water to meet the increasing demand for water during warm seasons. A small soil moisture reserve will inhibit transpiration too.

Biomass Productivity

Net biomass productivity is the difference between gross productivity (production of plant material by photosynthesis) and respiration. So long as the rate of production exceeds that of respiration, the plant will grow. Net productivity represents the amount of organic material produced by a plant. Net productivity is closely related to a number of environmental factors like climate, soils, and available nutrients. Net biomass production will be highest where there is an ample supply of moisture to meet the needs of plants. Biomass productivity is also high where soils are rich in nutrients and have a positive soil moisture balance. The figure below illustrates this well. With ample rainfall and sunlight, the tropical rain forest ranks the highest in terms of organic matter production.

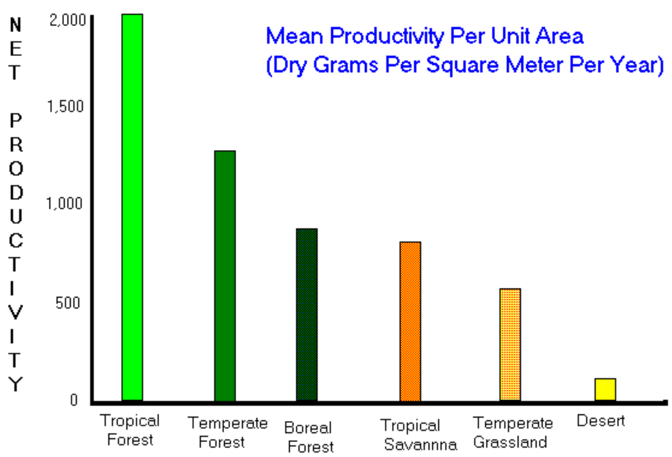


Figure 12.3.1: Net productivity of selected environments

Human pressure on land and vegetation resources for food, wood-based fuel, fiber, and building materials is calling into question whether the earth's net production can sustain such use. Scientists are employing satellite technology to determine the trends in human consumption of net primary production as described in the video below. Human use of earth's annual production rose from 20 to 25 percent from 1995 to 2005. As society looks to land conversion for biofuels, climate changes, and biodiversity loss occurs, a tipping point at which net production fails to meet demand may be reached in the not so distant future.

Video: Human Consumption of NPP. (Courtesy NASA GSFC)

Trophic Levels and Food Chains

The biotic elements that comprise an ecosystem fall into one of several **trophic levels**. The **trophic level** of an organism is its position in a ***food chain***, the sequence of consumption and energy transfer through the environment. For example, a simple grazing food chain is comprised of

Plant -> herbivore -> carnivore

Figure 12.3.2: Mushrooms are important for cycling nutrients through ecosystems. (Courtesy U.S. Bureau of Land Management. Source)

At the base of the food chain lies the **primary producers**. Primary producers are principally green plants and certain bacteria. They convert solar energy into organic energy. Above the primary producers are the **consumers** who ingest live plants or the prey of others. **Decomposers**, such as, bacteria, molds, and fungi make use of energy stored in already dead plant and animal tissues. Fungi, like mushrooms, absorb nutrients from the organisms by secreting enzymes to break up the chemical compounds that make up dead plants and animals.

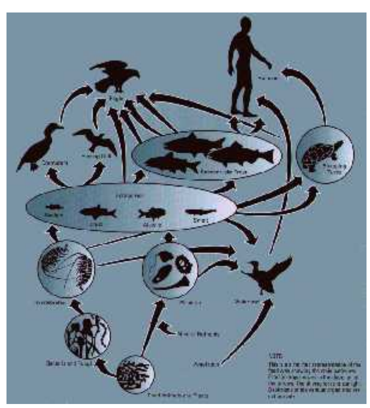


Figure 12.3.1: Great Lakes food web (Courtesy EPA GLINP; Click image to enlarge)

Two laws of physics are important in the study of energy flow through ecosystems. The **first law of thermodynamics** states that energy cannot be created or destroyed; it can only be changed from one form to another. Energy for the functioning of an ecosystem comes from the Sun. Solar energy is absorbed by plants where in it is converted to stored chemical energy.

The **second law of thermodynamics** states that whenever energy is transformed, there is a loss energy through the release of heat. This occurs when energy is transferred between trophic levels as illustrated in a **food web**. When one animal feeds off another, there is a loss of heat (energy) in the process. Additional loss of energy occurs during respiration and movement. Hence, more and more energy is lost as one moves up through trophic levels. This fact lends more credence to the advantages of a vegetarian diet. For example, 1350 kilograms of corn and soybeans is capable of supporting one person if converted to beef. However, 1350 kilograms of soybeans and corn utilized directly without converting to beef will support 22 people!

12.4: Review and Additional Resources

Review

Figure 12.4.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **Biogeography**
  the study of the geographical patterns of plant and animal species
- **Ecology**
  the study of the interactions among organisms
- **ecosystem**
  a functioning entity of all the organisms in a biological system generally in equilibrium with the inputs and outputs of energy and materials in a particular environment
- **habitat**
  the natural environment in which an organism lives
- **niche**
  the function or occupation, of a life-form within a community. An organism's niche incorporates the physical (habitat), chemical, and biological factors that maintains the health and vitality of the organism.
- **photosynthesis**
  the process of converting solar energy, water, and carbon dioxide into carbohydrates and oxygen
- **transpiration**
  the loss of water from plant leaves
- **respiration**
  the process of "burning" stored chemical energy, basically through oxidation, for maintaining plant metabolism
- **net biomass productivity**
  the difference between gross productivity (production of plant material by photosynthesis) and respiration
- **trophic level**
  an organism's position in a food chain

- **primary producer**

  the bottom of the food chain; They convert solar energy into organic energy.

- **decomposer**

  make use of energy stored in already dead plant and animal tissues

- **food chain**

  the sequence of consumption and energy transfer through the environment

- **First law of thermodynamics**

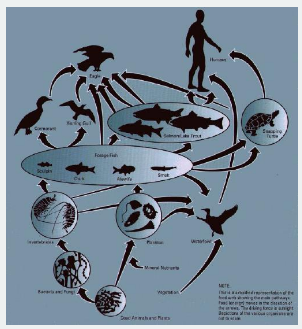
  energy cannot be created or destroyed

- **Second law of thermodynamics**

  whenever energy is transformed, there is a loss energy through the release of heat

- **food web**

  illustrates energy transfer between trophic levels



- **plant succession**

  evolution of natural vegetation of a particular location

- **open forest**

  lack of light for understory growth allows you to see into for some distance

- **closed forest**

  canopy density is low, more light filters to the surface creating a thick ground cover; nearly impossible to see more than a few meters into it

? Review Questions 12.4.1

How do plants and animals differ in their ability to occupy habitats?

Answer

The effectiveness of habitat occupation depends in part on the means of transportation. Animals must use their own locomotion, while plants disperse by wind, running water, ocean currents, and animals. Thus, climate and topographic barriers are more of an impediment to animals than plants. For either, continental drift poses a significant barrier to diffusion. The separation of continents has isolated plants and animals in the past thus preventing their complete occupation of a suitable habitat.

What is photosynthesis, respiration, and transpiration?

Answer

Photosynthesis is the process where by green plants convert carbon dioxide and energy into oxygen and stored carbohydrates. **Respiration** is the burning of stored chemical energy. **Transpiration** is the loss of water through the stomata of plant leaves.

What is the difference between a habitat and niche?

Answer

A **habitat** is the specific, physical location of an organism. Habitats can be identified at different spatial scales. A **niche** is the function or occupation, of a life-form within a community. An organism's niche incorporates the physical (habitat), chemical, and biological factors that maintains the health and vitality of the organism. An organism's interaction with the abiotic factors of its environment (heat and moisture) defines its niche.

Which biome has the largest annual amount of net primary production?

Answer

The tropical rain forest has the largest net primary production of all biomes.

How do plants adapt to extreme aridity?

Answer

Plants have adapted to dry conditions by evolving deep roots to extract water held deep beneath the surface. Some plants have extensive near surface root systems to catch infiltrating water, or thick fleshy leaves. Others have thick bark and or short waxy leaves to reduce transpiration. Plants go dormant during dry periods, drop their leaves, or have no leaves at all. They instead have thick moisture retentive, photosynthetic skin.

Describe the concpet of "plant succession".

Answer

Is the evolutionary process that tends toward a stable, diverse plant community (climax community). Each community prepares the environment for that which succeeds it.

What are the limiting factors to growth in the low latitudes? High Latitudes?

Answer

The limiting factor to growth in low latitudes is moisture. The limiting factor to growth in high latitudes is energy (solar radiation).

Explain what a food chain is. Your answer must include the concepts of trophic level, primary producer, consumer and decomposer.

Answer

A **food chain** is the sequence of consumption and energy transfer through an ecosystem. A food chain consists consists of different **trophic levels** which are the position of an organism in a food chain. At the base is the **primary producers** that convert solar energy into organic energy. Above the producers are the **consumers** that ingest live plants (primary consumer) or prey on other consumers (secondary consumer). **Decomposers** such as, bacteria, molds, and fungi make use of energy stored in already dead plant and animal tissues.

How do plant communities affect the local environment in which they are found?

Answer

Plant communities affect soil type when organic material decomposes into the soil altering soil moisture retention, infiltration capacity, soil structure and soil chemistry. Trees shade the forest floor, reducing incident solar radiation and lowering temperatures of both the soil and the air. Reduced incident light decreases evaporation keeping soils moister beneath the forest canopy. These impacts affect animal habitats and the diversity of animal species which are associated with these plant communities.

What is net biomass productivity and determines it? What types of environments produce high and low amounts of biomass productivity?

Answer

Net biomass productivity is the difference between gross productivity (production of plant material by photosynthesis) and respiration. Net productivity is closely related to a number of environmental factors like climate, soils, and available nutrients. Net biomass production will be highest where there is an ample supply of moisture to meet the needs of plants. Biomass productivity is also high where soils are rich in nutrients and have a positive soil moisture balance. Forest, especially tropical forest have high net biomass productivity while deserts have low productivity

? Self-Assessment Quiz 12.4.1

1. Desert plants have adapted to drought by having
   A. deep tap roots
   B. extensive near-surface root systems
   C. thick fleshy leaves
   D. all the above
2. "Energy cannot be created or destroyed" is a statement of the
   A. First Law of Thermodynamics
   B. Second Law of Thermodynamics
   C. The Adiabatic Law
   D. none of the above
3. Plant transpiration
   A. depends on the amount of water held in the soil
   B. cools the plant
   C. depends on the humidity of the air
   D. All of the above
4. A ______ is the natural environment in which an organism lives.
   A. habitat
   B. niche
   C. ecotone
   D. formation class
5. The function of a life-form within a community is called
   A. a niche
   B. an ecotone
   C. a habitat
   D. none of the above
6. The process of converting solar energy, water and carbon dioxide into carbohydrates and oxygen is called
   A. photosynthesis
   B. respiration
   C. transpiration
   D. none of the above
7. Climate and topographic barriers are more of an impediment to ___ than ____.
   A. plants; animals
   B. animals; plants
8. Deserts generally have ___ potential evapotranspiration and ___ moisture index.
   A. high; high

B. high; low
C. low; low
D. low; high

9. Which biome can be thought of as a "global-scale" ecotone?

A. Tundra
B. Forest
C. Grassland
D. Savanna

10. The multi-layered canpopy of the rain forest creates a(n) ____ forest structure.

A. open
B. closed

Answer

1. D
2. A
3. D
4. A
5. A
6. A
7. B
8. B
9. D
10. A

Additional Resources

Use these resources to further explore the world of geography

Connections: "Vietnam's Appetite For Rhino Horn Drives Poaching In Africa" (NPR, 2013)

World of Change: Global Biosphere (*NASA Earth Observatory*)

Multimedia

"Invasion of the Giant Pythons" Nature (PBS) Description from the site: "Florida's Everglades National Park is one of the last great wildlife refuges in the U.S., home to numerous endangered animals and plants, as well as alligators. But the park has become a dumping ground for a variety of non-native species, including what may be tens of thousands of Burmese pythons. Some were intentionally released by pet owners, others were set free when hurricanes hit Florida's animal warehouses. Pythons have moved into their new home with a vengeance, thriving in the protected wilderness and disrupting its delicate ecosystem. Follow scientists and snake hunters as they study the problem and try to find solutions to the growing crisis. This film premiered February 21, 2010."

"Alien Invasion" *Online News Hour with Jim Lehrer*. July 1, 2004 report on efforts to combat invasion of alien plant and animal species in the United States.

"Hot Times in Alaska" *Scientific American Frontiers*. This episode investigates the impact of climate change on Alaska's ecosystems.

World's Biggest Tiger Preserve - NPR/National Geographic *Radio Expeditions* visits The Hukawng Valley in Myanmar where an entire valley nearly the size of Vermont is being set aside as a tiger reserve.

"The Birds of the Boreal" NPR/National Geographic *Radio Expeditions*

"The Last American rain forest" - *Morning Edition* (NPR) segment from Oct. 22, 1998 reports on the last great temperate rain forest in America, Alaska's Tsongass National Forest. (8:36) (RealAudio Required)

"Drugs and Bugs" - Ethnobotanist Mark J. Plotkin, Ph.D, talks with host David Wright about the healing secrets of the rainforest in the segment of *All Things Considered* from July 23, 2000. (RealAudio Required)

Readings

Where Have All the Songbirds Gone? from the "Why Files " Web site

Grassland Initiative (NASA EOS)

"Root Causes of Biodiversity Loss" - *CIESN, World Resources Institute.*

Web Sites

Wild World: Terrestrial Ecoregions (NGS/WWF) - rich resource for information about global ecosystems. Organized by biogeographical realm.

Biodiversity Hotspots - investigate endangered regions at this web site.

CHAPTER OVERVIEW

13: Earth Biomes

Learning Objectives

By the end of this chapter you should be able to:

- Describe the characteristics of the 8 biogeographical realms.
- Descrube the major terrestrial biomes and locate them on a world map.
- Explain how human activities are affecting terrestrial biomes.

The biogeography of Earth is expressed by the mosaic of biomes that occupy its land and waters. In this chapter we'll look at the characteristics of Earth's terrestrial biomes and their distribution. We'll investigate how human activities are changing the distribution and diversity of plant and animal species, and suggest how our changing climate may affect Earth's biomes.

13.1: Patterns of the Biosphere
13.2: The Forest Biome
13.2.1: Tropical Forests
13.2.2: Midlatitude Forests
13.2.3: Northern Forests
13.3: Savanna Biome
13.4: Grassland Biome
13.5: The Desert Biome
13.6: Tundra Biome
13.7: Review and Additional Resources

13.1: Patterns of the Biosphere

The current distribution of plants and animals reflects a long evolutionary response to the changing climate and configuration of continents and oceans. Biomes are defined by the plants and animals adapted to the environmental conditions found in them. Like other physical systems, the geography of world biomes is highly dependent on climate. Recent climate change has already made small changes in the distribution of some plants and animals. If climate change continues into the future, the distribution of Earth biomes could be quite different.

Biogeographical Realms

Biogeographical realms are geographical regions out of which assemblages of plants and animals evolved and dispersed. The Nearctic realm includes most of North America and Greenland. THe Nearctic realm possesses a great diversity of biomes including the tundra, grassland, deciduous and coniferous forest, chaparral, and desert biomes. The Nearctic realm has been separated from Neotropical by deserts, and until recently, an absence of a land bridge between them. The Palaearctic realm stretched across Europe, most of Asia, the Mediterranean, North Africa. It is very similar to the Nearctic in terms of the diversity of biomes including tundra, grassland, deciduous and coniferous forest, chaparral, and desert biomes. The Neotropical realm found throughout most of central and South America is dominated by tropical forests, savannas, and deserts. The Afrotropical realm is inhabited by tropical forests, savannas, and deserts and is found in Africa south of the Sahara. The Australian (or Australasian) realm has a desert core, surrounded by tropical forest and savanna. The Australian realm boasts a unique variety of plants and animals as they have evolved in isolation from outside influence. Pouched marsupial mammals, like the Kangaroo, are found in the Australian realm. The Indomalayan realm includes much of southeast Asia and is nearly exclusively tropical forest. It was isolated from the Palaearctic by the Himalayan Mountains. The Indomalayan realm was previously separated by a sea lane that has subsequently been closed by continental drift. The Antarctic realm exhibits a diverse set of ecosystems from temperate forest and grassland in New Zealand to tundra and ice sheets in Antarctica. Many of New Zealand's mammals are like those frequenting Antarctic shores. The Oceanian realm includes tropical islands of the Pacific ocean and dominated by tropical forests. Physical barriers are often the most imposing barriers to diffusion.

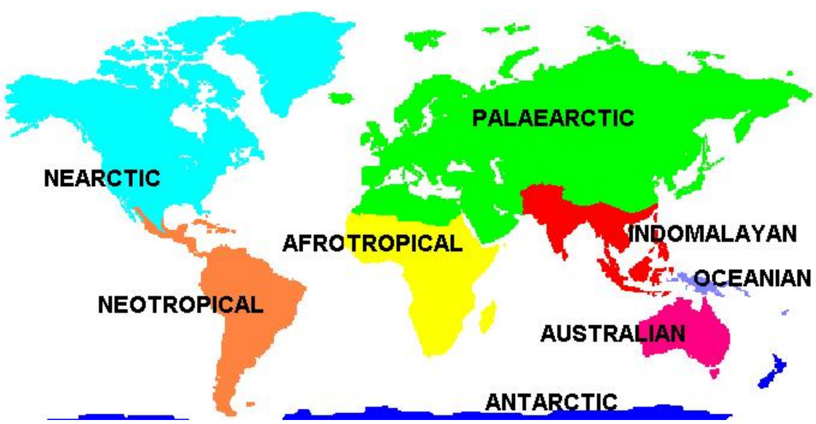


Figure 13.1.1: Biogeographical Realms

Biomes

In "The Fundamentals of Biogeography", a biome was defined as a large stable terrestrial ecosystem. Classification of biomes vary, and no one system dominates biogeography studies. Five principal biomes, forest, savanna, grassland, desert and tundra are distinguished on the basis of unique plant and animal communities are recognized in this book. Within each biome may be several formation classes that are vegetation units defined on the basis of the dominate plants in a terrestrial ecosystem. For instance, the forest biome includes the tropical rain forest, seasonal forest and shrub, Mediterranean woodland, Midlatitude broadleaf deciduous and mixed forests, broadleaf evergreen, and marine west coast forest to name a few.

SECTION OVERVIEW

13.2: The Forest Biome

The forest biome consists of close growing trees with leaf canopies that generally overlap. Much sunlight can be prevented from reaching the forest floor if tree limbs and foliage tightly intermingle. The lack of sunlight inhibits the development of undergrowth, creating an **open forest structure**. If the canopy is open, sunlight can reach the forest floor and promote the development of undergrowth resulting in a **closed forest structure**. Forests require ample amounts of annual precipitation to support their growth. The shaded conditions of the closed forest keep soils relatively moist.

Forests are found over a wide range of temperature regimes from the hot equatorial regions to the cold subarctic. Forests occupy approximately one third of Earth's land surface, but their areal extent is shrinking as humans cut the forest for material needs and economic gain.

13.2.1: Tropical Forests

13.2.2: Midlatitude Forests

13.2.3: Northern Forests

13.2.1: Tropical Forests

The Tropical Rain forest

The **Tropical Rain forest** contains trees standing 30 to 55 meters in height, creating a continuous canopy of foliage. The enclosed canopy shades the forest floor, creating an open forest formation. Few pure stands of trees exist in the rain forest. Instead, individual trees are widely dispersed throughout the forest. Mahogany, teak and other tropical hardwoods are harvested for creating fine furniture. The lush vegetation and great animal diversity should be expected in the tropical rain forest climate.

Figure 13.2.1.1: The multistory canopy of the tropical rain forest (Congo) (Image courtesy FAO)

Peering into the canopy reveals a multistory appearance of broad leaf, evergreen vegetation called "selva". The typical three-tiered zonation includes an *emergent layer* of solitary, giant trees reaching heights of 55 meters (180 ft) for the sunlight they require. Beneath is an intermediate zone (*canopy*) of continuous foliage 9 to 18 meters (30 to 60 ft) high. The forest floor is relatively open as the shade of the closed canopy inhibits plant growth. It is a damp and dim world as one walks through the aroma of decaying vegetation. Giant woody vines called "*lianas*" snake their way up the trunks of trees. *Epiphytes ("air plants")*, like the brilliantly colored bromeliad, grow in the hollows of trees or the upper surfaces of horizontally-growing branches capturing nutrients and moisture from the air.

Figure 13.2.1.2: Bromeliads clinging to a rain forest tree (Image courtesy FAO)

A cloud forest exists on extremely moist mountain slopes above the elevation of the true rain forest. The cloud forest differs from the rain forest found at lower elevations in that trees are much shorter and the forest floor is virtually impenetrable.

Plants have adapted to this environment in unique ways:

> *"The canopy itself, the ceiling of the jungle, is a dense continuous layer of greenery some 6 or 7 meters deep. Each leaf is accurately angled to ensure that it will collect the maximum amount of light. Many have a special joint at the base of the stalk that enables them to twist and follow the sun as it swings overhead from east to west each day. All except the topmost layer is screened from the wind, so the around them is warm and humid".*
>
> ***The Living Planet***
> D. Attenborough

The rain forest is a treasure trove of different animal and plant species. The numerous species that inhabit the rain forests are not well documented. The intense precipitation of the tropical rain forest climate heavily leaches the soil. Oxisol soil common to the rain forest is relatively infertile due to intense weathering and a lack of available nutrients. Deforestation and habitat destruction is severely crippling the rain forest ecosystem. View the "Secret Life of the Rainforest" provided by the Smithsonian Channel.

Tropical Monsoon/Seasonal Forest and Shrub

The Tropical Monsoon/Seasonal Forest and Shrub contains trees of smaller stature than those found in the rain forest. The Monsoon forest may include deciduous trees, as well as, broadleaf evergreen trees reflecting the seasonal precipitation of the monsoon climate. The trees of the Monsoon Forest have a more open canopy than the rain forest, creating a dense, closed forest at the floor, or what we think of as a "tropical jungle". The thick surface undergrowth makes navigating through the forest difficult. Jungle growth is also found along streams, and in openings created by humans.

Figure 13.2.1.3: Monsoon forest of India (Image courtesy; FAO)

Like the tropical rain forest, the monsoon forest supports a diversity of plant and animal species. And like the rain forest, it's biotic system is being stressed by human activities.

Investigate the effects of human activities on the tropical forest biome by "Digging Deeper: Human Activities and the tropical Forests" or continue to the next topic.

Digging Deeper: Human Activities and the Tropical Forests

Species Endangerment in the Tropical Forests

Habitat encroachment and destruction have been a primary cause of declining animal and plant species, threatening many with extinction. For example, habitat encroachment and sport hunting has led to the rapid decline of the Bengal tiger and are considered a threaten species. Solitary animals, tigers can weigh up to 500 pounds and measure nine feet in length. The main diet of the tiger consists of deer, antelope, and wild pig.

Figure 13.2.1.4: Sumatran Tiger (Image courtesy USFWS)

Logging and agriculture in the densely populated countries of southeast Asia have literally squeezed the tiger out of its home. Human encroachment on the tiger's habitat has led to more frequent conflicts between tigers and humans. However, human fatalities from tigers are a result of injured or sick animals to weak to hunt wild animals.

Sport hunting and killing to use body parts for traditional medicines since 1900 has significantly contributed to the decline of the tiger. In the early 1900's it was estimated that 100,000 tigers roamed Asia. In 1900, approximately 40,000 lived in India. By the 1960's this number fell to 4,000. By the early seventies fewer that 2,000 remained in India. Recognizing the potential loss of their national treasure, intensive conservation efforts by the Indian government and the world community has doubled their numbers in recent years. The world-wide population of tigers is estimated to be 5,100 to 7,500 individuals (World Wildlife Fund).

Illegal hunting to support the bush meat trade has taken a devastating toll on animal species. The bushmeat trade ranks among the greatest threats to tropical wildlife according to some environmentalists. Research has shown that increased poaching in Ghana has resulted in significant declines in 41 wild animal species. This research speculates that the bushmeat trade has grown partly in response to over fishing off West Africa by foreign and domestic industrial fleets. With dwindling resources for protein, people turn to the forest for food.

Deforestation in the Tropical Forests

Figure 13.2.1.5: Land clearing for agriculture on steep slopes in Uganda (Courtesy FAO)

Human activity has drastically altered the natural distribution of forests through history. Deforestation and habitat destruction is severely crippling the rain forest ecosystem. Rain forests are being destroyed at a rate of 78 million acres (31 million hectares) per year; an area larger than Poland. With habitat destruction comes loss of species. The World Resources Institute predicts that deforestation rates of 15 million hectares would reduce species in the closed canopy forests by 35% by 2040. In Brazil, the estimated average rate of destruction between 1979 - 1990 was 5.4 million acres per year. In 2003 a record 10,000 square miles of Brazil was cleared (Lobe, 2004).

Deforestation causes a multitude of effects on the natural environment as shown below. Vegetation is degraded due to a loss of nutrient-rich litter and microorganisms to decompose organic matter. The loss of shade accelerates leaching, soil erosion and drying. The hard surface caused by baking impedes water infiltration causing excess runoff and flooding. In addition to the effect on the local vegetation and hydrology, forest removal impacts atmospheric composition, evapotranspiration, and precipitation.

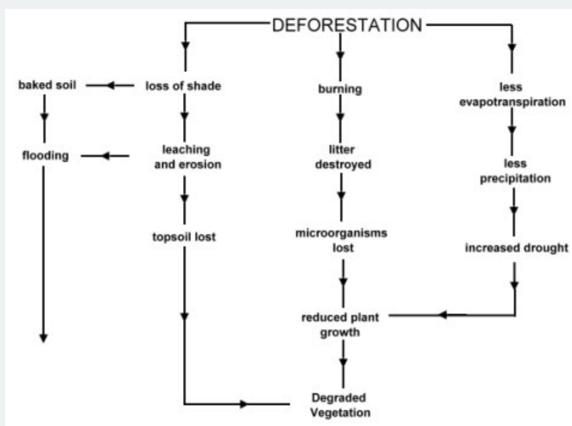


Figure 13.2.1.6: Effects of deforestation (after Drew,1983)

Soil degradation from forest clearing for agriculture happens quickly. Soil fertility can decrease by 80% in only a few years after forest removal.

Soil fertility loss due to forest clearing (Drew,1983)

Soil Characteristics (%)

Land use	Organic Content	Cation Exchange Capacity	Nitrogen	Phosphorus
Virgin Forest	100	100	100	100
1 Year after clearing, unused	104	82	66	120
After 2 years cultivation	46	51	36	75

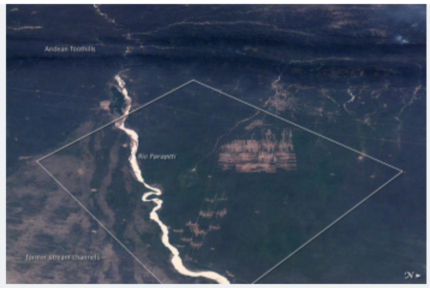


Figure 13.2.1.7a: Bolivian forest clearing (1995) along the Rio Parapetí in Bolivia (south of Santa Cruz, not shown) Courtesy NASA EOS (Source)

Figure 13.2.1.7b: Bolivian forest clearing (2008) along the Rio Parapetí in Bolivia (south of Santa Cruz, not shown) Courtesy NASA EOS (Source)

Government policies in some countries have fostered the exploitation of forest resources. Encouraging the population to develop forest land has opened the forest to continued degradation. In the 1990's the Bolivian Government began a large-scale program to increase the rate of forest removal for commercial agriculture (primarily soy and sugar cane, but also cocoa) on the Amazon Basin side of the Andean highlands. The dramatic effect of this action is seen in Figures BE21a and BE21b. Forest clearings began as small tracts perpendicular to access roads taking on a herringbone pattern when seen from the Space Shuttle in 1995. By 2008, the cleared area has greatly expanded. The impact of clearing on soil erosion and stream sediment load is evident in the brown, silt-laden Rio Parapetí that flows through the region.

Figure 13.2.1.1: The heavily eroded Betsiboka River watershed of in NW Madagascar empties into the Bay of Bombeteka. (Courtesy NASA)

The heavy seasonal rain of the monsoon forest poses a great danger, generating rapid runoff, mudflows and flash flooding. A result of unregulated deforestation, rivers become choked with sediment degrading the aquatic environment.

Deforestation has had a significant impact on indigenous cultures too. Six to nine million indigenous people inhabited the Brazilian rain forest in 1500. Today less than 1% of Brazil's 177 million people are full-blooded indigenous Indians (Source: US State Department). The loss of indigenous cultures destroys a wealth of knowledge about the environment in which they lived.

13.2.2: Midlatitude Forests

Mediterranean Woodland

The Mediterranean woodland is a **sclerophyll forest** consisting of low branching trees with small hard leaves and gnarled thick bark. The Mediterranean Woodland is found on west coast of continents in the midlatitudes and bordering the Mediterranean Sea, in close association with the Mediterranean (Dry Summer Subtropical) climate. Mediterranean woodland in North America is found along much of coastal southern California.

Figure 13.2.2.1: Chaparral vegetation typical of the Mediterranean Woodland. (Courtesy USBLM; Source)

Thick bark and small, waxy leaves are two adaptations to prevent excessive loss of moisture during the severe summer drought experienced in the dry summer subtropical climate. Chaparral vegetation grows to a height of 1 to 3 meters and has leathery leaves to prevent moisture loss. Chaparral has evolved fire-related adaptations as wildfires are common in this environment. Many chaparral species resprout and germinate after a fire. The cones of the Tecate cypress stay closed and on the tree until heat from a fire opens them and releases the seeds. Other species like toyon depend on resprouting from underground root systems that survive after a fire. Canopy of the typically hardwood, evergreen vegetation covers about 25 to 60 % of the terrain. The sparseness of the vegetative cover is due to the severe summer moisture stress and human disturbance.

Figure 13.2.2.2: Chaparral burning (USA). (Source: U.S. Forest Service)

Figure 13.2.2.3: Wildflowers, grasses, and shrubs regenerate after fire in the chaparral. (U.S.A.) (Source: U.S. Forest Service)

Midlatitude Broadleaf Deciduous and Mixed Forest

The Midlatitude Broadleaf Deciduous and Mixed Forest of the humid midlatitudes contains evergreen and/or deciduous trees reaching heights of 15 to 25 meters. The broadleaf forest dominates equatorward, while toward the north, conifers intermingle to create a mixed forest. Needle leaf trees are well adapted to the cool to cold temperatures which occur on the poleward limits on the humid continental climate. Conifer needles are thicker than broadleaf leaves and have waxy coatings that promote water conservation. The small but large number of needles effectively capture a large percentage of sunlight, especially important during the the winter when sun angles are low. Cold sensitive broadleaf trees enter a period of vegetative dormancy, reducing moisture content and shedding their leaves. Oak, maple, hickory, chestnut and beech are common tree types found in the broadleaf deciduous forest. In most cases the forest is an open forest with little under story growth, though some shade tolerant annual species occupy the ground. The dense canopy inhibits significant amounts of light to penetrate to the forest floor inhibiting growth at ground level.

Figure 13.2.2.4: Broadleaf deciduous forest in France. (Source: A. Vorontzoff. FAO.)

Many stands of different age and tree species are found together lending a patchwork character to the forest. The forest may be comprised of pure stands, or contain 2 to 3 species. Temperate forests are found in the Humid Continental climate and stretching into the Humid Subtropical Climate. Alfisol soils are found developing beneath much of the temperate midlatitude forest. Spodosols are found where conifers dominate.

Figure 13.2.2.5: Mixed forest of Wisconsin, USA. (Source: M. Ritter)

The midlatitude broadleaf deciduous and mixed forest has been drastically changed over time by human activities. By A.D. 1000, China was virtually "treeless". Much of England's forests had been cut by 1700. Today, acid rain threatens the temperate forest in many locations.

Subtropical Evergreen Forest

There are two variants of the **subtropical evergreen forest**, the broadleaf evergreen and needle leaf subtropical forest. The subtropical broadleaf evergreen forest is found in New Zealand, southeastern Australia, and Southern Chile. Here, mild maritime air masses keep conditions moist enough to suppress any summer drought and provide temperatures warm enough to prevent a threat of frost. Small pockets of broadleaf evergreen species like evergreen oak and magnolia, are found in the United States in Florida and along the Gulf Coast.

The subtropical needle leaf forest is found as a southern pine forest in the southeastern United States. The forest has developed on the sandy deposits along the fringe of the Atlantic and Gulf Coasts.

Figure 13.2.2.6: Broadleaf evergreen forest, New Zealand's South Island. (Photo credit: T. Detwyler)

Temperate Rain Forest (Marine West Coast Forest)

The **temperate rain forest**, or sometimes called the **marine west coast forest**, is known for its lush vegetation occurring along narrow margins of the Pacific Northwest in North America. However, the temperate forest lacks the diversity that the tropical rain forest has. The rain forest of the Pacific Northwest is composed of a few species of broadleaf and needle leaf trees, huge ferns, and a thick undergrowth. Lying on the windward slopes of the Cascade and Coast Ranges, this forest receives over a hundred inches a year in marine west coast climate, as much precipitation as some tropical rain forests.

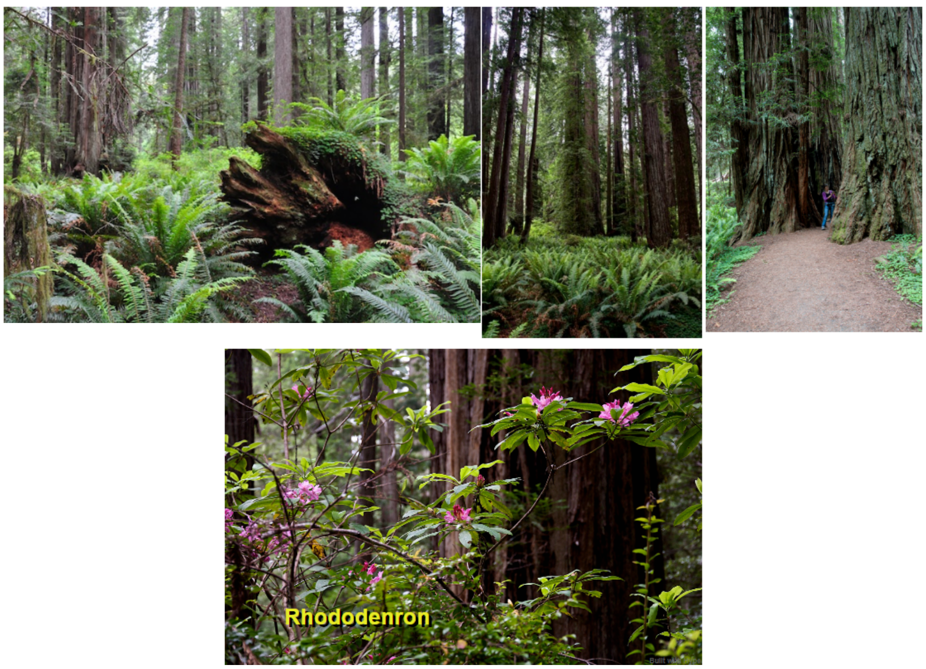


Figure 13.2.2.7: Marine West Coast forest of Redwoods National Park (Source: Michael Ritter)

The temperate rain forest is home to some of the largest trees and oldest living organisms on earth - the coast redwoods. Exceeding 200 to 300 feet in height and having diameters over 20 feet, these trees can live well over a thousand years. The redwood forest floor is covered and epiphytes dangle from the trees. The cool and shady redwood forests of North America create a habitat for a variety of animals, including the northern spotted owl, Stellar's Jay, banana slugs, Pacific tree frog, and black bear.

Old growth forests of Douglas fir, spruce, cedar and hemlock have been devastated by logging. With only 10% of the original forest left, biodiversity loss is a great concern to ecologists.

13.2.3: Northern Forests

The Northern Coniferous Forest

The northern coniferous forest of the *Subarctic* climate, also known as the **boreal forest**, is dominated by coniferous trees, with hardy deciduous trees like birch mixed in. To the south lies the temperate forest and the north the tundra. An ecotone found between northern coniferous forest and tundra vegetation called the ***taiga***. Taiga is a more open form of boreal forest with low growing conifers. Historically, the pine forests of North America and Europe have been an important timber resource. Trees are typically shallow rooted due to the poor soils (spodosols), rocky conditions, discontinuous permafrost.

Figure 13.2.3.1: Snow covered conifers of the Northern Coniferous forest. (Source: Tom Smylie U.S. Forest Service)

Coniferous forests (taiga) circles the globe and contains a third of all the trees on earth. On its northern edge the growing season is a mere one month long. It's a silent world, lacking many animal species as there is little palatable food, the resinous conifer leaves make them quite distasteful to most animals. Food for larger animals is sparse in such an ecosystem and they are likely found where wind throw or fire has created openings in the forest for deciduous shrubs such as birch, aspen and willow to invade colonize.

Trees in the northern coniferous forest primarily possess pine needles instead of broad leaves like those of the temperate forests to the south. Being dark in color they absorb what little light falls on their surfaces. Retaining their needles at the end of each growing season gives the tree a head start at growth during the spring as they do not have to waste their energy in producing new foliage. The sloping sides of the conical canopy helps catch the low angle sun rays typical of high latitude locations. Usually there is only one tree layer creating a shading effect that precludes the growth of any lower tree layers.

Figure 13.2.3.2: Birch intermixes with spruce in an open canopied Northern Coniferous forest. (Source: H. Peter Wingle U.S. Forest Service)

Conifers possess a shallow, extensive, yet compact, network of roots. Waxy, resinous needles and low bacterial activity in the cold subarctic climate combine to produce a thick mat of undecayed litter on the forest floor. Soils (spodosols) are poor and acidic since few nutrients are released into the soil. Filamitous fungi surrounding the root ball extend hairs into the needles lying at the surface, breaking them down into substances usable by the trees.

Figure 13.2.3.3: Close-up of spruce needles damaged by acid rain (Source: U.S. Forest Service)

Much of the northern coniferous forest of Europe and the eastern United States has suffered from the affects of acid deposition. *Acid deposition* refers to the depositing of acids in both solid and liquid form. The most common form of acid deposition is acid rain. Much of the source of sulfur is from industrial activities. Acid rain forms when sulfur compounds combine with water in the atmosphere to form sulfuric acid. Acid rain can severely damage the structure of pine needles making them vulnerable to invasion by other diseases and organisms. Soils in which the plants grow are acidified, mobilizing soluble metals in the soil water and proving toxic to plant roots.

Figure 13.2.3.4: Acid damaged forest in the northeastern United States (Source: U.S. Forest Service)

For many years, scientists suspected that acid rain could damage forest ecosystems. It wasn't until relatively recently that they have for direct evidence to support their suspicions. Find out how in this *All Things Considered* (NPR) segment from October 28, 1999 about scientist's direct link between forest degradation and acid rain. (3:49)

13.3: Savanna Biome

The **Savanna biome** is characterized by an extensive cover of grasses with scattered trees. It is a transitional biome between those dominated by forests and those dominated by grasses. The Savanna biome is associated with climates having seasonal precipitation accompanied with a seasonal drought. A midlatitude variant, the parkland, is located in the drier portions of the humid continental climate.

Tropical Savanna

The **tropical savanna** is generally found in regions dominated by the Wet-Dry Tropical climate. An extensive cover of tall grasses, sometimes reaching a height of 3 meters, is found in the tropical savanna. Most savanna grass is coarse and grows in tufts with intervening patches of bare ground. Scattered, individual trees or small groves of trees are common. The umbrella shaped Acacia tree is a notable species of the Savanna biome. The acacia tree uses its long tap roots draw water from deep below the surface during the dry season of the savanna. The tree's long thorns are home to small stinging ants, both of which ward off herbivorous animals. Only the giraffe can tolerate the acacia foliage. The tree's small leaves reduce water loss. Its umbrella shape maximizes the exposure of the small leaves to solar radiation.

Figure 13.3.1: Acacia Tree (Courtesy USFWS)

The small amount of high sun rainfall in the savanna is not enough to sustain trees in the savanna biome. Other regional factors play an important role in maintaining the savanna. In eastern Africa where precipitation is higher, savanna vegetation is maintained by periodic fires. Fires burn back the forest and stimulates the growth of grasses like that which occurs in the prairie grasslands. Savannas, like those found in Venezuela and Brazil, develop on soils that have a hard crust and are subject to cracking. Trees flourish where their roots can follow the cracks down to water held deep beneath the surface. Grasses grow in the crust above.

Figure 13.3.2: The Baobab tree found in the Savanna of Senegal. (Source: UN/DPI Photo #187250C by Evan Schneider)

Plants in the savanna have adapted to the long dry season in a number of ways. The Baobab tree stores water in its huge trunk, drawing on the moisture during periods of drought stress. Many grasses and trees of the savanna flourish during the brief wet season and then go into a state of dormancy. Grasses turn brown and trees lose their leaves to reduce the loss of water by transpiration.

A number of different animal species inhabit the tropical savanna like lions, zebras, elephants and giraffes. The long neck of the giraffe is a unique adaptation to the savanna woodlands; its long neck permits browsing on the higher foliage of trees.

Thorntree and Tropical Scrub

The **Thorntree and Tropical Scrub** is characterized by short, thorny trees and shrubs. The vegetation may form a continuous cover eliminating grasses. This vegetation formation is a response to a longer, and more intense drought period.

Figure 13.3.3: Livestock grazing severely damages the thorntree savanna leading to problems of desertification. Burkina Faso* (Picture credit: Carolyn Redenius, United Nations)

The thorntree and tropical scrub has suffered under the misuse of human activity. Overgrazing has reduced the capacity of the system to withstand the erosive forces of wind, and to a lesser extent water. Without the protective restraint plants, soil and sand, along with valuable soil nutrients, can blow free from the surface. Deserts are rapidly encroaching and replacing the savannas and steppe grasslands. Many years of prolonged drought combined with human pressures on the biome increases the likelihood for desertification of these areas.

Midlatitude Savanna

Figure 13.3.4: Bald Top Oak Savanna, Oregon. (Photo Credit: US FWS Source)

A **Midlatitude savanna** is sometimes called a ***parkland***. Here, grasses are broken by patches or ribbons of broadleaf trees. The midlatitude savanna is located in a transitional area between the humid continental and midlatitude steppe climates. Parkland often is a step in the successional evolution of plant communities on abandoned farm fields of the eastern United States. For more see "Prairie Parkland (Temperate) Province ".

Human activities and the Savanna Biome

Many animals of the savanna biome like the rhinoceros are endangered and threatened with extinction due to hunting and habitat loss. Most species of elephants are in danger of extinction due to poaching for their ivory tusks. Several means to protect these animals have been tried, even removal of the rhinoceros's horns and the elephant's tusks. Many countries have banned the sale of ivory to discourage poaching under the Convention on International Trade in Endangered Species (Cites) in 1989. The stronger enforcement against poaching nearly brought it to a halt.

Figure 13.3.5: Square lipped rhinoceros, Zambia. (Source: M.Boulton, FAO. Used with permission)

The success of the ban encouraged some countries to negotiate its lifting to sell stockpiled ivory from seizures. A significant increase in elephant poaching has resulted from a substantial rise in the value of ivory. A 2008 research report indicated that African elephant death rate from poaching was at 8 per cent, higher than the 7.4 per cent rate that led to the international ban on ivory trade. African elephant population was estimated at 1 million, with about 70,000 elephants killed each year. In 2008, the population was less than 470,000. At this rate, it is estimated that African elephants could be extinct by 2020. A significant demand in rhino horn as sparked and increase in rhino poaching. In this NPR *All Things Considered* story from May 13, 2013, Frank Langfett describes how "Vietnam's Appetite for Rhino Horn Drives Poaching in Aftica". The NPR *Morning Edition* segment "Radiocarbon Clues Help Track Down Poached Elephant Ivory" from July 2, 2013 looks out how conservation scientists use high tech means to uncover the source of poached ivory.

Video: Biomes: Savanna (Courtesy Great Pacific Media)

13.4: Grassland Biome

The **Grassland biome** is dominated by grasses of a variety of species, all having adapted to the summer drought common to their semiarid habitat. The broad expanse of the grasslands is occasionally broken by stands of trees. The midlatitude grasslands of have been exploited more than any other biome by humans. Ninety nine percent of the United State's tall grass prairie and 70 percent of the mixed grass and short grass in some states have disappeared. Eight-five percent of the state of Iowa was once covered in native prairie, only one percent is left. The grasslands, especially the tall grass prairies are the world's most productive agricultural areas. The famous corn belt of the United States was created on top of the rich brown mollisol soils that developed beneath the surface.

The Prairies

Prairies are found on the humid side of the grassland biome and are often referred to as the *tall-grass prairie*. A favorable annual moisture balance supports a dense ground cover of tall grasses. Grasses range in height between .6 to 1.2 meters (2 to 4 ft.), with some as tall as 8 feet or more on the eastern margin of the prairies in the United States. In the tall-grass prairie of Iowa, for example, typical grasses are big bluestem and little bluestem; a typical forb is black-eyed Susan. Trees and shrubs are generally limited to moist sites along stream channels or hill slopes facing away from the sun. The nutrient - rich soil beneath the grasslands drew farmers to these regions. Now, most natural tall-grass prairie has been replaced by agriculture. Extensive grasslands also occur in Argentina and the Ukraine.

Figure 13.4.1: Tall grass prairie once common to the eastern Great Plains of Kansas (Courtesy NRCS)

The native grasslands of the world support a diversity of animal life. In North America, large grazers like the bison roamed the grasslands until hunted to near extinction by settlers moving west.

Steppe Grassland

On the drier side of the grassland biome lies the **steppe grasslands**. Vegetation must cope with the summer soil moisture deficit common to the *steppe climate* in which this formation class is found. Here, tall grass prairie gives way to grasses smaller than a half meter (2 ft).

Figure 13.4.2: Mixed Tall and Short grass prairie of the U.S. Great Plains (Courtesy NRCS)

Toward the drier portions the ground cover becomes sparse with patches of open ground found between clumps of grass. Overgrazing of the steppe vegetation leads to accelerated wind erosion and desertification.

Fires, especially those started by lightning, are a natural occurrence in the grassland biome. Fire destroys invasive species that compete with grasses. Fire suppression and farmland conversion have severely disrupted grassland ecosystems. Resource mangers now use prescribed burning to restore the health of prairie grasslands.

The Kalahari Desert actually isn't a desert under present conditions, though it is covered with much sand. It is a fossil desert found in the tropical steppe biome. Parts receive over 250 mm of precipitation, enough to support a cover of vegetation. It is a fossil desert found in the steppe biome. It' name is derived from the tribal word Khalagari, Kgalagadi or Kalagare meaning "a waterless place" or the Tswana word Keir, meaning "the great thirst".

Figure 13.4.3: Wild Pronghorn Antelope cross the short grass prairie of Wyoming. (Courtesy NRCS)

Burrowing animals like ground squirrels, prairie dogs, pocket gophers are common in the steppe grasslands of North America. Burrowing predators like the black footed ferret are considered an endangered species.

Video: " National Bison Range Wildlife Refuge - near Missoula, Montana, MT."

13.5: The Desert Biome

The desert biome has the lightest cover of plants of any biome. Lack of moisture prevents plants from establishing themselves in this harsh climate. Many unique adaptations to the extreme heat and lack of moisture enable some plants to survive. Plants adapted to drought are called **xerophytes**. Aridisol soils, common to deserts, are typically coarse, lack much organic material, and are often weakly developed.

Dry Desert

The dry deserts are typically found in subtropical latitudes and are produced by subsidence associated with the eastern sides of the subtropical high. These are extremely dry regions, some places hardly receiving any measurable precipitation during the year. Plant cover is non-existent over much of the dry desert.

Figure 13.5.1: Grand Erg Occidental Desert, Algeria (Photo credit: J.Van Acker, FAO Used with permission)

Like many dry deserts, a layer of coarse material blankets the surface. This "desert pavement" protects the underlying surface from erosion. When disturbed, wind easily dislodges particles and transports them away in a process called ***deflation***. This makes the establishment of plants very difficult.

Figure 13.5.2: Desert encroaching on desert oasis. (Photo credit: Mauritania. I.Balderi, FAO Used with permission)

Plants occur only under the most favorable microclimatic settings like those surrounding an **oasis**. Oases are created where the water table is near the surface. Groundwater can be easily extracted to support vegetation and wildlife.

Plant growth and reproduction are quite slow under desert conditions. Surface erosion by wind or water restricts the establishment of plants. Infrequent storms causes water to sweep across the barren surface carrying away massive amounts of material along with plants. The rapid movement of sand dunes covers and prevents the establishment of a plant cover too.

Shrub Desert

The *Shrub desert* of the midlatitudes supports a more diverse community of plants and animals. Associated with the midlatitude desert climate, more precipitation and cooler temperatures help support a more complete ground cover. This is especially true along dry stream beds where moisture is often more plentiful. Large cacti like the Saguaro cactus, and xerophytic shrubs are found in the Shrub desert of North America.

Figure 13.5.3: Joshua Tree National Park, California near Sheep Pass, 1962 (Courtesy USGS; Source)

Some xerophytic vegetation are widely spaced, and have extensive root systems to capture moisture in the soil. Others have waxy leaves or fleshy tissues to store moisture. Enlarged green stems like those found on cacti take over the function of leaves in photosynthesis. Some desert vegetation may shed parts of branches during extreme drought.

Deserts have been expanding worldwide in response to several natural and human-induced reasons. Learn more by "Digging Deeper into Desertification" or skip and continue reading.

Digging Deeper into Desertification

Desertification is the expansion of dry lands due to poor agricultural practices (e.g. overgrazing, degradation of soil fertility and structure), improper soil moisture management, salinization and erosion, forest removal, and climate change.

Figure 13.5.4: Desertification in Africa (Courtesy FAO)

Two common misconceptions prevail about desertification, that it spreads from a desert core and drought is responsible. Desertification spreads outward from any where excessive abuse of the land occurs and far from any climatic desert. Droughts do increase the possibility of desertification if the carrying capacity of non-irrigated land is exceeded. Well-managed land can recover from the effects of drought. Combining drought with land abuse sets the stage for desertification.

Cause of Desertification

Desertification comes about by a complex interaction between the natural environment and human activities. The cause may vary from region to region on account of economic conditions, population pressure, agricultural practices, and politics. Human activities that destroys surface vegetation, degrades soil structure and fertility, impedes water infiltration, and causes soil drying promotes desertification. This is especially true for the fragile transition zone between arid and semiarid land where human activity has stretched the ecosystem to its limit causing expansion of deserts.

Population growth and its demand on agricultural resources has promoted the desertification process. Over cultivation, for example, causes declining soil fertility leading to falling crop yields. Over use leads to crusting of exposed topsoil by rain and sun that increases runoff, water erosion and gullying. Soil drying promotes wind erosion and encroachment of sand dunes on arable land.

Overgrazing has several effects. It:

- Causes a decline in pasture vegetation and palatable grass species.
- Replaces perennials with short-lived annual species that do not hold soil against erosion.
- Compacts soil under trampling hoofs.
- Destabilizes dunes when crest vegetation is eaten.

Forest cutting for fuel wood has deforested large tracks of land in Africa and Asia encouraging desertification.

Desertification around the world

The United Nations Conference on Desertification ranks desertification hazard on the basis of a drop in agricultural productivity:

None - less than 10%

Moderate - 10% to 25 %

High - 25% to 50%

Very high - more than 50%

Desertification is a global problem occurring in many places but is prevalent along the margins of semiarid and arid lands in Asia, central Australia, portions of North and South America, and Africa. A world map prepared by the United States NRCS shows just how widespread the problem is.

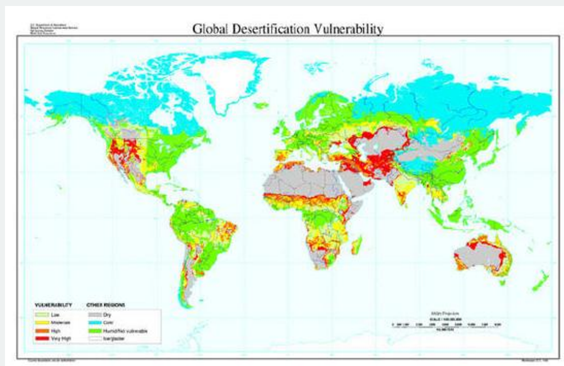


Figure 13.5.5: Desertification Vulnerability (Courtesy NRCS; High Resolution copy)

Africa has been significantly impacted by desertification. Almost three quarters of Africa's agricultural drylands are already degraded to some degree. The impact on desertification on the greatest number of people occurs in Asia. Degraded regions include the sand dunes of Syria, the eroded mountain slopes of Nepal, and the deforested and overgrazed highlands of Laos. The Northern Mediterranean region is the cradle of civilization and has borne the effects of poor agricultural practices. Salinized, infertile soils are the result of natural hazards e.g. droughts, floods and forest fire, as well as overtilling and overgrazing. Soil degradation is high through much of Central and Eastern Europe, and very high in some areas, for example along the coast of the Adriatic Sea. Poor irrigation practices and the unsustainable exploitation of water resources are contributing to chemical pollution, soil salinization and aquifer depletion. Nearly a quarter of the inhabitants of Latin America and the Caribbean live below the poverty line fueling practices that lead to land degradation. Erosion and water shortages are intensifying in many East Caribbean islands.

13.6: Tundra Biome

The Arctic Tundra

We find the arctic tundra biome at high latitudes closely associated with the tundra climate. Notable areas of arctic tundra are found along the arctic coastal North America, Europe, Asia and Greenland. Short grasses, flowers, and grass-like sedges, along with covers of mosses and lichens are the dominate forms of vegetation in the tundra. Seasonal frost heave disrupts root systems preventing support for tall vegetation. The arctic tundra looks like a treeless plain, interrupted by patterned ground and an occasional tree in selected microenvironments.

Figure 13.6.1: View of the Alaskan Tundra. (Courtesy US Fish & Wildlife Service)

Pattern ground shown in Figure 13.6.1 is typical of the tundra landscape. Stone polygons, soil circles, stone or soil stripes and terraces are common to both arctic and alpine tundra. These features are created by thrusting action of repeated freezing and thawing of moist soil over a solid substrate like rock or permanently frozen ground. Polygonal patterns dominate flat surfaces. Vegetation is usually confined to the stable parts of the patterns.

Figure 13.6.2: Tilted poles on Northway access road, Yukon region Alaska. (Courtesy: USGS Digital Data Series CD-ROM DDS-21)

Permafrost is a common feature of the arctic tundra climate and biome. Permafrost refers to permanently frozen ground. Actually, the ground has two layers which freeze. A surface layer, called the active layer, thaws during the short "summer" and often subsides. Beneath the active layer is the inactive layer which stays frozen throughout the year. Permafrost creates a barrier to the root development. Larger trees can grow along better drained river valleys where the depth to permafrost is greater. The annual freezing and thawing disrupts root systems inhibiting the growth of very tall vegetation.

Figure 13.6.3: Trans-Alaska pipeline snakes across the Alaskan tundra (Courtesy: United States Bureau of Land Management)

Permafrost creates an engineering nightmare for the construction of buildings and other structures. You can see in Figure 13.6.2 how telephone poles have been tilted from the heaving of the surface during freezing and thawing. Much concern for damage to the environment was raised over the construction of the Trans-Alaska Pipeline. The heated oil running though the pipeline is insulated from the cold permafrost where it runs underground. In places it zigzags over the surface on stilts that allow it to expand and contract.

Figure 13.6.4: Musk Ox of the Alaskan arctic tundra. (Courtesy: U.S. Fish and Wildlife Service)

The Musk Oxen is a well-known inhabitant of the arctic tundra. A dense fur coat protects them from the severe climatic conditions in the tundra. Beneath is a dense fine undercoat that is fairly waterproof. Adults gather in a protective wall to keep the calves safe from predator attacks and severe storms. Musk oxen inhabited much of Eurasia and North America during the Ice Ages, but now survive only in parts of Greenland and northern Canada.

Video: Arctic National Wildlife Refuge (Courtesy USFWS)

The Alpine Tundra

The tundra biome is found at high elevations in mountainous terrain, as well. Many, if not all, the same features of the arctic tundra are found in the alpine tundra. Microclimate is an important control over the distribution of plant species as slope and exposure control the availability of light and moisture. The landscape is dotted with small cushion plants, lichens and mosses. Willows are found where moisture is abundant. Other factors like soil development, movement of soil by animals, and drainage determine vegetation community distribution.

Vegetation consists of low growing shrubs, cushion plants, small forbs exploding with colorful flowers and lush meadows of sedges and grasses. These plants cover gentle slopes and rock crevices. Rock surfaces are dotted with a cover of lichens and mosses. Most species are slow-growing perennials. Plants have been forced to adapt to such an extreme environment. Plant roots store nutrients and energy during poor growing periods. Roots make up ninety percent of some plants in the alpine tundra. Flowers often are large on tundra plants. Other parts of the plant are small to save energy and reducing exposure to wind. Some plants have waxy coatings or hairs thus losing minimal heat and water to the wind. The location of plant communities is correlated with the duration of snow cover. While snow is blown free from exposed sites, it accumulates in the lee of obstructions and in depressions. Community location is also related to soil, drainage, and movement of soil by burrowing animals, and frost action throughout much of the alpine tundra. Dense willow thickets often occupy moist depressions on the lee side of ridges. A deep cover of snow during the winter protects buds from the wind and freezing temperatures. These are the tallest perennials growing above the krummholz of the ecotone.

Figure 13.6.5: Alpine tundra fell field (foreground) and on a rocky knoll (upper right) Colorado, USA. (Courtesy UNESCO)

Fell fields are colorful rock gardens exposed to the rigors of the wind. Wind removes snow throughout the season subjecting the plants to desiccation. Low-lying mats and cushion plants nestle against the rocky surface.

The climate of the tundra is exceedingly harsh. Annual precipitation is around 40 inches, but effective precipitation is far below that amount. Snow remains as permanent snow fields at some sites. Wind speeds can exceed 100 mph and mean annual temperature is below freezing. Diurnal temperature ranges are small because the air is mixed by the constant winds. The frost free season is approximately 1 1/2 months.

Soils are quite variable in the tundra. Thin soils lie in the valleys scoured by glaciers. Mature residual soils are found on unglaciated ridges and between rocks brought to the surface by frost heave to form polygons. Soil ice is found in all soils in winter, and soil temperatures are low enough to form patches of permafrost.

Solifluction terraces are a common landscape feature of the alpine tundra. Late lying snow patches keep conditions moist to permit willow growth. Reaching a few feet high, willows are covered in snow to protect the over-wintering buds. Willows are the tallest of any species in the alpine tundra.

The plant communities mentioned above are considered climax communities mainly because they change so slowly. Communities are often disturbed by small burrowing animals like the pocket gopher that churn up the soil and eat plant roots, or voles which can devastate above - ground biomass. Recovery after disturbance proceeds exceedingly slow, slower than any other mountain ecosystem.

Digging Deeper: The Fate of Arctic Habitats

In comparison to other portions of the Earth, the Arctic is undergoing the most rapid change in temperature as a result of climate change. Recent warming has had a drastic affect on surface processes, the well-being of animal species, and the geography of plants. The dramatic warming in Alaska has increased the growing degree days for agriculture and forestry by twenty percent. Boreal forests are expanding their range at a rate of 100 to 150 km per ^oC increase in temperature. With warmer temperatures comes longer and deeper thaw cycles resulting in thermokarst and wetlands in the forest. The annual area burned in northwestern North America has doubled over the last twenty years and Eurasian forests have experienced similar trends.

Warming temperature in the Arctic is thawing permafrost making coasts and slopes along streams more susceptible to erosion and mass movement. Thaw slumps, sliding masses of soft soil, slide into pristine streams turning them muddy and smothering fish eggs waiting to hatch from gravels that line river beds. Coastal erosion results in a loss of land habitat for those living on the North Slope, a trend that is predicted to continue into the future.

A Pew Center review of current research indicates that nearly half of known wild species have been affected by global warming. For example, polar bear populations are on the decline as arctic sea ice thins making for precarious hunting conditions. Polar bears prowl the ice floes in search of food, notably seals. These white giants capture their prey by waiting for seals to appear in air holes in the ice. Packing on fat from rich seal meat enables them to survive when the ice melts making prey harder to find.

Figure 13.6.6: Polar bear on ice floe. (Courtesy NOAA)

The warming oceans and melting sea ice have shortened polar bear access to food. In Canada's West Hudson Bay, sea ice is breaking up three weeks earlier as a result of changing climate conditions. Polar bear populations are down twenty percent in the last ten years as fewer cubs are born or make it to adulthood. Ice pack break up leaves polar bears stranded farther from land, sometimes drowning from trying to swim longer distances. In the northern part of Alaska polar bears are moving inland as the Arctic sea ice coverage shrinks.

Video: "Melting Ice Could Erode Way of Life for Alaska's North Slope" (Courtesy PBS Newshour)

New novel climates will appear while other climates may disappear with future global warming. The Arctic is forecast to undergo some of the greatest changes in climate patterns. Climate models indicate that the tundra will be retreat to northern coasts and islands of the Arctic Ocean. Tundra vegetation will be replaced by boreal forests and shrubs.

13.7: Review and Additional Resources

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **biogeographical realm**
  geographical regions out of which assemblages of plants and animals evolved and dispersed
- **Palaearctic realm**
  stretched across Europe, most of Asia, the Mediterranean, North Africa. It is very similar to the Nearctic in terms of the diversity of biomes including tundra, grassland, deciduous and coniferous forest, chaparral, and desert biomes
- **Nearctic realm**
  includes most of North America and Greenland. The Nearctic realm possesses a great diversity of biomes including the tundra, grassland, deciduous and coniferous forest, chaparral, and desert biomes
- **Neotropical realm**
  found throughout most of central and South America is dominated by tropical forests, savannas, and deserts.
- **Afrotropical realm**
  inhabited by tropical forests, savannas, and deserts and is found in Africa south of the Sahara
- **Australian realm**
  has a desert core, surrounded by tropical forest and savanna. The Australian realm boasts a unique variety of plants and animals as they have evolved in isolation from outside influence
- **Indomalayan realm**
  includes much of southeast Asia and is nearly exclusively tropical forest
- **Antarctic realm**
  exhibits a diverse set of ecosystems from temperate forest and grassland in New Zealand to tundra and ice sheets in Antarctica.
- **Oceanian realm**
  includes tropical islands of the Pacific ocean and dominated by tropical forests
- **biome**
  a large stable terrestrial ecosystem
- **Forest biome**
  consists of close growing trees with leaf canopies that generally overlap
- **Tropical rain forest**
  contains trees standing 30 to 55 meters in height, creating a continuous canopy of foliage. The enclosed canopy shades the forest floor, creating an open forest formation
- **Tropical Monsoon/Seasonal Forest and Scrub**
  contains trees of smaller stature than those found in the rain forest; open canopy that creats a dense, closed forest at the floor, or what we think of as a "tropical jungle".

- **Mediterranean Sclerophyllus Woodland**

  consists of low branching trees with small hard leaves and gnarled thick bark
- **Midlatitude Broadleaf Deciduous and Mixed Forest**

  contains evergreen and/or deciduous trees reaching heights of 15 to 25 meters. The broadleaf forest dominates equatorward, while toward the north, conifers intermingle to create a mixed forest. In most cases the forest is an open forest with little under story growth, though some shade tolerant annual species occupy the ground.
- **Broadleaf evergreen forest**

  mild maritime air masses keep conditions moist enough to suppress any summer drought and provide temperatures warm enough to prevent a threat of frost.
- **Temperate rain forest (Marine west coast forest)**

  known for its lush vegetation occurring along narrow margins of the Pacific Northwest in North America. Composed of a few species of broadleaf and needle leaf trees, huge ferns, and a thick undergrowth.
- **Northern Coniferous forest**

  aka boreal forest; dominated by coniferous trees, with hardy deciduous trees like birch mixed in
- **Boreal forest**

  aka northern coniferous forest; dominated by coniferous trees, with hardy deciduous trees like birch mixed in
- **Taiga**

  a more open form of boreal forest with low growing conifers
- **Savanna biome**

  characterized by an extensive cover of grasses with scattered trees. It is a transitional biome between those dominated by forests and those dominated by grasses
- **Tropical savanna**

  An extensive cover of tall grasses, sometimes reaching a height of 3 meters; Most savanna grass is coarse and grows in tufts with intervening patches of bare ground. Scattered, individual trees or small groves of trees are common.
- **Thorntree and tropical scrub**

  characterized by short, thorny trees and shrubs
- **Midlatitude savanna (Parkland)**

  grasses are broken by patches or ribbons of broadleaf trees
- **Grassland biome**

  dominated by grasses of a variety of species, all having adapted to the summer drought common to their semiarid habitat. The broad expanse of the grasslands is occasionally broken by stands of trees.
- **Prairie**

  found on the humid side of the grassland biome and are often referred to as the tall-grass prairie. A favorable annual moisture balance supports a dense ground cover of tall grasses. Grasses range in height between .6 to 1.2 meters (2 to 4 ft.), with some as tall as 8 feet or more
- **Steppe grassland**

  grasses smaller than a half meter (2 ft); toward the drier portions the ground cover becomes sparse with patches of open ground found between clumps of grass.
- **Desert biome**

has the lightest cover of plants of any biome. Lack of moisture prevents plants from establishing themselves in this harsh climate. Many unique adaptations to the extreme heat and lack of moisture enable some plants to survive

- **Dry desert**
  Extremely dry regions, some places hardly receiving any measurable precipitation during the year. Plant cover is non-existent over much of the dry desert.
- **Shrub desert**
  supports a more diverse community of plants and animals; more precipitation and cooler temperatures help support a more complete ground cover
- **oasis**
  created where the water table is near the surface. Groundwater can be easily extracted to support vegetation and wildlife.
- **xerophyte**
  Plants adapted to drought
- **deflation**
  when wind dislodges particles and transports them away
- **desertification**
  the expansion of dry lands due to poor agricultural practices (e.g. overgrazing, degradation of soil fertility and structure), improper soil moisture management, salinization and erosion, forest removal, and climate change.
- **Tundra biome**
  found at high elevations in mountainous terrain
- **Arctic tundra**
  Short grasses, flowers, and grass-like sedges, along with covers of mosses and lichens are the dominate forms of vegetation in the tundra. Seasonal frost heave disrupts root systems preventing support for tall vegetation; looks like a treeless plain, interrupted by patterned ground and an occasional tree in selected microenvironments
- **Alpine tundra**
  landscape is dotted with small cushion plants, lichens and mosses. Willows are found where moisture is abundant; Vegetation consists of low growing shrubs, cushion plants, small forbs exploding with colorful flowers and lush meadows of sedges and grasses. These plants cover gentle slopes and rock crevices. Rock surfaces are dotted with a cover of lichens and mosses.

Review Questions 13.7.1

Compare and contrast the canopy and forest floors of the tropical rain forests and the tropical monsoon forests.

Answer

The tropical rain forests are considered an open forest while the tropical monsoon is considered a closed forest. The crowns of tropical rain forest trees intermingle creating a dense canopy that inhibits the penetration of light to the surface. This prevents much dense undergrowth to develop on the forest floor. The tropical monsoon forest has a dense undergrowth as the canopy is more open allowing light to the surface.

Describe how the vegetation and climate change going from the Arctic coast of Canada to the Gulf Coast of the United States along the 90th meridian.

Answer

Arctic Tundra (Tundra Climate) -> Northern Coniferous Forest (Subarctic Climate) -> Midlatitude Broadleaf and Mixed Deciduous Forest (Humid Continental) ->Tall Grass Prairie (Humid Continental) ->Southern Coniferous Forest (Humid Subtropical Climate)

Describe how the vegetation and climate change going from the west coast to the east coast of the United States along the 35N parallel.

Answer

Sclerophyllus Woodland (Dry Summer Subtropical Climate) ->Mountain (Undifferentiated Mountain Climate)-> Cool Shrub Desert (Midlatitude Desert Climate) Short Grass Prairie (Midlatitude Steppe Climate) -> Tall Grass Prairie (Humid Continental Climate) Midlatitude Deciduous Forest (Humid Continental Climate) -> Southern Coniferous Forest (Humid Subtropical Climate).

What is a savanna and which climate(s) is a savanna usually associated with?

Answer

The savanna biome is characterized by drought tolerant grasses with scattered trees. The tropical savanna is associate with the wet/dry tropical climate.

Compare and contrast the vegetation and climate conditions associated with short and tall grass prairies.

Answer

The short and tall grass prairies reflect the climate the flourish under. Short grass prairie, as its name implies, is comprised of short grasses (e.g., little bluestem grasses, generally less than 2 feet tall and will appear in clumps or patches, especially where the climate (midlatitude steppe) is drier. The tall grass prairie lying on the drier side of the humid continental and moist side of the midlatitude steppe has grasses that stand 2 to 4 feet and sometimes taller. Big bluestem grasses and Black-eyed Susans are common plants.

Permafrost is common to the tundra. What is permafrost and how does it influence the habitability of the tundra for both vegetation and humans?

Answer

Permafrost refers to permanently frozen ground. Actually, the ground has two layers which freeze. A surface layer, called the active layer, thaws during the short "summer" and often subsides. Beneath the active layer is the inactive layer which stays frozen throughout the year. Permafrost creates a barrier to the root development. Larger trees can grow along better drained river valleys where the depth to permafrost is greater. The annual freezing and thawing disrupts root systems inhibiting the growth of very tall vegetation. Permafrost creates an unstable surface for the construction of buildings and other structures.

Explain how the vegetation of the Mediterranean woodland has adapted to the dry summer subtropical climate.

Answer

Thick bark and small, waxy leaves are two adaptations to prevent excessive loss of moisture during the severe summer drought experienced in the dry summer subtropical climate.

How does desertification occur?

Answer

Desertification is the expansion of dry lands due to poor agricultural practices (e.g. overgrazing, degradation of soil fertility and structure), improper soil moisture management, salinization and erosion, forest removal, and climate change.

Describe the characteristics of the temperate rain forest (marine west coast forest) and explain what is responsible for them.

Answer

The temperate rain forest is comprised of lush vegetation and home to some of the largest trees on earth, the coast redwoods. It lacks the diversity of species that the tropical rain forest has made up mostly of a few species of broadleaf and needle leaf trees, huge ferns, and thick undergrowth. The lush vegetation is due to its location on the windward slopes of the Cascade and Coast ranges in North America that receive over 100 inches of rainfall.

Describe the characteristics of the Northern Coniferous Forest (boreal forest) and explain how it has adapted to the subarctic climate in which it is found.

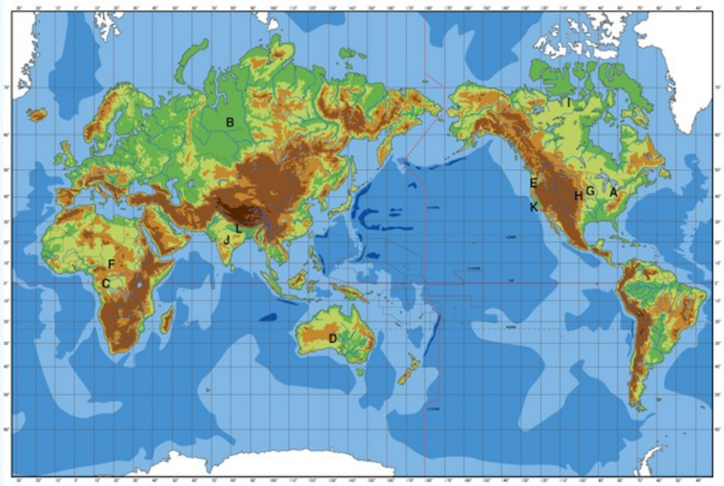
Answer

The Northern Coniferous forest is dominated by coniferous trees, with hardy deciduous trees mixed in. Trees in the northern coniferous forest primarily possess pine needles instead of broad leaves like those of the temperate forests to the south. Being dark in color they absorb what little light falls on their surfaces. Retaining their needles at the end of each growing season gives the tree a head start at growth during the spring as they do not have to waste their energy in producing new foliage. The sloping sides of the conical canopy helps catch the low angle sun rays typical of high latitude locations.

? Self-Assessment Quiz 13.7.1

1. Lianas and epiphytes are typically found in
   - A. the tall grass prairie.
   - B. the southern coniferous forest
   - C. taiga.
   - D. tropical rain forest.
2. Chaparral vegetation is closely associated with the
   - A. humid continental climate.
   - B. midlatitude steppe climate.
   - C. dry summer subtropical (Mediterranean) climate .
   - D. northern coniferous forest.
3. Taiga is found on the poleward limits of the
   - A. Midlatitude Steppe
   - B. Broadleaf Evergreen forest
   - C. Midlatitude Broadleaf Deciduous Forest
   - D. Northern Coniferous Forest
4. Which of the following biogeographical realms is dominated nearly exclusively by tropical forest?
   - A. Neotropical
   - B. Nearctic
   - C. Afrotropical
   - D. Indomalayan

Use this map to answer the following questions.



5. The most likely location to find a tall grass prairie is
   - A. A
   - B. G
   - C. J
   - D. D
6. Xerophytic vegetation is most likely found at
   - A. B
   - B. C
   - C. D
   - D. none of the above
7. A temperate rain forest is most likely found at
   - A. C
   - B. F
   - C. H
   - D. E
8. A mediterranean woodland is most likely located at
   - A. F
   - B. K
   - C. J
   - D. H
9. Which of the following would I most likely find at location H
   - A. Midlatitude Steppe
   - B. Southern Coniferous Forest
   - C. Midlatitude Broadleaf Deciduous Forest
   - D. Northern Coniferous Forest
10. Which of the following would I most likely find at location I
    - A. Midlatitude Steppe
    - B. Midlatitude broadleaf deciduous and mixed forest
    - C. Tundra
    - D. Northern Coniferous Forest

Answer

1. D
2. C
3. D

4. D
5. B
6. C
7. D
8. B
9. A
10. C

Additional Resources

Use these resources to further explore the world of geography

Connections: "Monitoring Monarchs" NPR (2013) *Talk of the Nation* report on how habitat loss in Mexico and Miklweed decline in US spells diaster for Monarch butterflies.

World of Change: Amazon Deforestation

Multimedia

"Hot Times in Alaska" *Scientific American Frontiers*. This episode investigates the impact of climate change on Alaska's ecosystems.

World's Biggest Tiger Preserve - NPR/National Geographic *Radio Expeditions* visits The Hukawng Valley in Myanmar where an entire valley nearly the size of Vermont is being set aside as a tiger reserve.

"The Birds of the Boreal" NPR/National Geographic *Radio Expeditions*

"The Last American rain forest" - *Morning Edition* (NPR) segment from Oct. 22, 1998 reports on the last great temperate rain forest in America, Alaska's Tsongass National Forest. (8:36) (RealAudio Required)

Readings

Grassland Initiative (NASA EOS)

Web Sites

Wild World: Terrestrial Ecoregions (NGS/WWF) - rich resource for information about global ecosystems. Organized by biogeographical realm.

CHAPTER OVERVIEW

14: Earth Materials and Structure

Learning Outcomes

By the end of this chapter you should be able to:

- Diagram a cross section of the Earth's interior and describe each layer.
- Diagram the rock cycle
- Define what a mineral is and describe the major mineral families that make up most rocks.
- Describe the origin and characteristics of sedimentary, metamorphic, and igneous rocks.
- Create a diagram of intrusive igneous rock bodies.
- Compare and contrast the orders of relief.

Physical geographers recognize that to uncover the spatial relationships of earth surface phenomena they must have a good understanding of what the Earth is composed of and how it affects landscape development. Here we will review the fundamental building blocks of Earth, how they change through time, and what effects they have on Earth surface processes and form.

14.1: The Earth's Interior

14.2: Forces that Shape the Surface of the Earth

14.3: Orders of Relief

14.4: Minerals

14.5: Rocks

- 14.5.1: Rocks and the Rock Cycle
- 14.5.2: Igneous Rocks
- 14.5.3: Sedimentary Rocks
- 14.5.4: Metamorphic Rocks

14.6: Review and Additional Resources

14.1: The Earth's Interior

The deep interior of the Earth remains somewhat of a mystery as we have only penetrated the very most outer portion with our deep drilling exploration. What knowledge we do have comes from seismic wave data or lava that has extruded onto the surface. What we do know is that the Earth's interior is somewhat like a concentric series of rings, progressing from the dense and intensely hot inner core toward the brittle outer shell of the crust. Geoscientist describe the layered interior of the earth on the basis of chemical composition or mechanical (physical) properties, like its ability to flow.

Investigating the Earth's interior

Figure 14.1.1: Seismograph recording seismic activity. (Courtesy USGS Hawaii Volcano Observatory)

Seismic activity gives us clues as to the internal structure of the Earth. Geoscientists obtain seismic data from naturally occurring earthquakes or human-induced explosions. Seismic energy produces two kinds of waves that are useful in studying the Earth's interior. ***Compressional (P) waves*** generate a back-and-forth motion parallel to the direction of travel. ***Shear (S) waves*** move up-and-down perpendicular to the direction of wave transmission. Seismometers detect these motions and record them on a ***seismograph***.

When seismic waves pass through rock, their amplitude and direction changes. For instance, wave velocity generally increases as rock density increases. Shear waves do not penetrate molten masses and when they encounter a boundary between two rock types of differing densities, a portion of the wave travels along the boundary while another part returns to the surface. Such changes in seismic wave velocities led Yugoslavian geophysicist Andrija Mohorovicic (1857-1936) to discover the boundary between the crust and underlying mantle. Wave velocity increases through the "***Moho***" discontinuity. It is believed that the discontinuity represents a zone where sima-type minerals undergo a phase change that produces a new and denser combination of minerals. "Examine P and S waves moving through Earth's interior." (Courtesy NSF/TERC/ McDougall Littell)

Video: The Solid Earth. Watch Professor Paul Tackley (Dept. of Earth and Space Sciences, UCLA) describe how the solid interior of the earth affects the outer layer through mountain ranges, volcanoes and plate tectonics. (Courtesy of www.HippoCampus.org)

Layers based on composition

The outer brittle shell of the Earth is the ***crust*** that forms the "skin" of the lithosphere. The crust is primarily composed of silicate rocks and ranging in thickness of about 5 to 70 km (about 3 to 43.5 mi) The crust is broken into several continental and oceanic tectonic (lithospheric) plates. These plates ride atop the more pliable mantle beneath, colliding to create great mountain systems and spreading apart to form rift valleys.

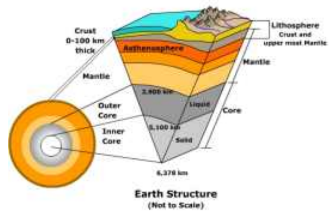


Figure 14.1.2: Interior Structure of the Earth (Click image to enlarge)

The crust is divided into a basal zone of oceanic crust called the *sima* layer, and a less dense continental crust known as the *sial* layer. The *sima* is primarily composed of a heavy, dark group of basaltic rocks. Primarily composed of silica and magnesium, their high density (2800 to 3300 kg/m^3) is due to the large amounts of iron and magnesium. The *sial*, named for the two predominate elements silicon and aluminum, is lighter in weight with densities around 2700 - 2800 kg/m^3. Often geoscientists refer to rocks of the sial as "granitic rock" as granite is a predominant rock type. The lower boundary of the sial grades into the upper portion of sima. The sial actually has quite a diversity of rock types, including large amounts of basaltic rocks. The sima however is almost exclusively basaltic in composition. Separating the upper mantle from the oceanic crust is the *Moho Discontinuity*. Seismic waves passing though this boundary increase their wave velocity from 7 km (4 mi) per second to 8 km (5 mi) per second. The shift of wave velocity is due to the change in rock composition and density. The ***mantle*** is over 2900 km thick (1801 mi)and comprises 80% of the Earth's total volume. It is mainly composed of a dark, dense ultramafic rock called peridotite 📷 that is rich in iron and magnesium. Seismic wave velocity increases steadily through this zone. The ***core*** is composed of iron and nickel with a liquid outer region and a solid core. The core is about half the diameter of the Earth.

Layers based on physical properties

The ***lithosphere*** is a rigid cool layer composed of the crust and the uppermost mantle. The ***asthenosphere*** is the least rigid portion of the mantle. It is a soft, easily deformed layer that is susceptible to slow convection caused by pockets of increased heat from the decay of radioactive elements. The ***mesosphere*** (not to be confused with the atmospheric layer of the same name) lies between the asthenosphere and core where the pressures are so great the mantle is solid. Finally, the **core** with its molten outer and rigid inner layers. Though intense heat is generated at such great depths, geoscientists believe that under the enormous overlying pressure the ***inner core*** is made of solid iron and nickel. The ***outer core*** is thought to be molten iron because shear-wave velocities drop to zero which occurs when they encounter a liquid. The interaction between the inner and outer core is thought to produce Earth's magnetic field.

Video: Difference between the crust and lithosphere (Courtesy Kahn Academy)

14.2: Forces that Shape the Surface of the Earth

In Chapter 2 you were introduced to sources of energy that drive earth system processes. The lithosphere is constantly being altered by these forces originating from within and outside the Earth system. Great forces from within causes the surface to heave and buckle, sometimes with disastrous consequences to humans. Energy received from the sun drives processes like those that create majestic sand dunes and carve magnificent stream valleys.

Endogenic Processes and the Lithosphere

Recall that ***endogenic forces or processes*** are those that are are driven by the Earth's vast heat engine. The movement of tectonic plates is thought to be a product of convection currents in the mantle. Deep within the Earth's core, heat is generated by the radioactive decay of elements like uranium, thorium, and potassium. The heat is transferred upward to warm the mantle causing it to slowly circulate and tug on the plates above. (For more see Some Unanswered Questions, *The Dynamic Earth*, USGS). As the crustal plates are moved about, they interact by colliding, sliding by, or diverging from one another. The result of such movement produces faults and earthquakes, volcanoes, the creation of mountain systems, or deep valleys and trenches. The great mountain systems of Earth like the Himalayas are a product of the collision of lithospheric plates. Similarly, the huge trenches found on the ocean floor, like the Marianas Trench, are caused by plate interaction.

Figure 14.2.1a: Mt. Shishaldin, Alaska is a composite volcano (Image courtesy USGS)

Figure 14.2.1b: Teton Mountains were created by faulting (Image courtesy USGS)

Exogenic Processes and the Lithosphere

Those processes acting at the surface of the earth and primarily driven by solar energy are called ***exogenic processes***. For instance, wind is created by the variation in pressure over distance (pressure gradient force). Pressure variations are, in part, created by the variation of surface heating due to the unequal distribution of solar energy receipt. As wind blows it exerts an erosive force on the surface to detach and transport soil particles. Wind erosion is therefore an exogenic process. Erosion by rain is likewise driven by the initial evaporation due to absorption of energy and subsequent conversion into precipitation by condensation processes. The geologic work of glaciers is considered an exogenic process. Glaciers form when summer temperatures decrease to the point where the previous winter's snowfall does not melt and accumulates over time eventually compacting and metamorphosing into ice. The accumulating ice spreads out as a great sheet sculpting the surface beneath it.

Figure 14.2.2a: Water Erosion. Severe sheet erosion on farm land (Image courtesy NRCS)

Figure 14.2.2b: Wind Erosion. Massive dust storm during the Dust Bowl era (Image courtesy USGS DDS21)

Figure 14.2.2c: Glacial Erosion. Alpine glaciers are found on all continents today at high altitudes (Image courtesy USGS DDS21)

14.3: Orders of Relief

The topography of the Earth is a product of endogenic and exogenic processes. ***Relief*** is simply the difference in elevation between two points. When the surface is relatively flat we say it has low relief. Conversely, mountainous regions have high relief. The relief features of the earth are be divided into three orders based on what created them and their size.

First Order Relief Features

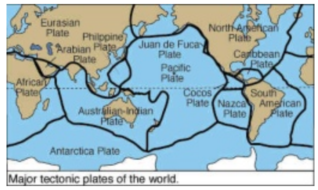


Figure 14.3.1: Crustal plates (Click image to enlarge) (Photo Courtesy; NASA)

First order relief features are the tectonic plates and are the largest in spatial extent. Two types of plates, *continental* and *oceanic* are differentiated by their rock and mineral composition. Continental plates are lighter in density and composed mostly of granitic rock material rich in silica and aluminum. The oceanic plates are made of dense, basaltic rock composed predominately of silica and magnesium.

Second Order Relief Features

Second order relief features are the result of plate collision or divergence. Rifts form where plates diverge from one another. If parallel rifting occurs, rift valleys, like the Great Rift Valley of Africa can form. Rifting can be accompanied by volcanic activity as magma pours out of the rift. Mt. Kilimanjaro was formed as a result of the rifting that created the Great Rift Valley of Africa.

Figure 14.3.2: Himalaya Mountains. North central India is to the north (top) Nepal in the middle and the Tibetan Plateau is in the lower third of the image. (Click image to enlarge) (Photo Courtesy NASA)

Great mountain systems or trenches are created when plates converge. When two continental plates collide it causes the Earth to fold and buckle. Such is the case when the Indian Plate collided with the Eurasian Plate creating the Himalaya Mountains. Marine fossils are found at high altitudes where they were pushed up as a result of the collision. The presence of fossil marine organisms on high mountain peaks was used as evidence to support the theory of plate tectonics. Today, the uplift continues as the Indian Plate forces its way northward against the Eurasian, increasing the height of the world's tallest peaks.

Extending from the northwest coast of the United States up along the Pacific Coast of Canada is the site where the Juan de la Fuca plate, an oceanic plate, is colliding with the North American plate, a continental plate. The denser and heavier oceanic plate dives beneath the lighter, less dense continental plate in a process of subduction. Subduction zones are noted for their frequent earthquake and volcanic activity. As the oceanic plate dives towards the interior of the earth the rock melts and some makes its way to the surface exploding with great fury to create spectacular volcanic cones.

Third Order Relief Features

Third order relief features are for the most part created by erosion and deposition of the surface as opposed to the movement of tectonic plates. Individual landforms are considered third order relief features. There is no upper or lower limit to the size of third order relief features. One way to distinguish between second and third order relief features is one can see the entire form of third order feature but not a second.

Figure 14.3.3: Pawnee Cirque, Colorado Front Range, USA (Photo Courtesy M. Ritter)

Pawnee cirque, the bowl shaped feature in the center of Figure 14.3.3 was caused by an alpine glacier eroding into the side of a mountain. The bowl-shaped depression left behind represents a third order relief feature of the earth. The picture was shot from across Isabelle Valley on Niwot Ridge. It is easy to see the full extent of the cirque but not the second order relief feature that it is located in, the Rocky Mountain system.

The surface features studied by physical geographers are not only dependent on the various forces that create them, but the material composition of the Earth as well. The mineral content of rock, and the type of rock greatly effect their resistance to geological agents of erosion and hence the surface features of our planet. To understand the geographical variation of Earth surface features, we need a fundamental knowledge of the materials that comprise the Earth and their mode of origin.

14.4: Minerals

A ***mineral*** is a naturally occurring inorganic substance with a unique crystal structure. The physical and chemical composition of a mineral is consistent between samples. There are nearly 3000 minerals, only 20 are common, and 10 make up 90% of the minerals of the crust.

Minerals may be composed of a single element, like gold (Au) or a combination of elements. Minerals composed of more than one element are bound together by electrical bonding. All minerals formed by more than one element are therefore bound together by positive and negative ions. By far the most abundant ions in minerals are the positively charged silicon (Si) and negatively charged oxygen (O). Silicon and oxygen are the foundation of the silicate minerals.

The most important mineral family is the ***silicates***. The silicates are a combination of silicon, oxygen, and another element. Depending on the element, the resulting mineral's density and color can vary considerably. The silicates are subdivided into the ferromagnesian and the nonferromagnesian (or aluminosilicates). Table 14.4.1 gives examples of other important mineral groups found in the crust.

Table 14.4.1: Important Mineral Families of the Crust

Type & Compound	**Examples**
Silicates - nonferromagnesian (Silicate ion; lack iron and magnesium ions)	Pyroxene Muscovite Mica Orthoclase (Potassium) feldspar Plagioclase feldspar Quartz
Silicates - ferromagnesian (Silicate ion+iron and magnesium ions)	Olivine Hornblende Biotite Mica
Oxides (Oxygen + element(s))	Limonite Hematite Magnetite
Sulfides (Sulfur + element(s))	Galena Pyrite Chalcopyrite
Carbonates (Carbon-oxygen ion + element(s))	Calcite; dolomite

SECTION OVERVIEW

14.5: Rocks

Rocks are assemblages of minerals. Unlike minerals, the composition of a particular rock type varies from sample to sample depending on the proportions of minerals contained within. A physical geographer needs a fundamental understanding of the properties and characteristic of rocks to understand the geographical variation of Earth surface features.

14.5.1: Rocks and the Rock Cycle

14.5.2: Igneous Rocks

14.5.3: Sedimentary Rocks

14.5.4: Metamorphic Rocks

14.5.1: Rocks and the Rock Cycle

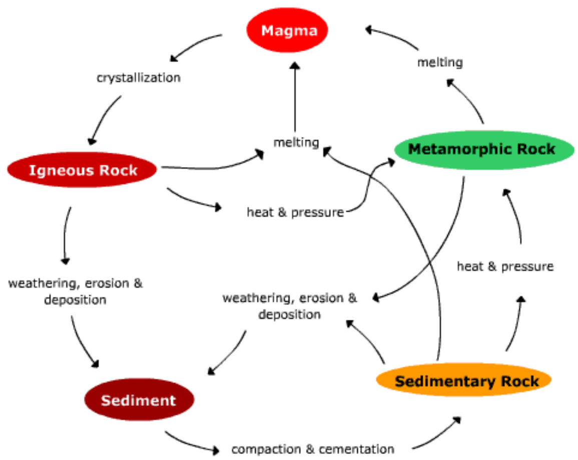


Figure 14.5.1.1: The Rock Cycle (After Lemke, et. al. 2003)

The rock cycle represents the alteration of rock-forming minerals above and below the Earth's surface. At the top of the diagram molten rock material, magma, cools (crystallization) to form ***igneous rocks***. If magma is extruded onto the surface it is called ***lava***. Cooling above the surface yields rocks with fine textures, while those that form from slow cooling beneath the surface typically have large crystals. Igneous rock may remelt when exposed intense heat to form magma again, or be changed into ***metamorphic rock***. Igneous rocks may also be exposed to weathering, erosion and deposition to form ***sediment***, fragments of weathered rock and the precursor for sedimentary rock.

As sediments accumulate they are subjected to compaction and cementation to form ***sedimentary rock***. Sedimentary rocks may be broken down by weathering and erosion to be deposited as sediment, exposed to intense heat and melting to return to magma, or be changed into a metamorphic rock.

Metamorphic rocks are those that have been altered by exposure to heat and/or pressure. The pressure can be created by the weight of material lying above them. The collision of lithospheric plates creates pressure and heat that alters rock. If entirely melted, the rock material forms magma. Erosion and weathering breaks down metamorphic rocks to form sediment, which can be compacted into sedimentary rock.

14.5.2: Igneous Rocks

Igneous rocks form by the cooling of ***magma*** (molten rock material beneath the surface) or lava (molten rock material extruded onto the surface). Magma which originates at depths as great as 200 kilometers below the surface consists primarily of elements found in silicate minerals along with gases, notably water vapor. Because the molten material is less dense than the surrounding solidified rock, it works its way toward the surface where it flows out onto the surface as lava.

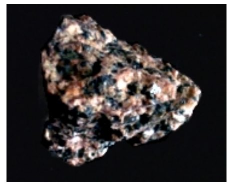


Figure 14.5.2.1: Granite, an intrusive igneous rock.

Cooling of the magma initiates the crystallization of elements contained within the molten rock. Usually, cooling does not take place at the same rate throughout the entire mass. As it cools, numerous small crystal develop and then ions are added around these centers of growth. Once the crystals grow enough for their edges to meet, growth ceases and crystallization commences in another part of the mass. Over time the magma cools into a solidified rock of interlocking crystals. The rate of cooling determines the degree to which crystals can grow. Those that form by slow cooling have large crystals and are described as being ***coarse-grained***. ***Fine-gained*** igneous rocks form by more rapidly cooling when the molten material is exposed at the surface. As a result, crystals don't have a chance to grow very large.

Intrusive Igneous Rock

When magma intrudes into pre-existing rock it cools rather slowly because the surrounding ***host*** or ***country rock***, as it is called, insulates the magma. As a result, crystals grow larger giving the rock mass a coarse texture. Such ***intrusive igneous, or plutonic rocks*** where the mineral grains are easily seen with the unaided eye are called ***porphyritic***. The rock mass itself is called a ***pluton***.

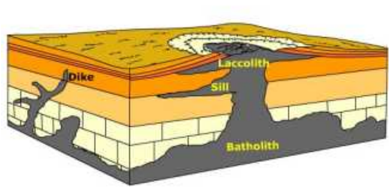


Figure 14.5.2.2: Intrusive igneous landforms

Physical geographers are especially interested in rocks that form beneath the surface after they have been exposed by erosion of the overlying host rock. A **batholith** is a huge intrusive igneous rock mass or pluton that when uncovered creates topographic highs in mountainous regions. The Idaho Batholith for example covers some 16,000 square miles. These landforms are massive in character lacking linear ridges and valleys.

Figure 14.5.2.3: Half Dome, a batholith in Yosemite National Park. (Courtesy of USGS)

When magma intrudes between the layers or rock and solidifies it creates a feature called a ***sill***. Sills form a hogback or cuesta when the layer of rock is dipping, or the tops of mesas when lying horizontal. If the magma solidifies as a pocket of igneous rock that warps the overlying rock it will form a dome or ***laccolith***. The Black Hills of South Dakota is such a domal feature. If magma cools in near vertical fractures a ***dike*** is formed . Dikes often form on the flanks of volcanoes. When exposed by erosion they take the form of a linear ridge. Shiprock, New Mexico a volcanic neck (Figure 14.5.2.4), has several dikes radiating away from it.

Figure 14.5.2.4: Shiprock, New Mexico to the right with a large dike on the left. (Courtesy of USGS DDS21)

Extrusive Igneous Rocks

Fine-grained rocks form if molten rock cools rapidly when it is extruded onto the surface. ***Basalt*** is a common extrusive igneous rock. Some fine grained rocks forming at the edge of a lava flow have small holes or ***vesicles*** which are void spaces left by escaping gasses. Very rapid cooling can produce rocks with a ***glassy texture*** such as obsidian.

Figure 14.5.2.5: Obsidian has a glassy appearance due to rapid cooling.

14.5.3: Sedimentary Rocks

Sedimentary rocks are those formed from the compaction and cementation of fragments of pre-existing rocks called ***clasts***, or plant and animals remains. The exogenic processes of weathering and erosion create the raw materials for sedimentary rocks. Earth material is loosened and moved from higher to lower elevations where it is deposited as transportation agents like water, wind or gravity lose their energy to move sediment. Streams and rivers transport sediment to lakes or oceans, or deposits it on nearby floodplains where it accumulates. On land, clastic sediments consist mainly of large boulders, cobbles, gravel, sand, and silt. On the continental shelves at the margin of continents, marine sediment is largely sand, silt, and clay. At the outer shelves and on the ocean floor, clays and chemically precipitated calcium carbonate and the remains of tiny marine animals accumulate.

Figure 14.5.3.1: Sandstone beds are easily seen in the cliffs of Paria-Vermillion Canyon, Arizona (Courtesy U.S. Bureau of Land Management)

As layers of sediment accumulate to great thickness, they are compacted and begin to harden into sedimentary rock. Each layer they form is called a ***bed*** or ***stratum***, the process by which this occurs is called ***stratification***. The separation between each bed is called a ***bedding plane*** and signifies a cessation of deposition at that location for a period of time. Beds can vary horizontally due to differences in the energy conditions and distance from the origin of the sediments. For instance, a bed may change from a conglomerate of cemented gravel, to compacted silt called siltstone, and finally to shale which is cemented clay, indicating the decreasing power of water to transport these different size materials from away from their source. Generally speaking, if the layers have not been disturbed, the oldest layers are at the bottom. Often there is a cementing agent that holds the materials together. Because many sedimentary rocks are formed from fragments of rocks, they are weaker than igneous or metamorphic rocks.

Types of sedimentary rocks

Sedimentary rocks are divided into two groups, ***clastic or detrital***, and ***nonclastic or chemical***. Among the chemical sedimentary rocks are those that are "biologic" in origin like coal. The clastic sedimentary rocks form from the compaction of rock fragments, while the chemical sedimentary rocks form by the precipitation of elements. ***Sandstone*** is a common clastic sedimentary rock formed by the compaction and cementation of sand (quartz grains). ***Conglomerate*** is another clastic sedimentary rock formed by the cementation of rounded boulders, cobbles, and pebbles. On the other hand, ***breccia*** forms from angular boulders, cobbles, and pebbles. ***Shale*** forms from the compaction of clays, while ***siltstone*** (mudstone) forms from the compaction of silt.

Figure 14.5.3.2a: Sandstone

Figure 14.5.3.2b: Conglomerate

Figure 14.5.3.2c: Limestone

You are probably familiar with several of the nonclastic sedimentary rocks. Limestone is composed of precipitated calcium carbonate. ***Limestone*** sometimes contains visible shells of marine organisms that have accumulates on the ocean floor. ***Dolomite*** is a calcium-magnesium carbonate rock that forms as a chemical precipitate or from the alteration of limestone. Limestone is very easily weathered in warm and moist climates to create ***karst topography***.

Coal is considered a sedimentary rock. Some might classify it as a biologic sedimentary rock as it forms from the compaction and alteration of accumulated plant matter. Coal is classified into one of three types depending on its level of development. *Lignite* is a soft, brown coal and is the least developed form. One might think of it as an intermediate step between peat and coal. *Bituminous coal*, also called soft coal though harder than lignite, is a product of deep burial and compaction. *Anthracite* is the hardest and most developed or pure form of coal. Anthracite forms when bituminous coal is metamorphosed in regions that have undergone mountain building. Anthracite is the most valued form of coal for its heat generating capacity and low sulfur content.

Figure 14.5.3.3: Limestone bluffs along the Missouri River. (Courtesy USFWS; Source)

14.5.4: Metamorphic Rocks

Metamorphic rocks are formed by the alteration of pre-existing rocks from exposure to heat and pressure while remaining in a solid form. Metamorphism occurs by breaking bonds between atoms in a mineral so that the atoms rearrange themselves into new, more stable, mineral forms. Rocks are transformed and remain in a solid state because not all the bonds in the rock's minerals are broken - if they were the rock would melt. Metamorphism occurs in solid rock because only some of the bonds between atoms are broken in an unstable mineral. As a result, the freed atoms and ions can migrate to another location within the mineral, or bond with atoms in a different mineral. The end result is to produce minerals that are more stable under the environmental conditions in which they exist.

Metamorphism involves the transformation of a pre-existing rock to form new minerals and textures. The original mineral content of a rock can change in several ways. Unstable minerals like clays will breakdown and their elements will recombine to form new minerals. More stable minerals like quartz, will stay quartz but change shape and size to form a new configuration. At high temperatures, atoms and ions may move into a new orientation and bond into more stable forms. Hence, the type of minerals and its texture may change but the chemical composition of the rock itself can stay the same.

Rocks buried deep beneath the Earth are exposed to ***lithostatic pressure***, the confining pressure created by the material that sits above a particular location. Lithostatic pressure is equal in all directions and compresses the volume of rock into a denser material. At the contacts between mineral grains, the pressure breaks the bonds between atoms allowing them to migrate toward regions of less pressure where they rebind with other atoms.

Figure 14.5.4.1: Gneiss displays the banding of minerals typical of a foliated metamorphic rock formed from granite. (Click image to enlarge or here to see QuickTime movie)

Along the boundary of tectonic plates where collision or subduction is occurring, ***directed pressure*** is exerted on rock. Under these circumstances, pressure is imposed in a particular direction. Directed pressure flattens and lengthens the rock in the direction of greatest pressure. The pressure is not great enough to affect new mineralization however. Instead, directed pressure affects the shape and arrangement the minerals. Under great pressure, mineral grains may be smeared or partially melted and recrystallized into bands aligned perpendicular to the direction of greatest pressure. This creates ***foliated metamorphic rocks*** with minerals in distinct bands. Where the pressure is not directed, ***nonfoliated*** metamorphic rocks are formed and lack the banding of minerals typical of foliated rocks.

Figure 14.5.4.2: Quartzite is a nonfoliated metamorphic rock formed from sandstone, a sedimentary rock.

Table 14.5.4.1: Common Metamorphic Rocks

	Rock	**Parent Rock**	**Key Minerals**	**Metamorphic Environment**
Foliated	Slate	Shale	Clay minerals, micas. chlorite. graphite	Relatively low temperature and pressure
Foliated	Schist	Shale, basalt, graywacke sandstone, impure limestone	Mica, chlorite, garnet, talc, epdiodte, hornblende, graphite, staurite, kyanite	Intermediate - to - high temperature and pressure

Foliated	Gneiss	Shale, felsic igneous rocks, graywacke, sandstone, granite, impure limestone	Garnet, mica, augite, hornblende, staurolite, kyanite, sillimanite	High Temperature and pressure
Nonfoliated	Marble	Pure limestone	calcite, dolomite	Contact with hot magma, or confining pressure from deep burial
Nonfoliated	Quartzite	Pure sandstone, chert	Quartz	Contact with hot magma, or confining pressure from deep burial

Occurrence of metamorphism

Metamorphism occurs under a variety of different conditions that controls the geographic distribution of metamorphic rocks and their significance to earth surface features. When magma intrudes into host rock, localized ***contact metamorphism*** occurs along the contact between the pre-existing rock mass and the cooling pluton. The heat introduced by the intruding magma controls the degree of metamorphism. Contact metamorphism occurs under low to moderate pressure and low to high temperature conditions. Temperatures of metamorphism vary widely from 400-1000°C. The amount of metamorphism is governed by a variety of factors, among which are the differences between the temperature of the pluton and the country rock, the heat capacity and conductivity of both magma and country rock. Hydrothermal fluids circulating through the surrounding rock are also important in metamorphosing the rock as they transport heat. Fluids are particularly important in the metamorphism of carbonate rocks.

Typically, contact metamorphism occurs at shallower levels of the crust, where the pressure is relatively low. At those shallow depths, the stresses characteristic of orogenic belts are generally small or absent thus producing metamorphic rocks that lack foliation. Contact metamorphism commonly produces fine-grained rocks. The metamorphosed rock surrounding the body of magma along the zone of contact is called an aureole. Many profitable mines are situated in metal-rich aureoles formed by contact metamorphism.

Regional metamorphism occurs over broad areas of the crust. There are two basic kinds of regional metamorphism, ***dynamothermal metamorphism*** and ***burial metamorphism***. Dynamothermal metamorphism occurs in areas that have undergone deformation during mountain building that have since been eroded to expose the metamorphic rocks. It is caused by the differential stress resulting from plate subduction or collision along plate boundaries. Regional metamorphism occurs in a linear belt in the plate overriding the subducting one due to increasing temperature and pressure as a result of compression, thrusting, folding, and intrusion of magmas from below.

Burial metamorphism occurs in deep basins where sediments or sedimentary rocks have accumulated. At a depth of about 10 kilometers, the confining pressure of the overlying material combined with geothermal heat is great enough to metamorphose rocks. Because the compression does not impose a directed pressure, metamorphic rocks formed from burial are unfoliated.

14.6: Review and Additional Resources

Review

Idyllwild. Suicide Rock, exfoliating granite dome.
Riverside County, California.
Courtesy USGS

Figure 14.6.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **compressional wave**
  generate a back-and-forth motion parallel to the direction of travel
- **shear wave**
  move up-and-down perpendicular to the direction of wave transmission
- **crust**
  outer brittle shell of the Earth; forms the "skin" of the lithosphere. The crust is primarily composed of silicate rocks and ranging in thickness of about 5 to 70 km
- **sima**
  basal zone of oceanic crust; primarily composed of a heavy, dark group of basaltic rocks
- **sial**
  less dense continental crust; predominate elements are silicon and aluminum
- **lithosphere**
  rigid cool layer composed of the crust and the uppermost mantle
- **asthenosphere**
  the least rigid portion of the mantle. It is a soft, easily deformed layer that is susceptible to slow convection caused by pockets of increased heat from the decay of radioactive elements
- **mesosphere**
  lies between the asthenosphere and core where the pressures are so great the mantle is solid
- **core**
  molten outer and rigid inner layers
- **mantle**
  over 2900 km thick (1801 mi) and comprises 80% of the Earth's total volume; mainly composed of a dark, dense ultramafic rock called peridotite (rich in iron and magnesium)

- **endogenic force**
  forces that are are driven by the Earth's vast heat engine
- **exogenic force**
  processes acting at the surface of the earth and primarily driven by solar energy
- **relief**
  the difference in elevation between two points
- **first order relief feature**
  the tectonic plates
- **second order relief feature**
  the result of plate collision or divergence
- **third order relief feature**
  created by erosion and deposition of the surface as opposed to the movement of tectonic plates. Individual landforms are considered third order relief features
- **mineral**
  a naturally occurring inorganic substance with a unique crystal structure
- **silicate**
  a combination of silicon, oxygen, and another element; see Table 14.4.1
- **oxide**
  see Table 14.4.1
- **sulfide**
  see Table 14.4.1
- **carbonate**
  see Table 14.4.1
- **rock cycle**
  represents the alteration of rock-forming minerals above and below the Earth's surface
- **rock**
  assemblages of minerals
- **magma**
  molten rock material
- **sediment**
  fragments of weathered rock and the precursor for sedimentary rock
- **igneous rock**
  cooled/crystallized magma or lava
- **sedimentary rock**
  formed by compaction and cementation of sediments
- **metamorphic rock**

formed by the alteration of pre-existing rocks from exposure to heat and pressure while remaining in a solid form

- **clastic sedimentary rock**
  form from the compaction of rock fragments
- **chemically precipitated sedimentary rock**
  form by the precipitation of elements
- **country rock**
  the pre-existing rock that insulates the magma that has intruded as it cools
- **sill**
  feature created when magma intrudes between the layers of rock and solidifies
- **dike**
  created when magma cools in near vertical fractures
- **laccolith**
  created when the magma solidifies as a pocket of igneous rock that warps the overlying rock
- **batholith**
  a huge intrusive igneous rock mass or pluton that when uncovered creates topographic highs in mountainous regions.
- **pluton**
  rock mass in which magma has intruded and solidified
- **vesicles**
  small holes; void spaces left by escaping gasses
- **stratum**
  individual layer of sedimentary rock
- **bedding plane**
  separation between each bed; signifies a cessation of deposition at that location for a period of time
- **lithostatic pressure**
  the confining pressure created by the material that sits above a particular location; equal in all directions and compresses the volume of rock into a denser material
- **directed pressure**
  flattens and lengthens the rock in the direction of greatest pressure; affects the shape and arrangement the minerals
- **burial metamorphism**
  occurs in deep basins where sediments or sedimentary rocks have accumulated. At a depth of about 10 kilometers, the confining pressure of the overlying material combined with geothermal heat is great enough to metamorphose rocks.
- **contact metamorphism**
  occurs at shallower levels of the crust, where the pressure is relatively low. At those shallow depths, the stresses characteristic of orogenic belts are generally small or absent thus producing metamorphic rocks that lack foliation
- **regional metamorphism**
  occurs over broad areas of the crust; occurs in a linear belt in the plate overriding the subducting one due to increasing temperature and pressure as a result of compression, thrusting, folding, and intrusion of magmas from below.

- **dynamothermal metamorphism**

  occurs in areas that have undergone deformation during mountain building that have since been eroded to expose the metamorphic rocks. It is caused by the differential stress resulting from plate subduction or collision along plate boundaries

- **foliated metamorphic rock**

  minerals in distinct bands

- **nonfoliated metamorphic rock**

  lack the banding of minerals

Review Questions 14.6.1

Compare and contrast compressional and shear waves.

Answer

Compressional (P) waves generate a back-and-forth motion parallel to the direction of travel. **Shear (S) waves** move up-and-down perpendicular to the direction of wave transmission. Shear waves do not penetrate molten masses and when they encounter a boundary between two rock types of differing densities, a portion of the wave travels along the boundary while another part returns to the surface.

Compare and contrast the sima and sial.

Answer

Sima refers to silica and magnesium, two important elements of the rocks forming the ocean basin like basalt. **Sial** refers to silica and aluminum, two important elements that comprise the rocks of the continents like granite.

Briefly describe the layers of the mantle.

Answer

The uppermost part of the mantle includes part of the lithosphere. Below the lithosphere is the asthenosphere, the least rigid portion of the mantle. Finally the mesosphere is the bottom most portion comprised of solid rock.

Describe the basic structure of the Earth's core.

Answer

The core is divided into the inner and outer cores. The **inner core** is made of solid iron and nickel. The **outer core** is thought to be molten iron.

Compare and contrast endogenic and exogenic forces. Give examples.

Answer

Endogenic forces are those driven by Earth's "heat engine" like volcanoes and earthquakes. **Exogenic** forces are driven by solar radiation like wind and water erosion.

Compare and contrast first, second, and third order relief features. Give an example for each.

Answer

First order relief features are the tectonic plates. **Second order relief** features are formed by plate interaction, e.g. mountain systems, ocean trenches. **Third order relief** features are produced by the erosion or deposition e.g., sand dunes, mountain peak.

What is a mineral and how is it different from a rock?

Answer

A mineral is an inorganic substance having a unique crystalline structure while a rock is a combination of minerals.

What is the rock cycle?

Answer

It is a model of the interrelationships between the three types of rocks and how they form.

Compare and contrast the physical features of intrusive and extrusive igneous rocks.

Answer

Extrusive igneous rock has smaller mineral grains and thus finer texture than intrusive igneous rocks.

Briefly describe how a sill, dike, batholith, and laccolith form.

Answer

Sill - magma intrudes between layers of host rock and solidifies. **Dike** - magma solidifies in a near vertical fracture. **Batholith** - huge subterranean mass of igneous rock. **Laccolith** - magma intrudes between layers of host rock, then warp the overlying layers.

Compare and contrast the various types of sedimentary rocks. Give examples.

Answer

Clastic sedimentary - formed from fragments, example = sandstone. **Chemical (nonclastic)** - formed from a precipitate. Example = limestone. **Biologic sedimentary** - Compaction of animal remains. Example = coal.

Compare and contrast the various types of metamorphism.

Answer

Contact metamorphism occurs along contact zones between pre-existing rock and a cooling pluton.

Regional metamorphism occurs over broad areas of the crust. There are two basic kinds of regional metamorphism: dynamothermal metamorphism - deformation during mountain building. burial metamorphism - occurs in deep basins where sediments or sedimentary rocks have accumulated.

What is the fundamental difference between foliated and nonfoliated metamorphic rocks.

Answer

Foliated metamorphic rocks display banding of minerals, nonfoliated do not.

? Self-Assessment Quiz 14.6.1

1. Waves of seismic energy propagated as a back-and-forth motion are called
   A. compressional waves
   B. shear waves
   C. surface waves
   D. none of the above
2. The sima is primarily composed of
   A. granitic-type rocks
   B. basaltic-type rocks
   C. limestone-like rocks
   D. none of the above
3. Which of the following layers are, we think, composed of solid nickel and iron?

A. The asthenosphere
B. The lithosphere
C. The outer core
D. The inner core

4. Which of the following is created by endogenic forces?

A. Glacial erosion
B. Water erosion
C. Wind erosion
D. Faulting

5. The Himalaya Mountains are a _____ relief feature of the Earth.

A. first
B. second
C. third
D. fourth

6. The most abundant mineral family is the

A. silicates
B. oxides
C. sulfides
D. carbonates

7. Metamorphic rocks form from

A. sedimentary rocks
B. igneous rocks
C. other metamorphic rocks
D. all the above

8. An intrusive igneous rock body formed by the cooling of magma in a nearly vertical fracture is called a

A. dike
B. sill
C. laccolith
D. batholith

9. Granite is

A. an extrusive igneous rock
B. a clastic sedimentary rock
C. a nonfoliated metamorphic rock
D. none of the above

10. Quartzite is

A. an extrusive igneous rock
B. a clastic sedimentary rock
C. a nonfoliated metamorphic rock
D. none of the above

Answer

1. A
2. B
3. D
4. D
5. B
6. A
7. D
8. A
9. D

10. C

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "Earth's Core" *Naked Science*

Connections: "Evolution of Landscape Change along Clear Creek, Colorado" USGS. A look at the effects of urbanization, aggregate mining and reclamation.

Multimedia

"The Chemistry of Earth" *The World of Chemistry* video series (Annenberg/CPB) "Silicon, a cornerstone of the high-tech industry, is one of the elements of the Earth highlighted in this program." Additional information about Earth structure and mineral formation is included. Go to the The World of Chemistry site and scroll to "The Chemistry of Earth". One-time, free registration may be required to view film.

"Intrusive Igneous Rocks" *Earth Revealed* video series (Annenberg/CPB)
Most magma does not extrude onto Earth's surface but cools slowly deep inside Earth. This magma seeps into crevices in existing rock to form intrusive igneous rocks. Experts provide a graphic illustration of this process and explain the types and textures of rocks such as granite, obsidian, and quartz. Once again, plate tectonics is shown to be involved in the process. Go to the Earth Revealed site and scroll to "Intrusive Igneous Rocks". One-time, free registration may be required to view film.

"Metamorphic Rocks" *Earth Revealed* video series (Annenberg/CPB) "The weight of a mountain creates enough pressure to recrystallize rock, thus creating metamorphic rocks. This program outlines the recrystallization process and the types of rock it can create — from claystone and slate to schist and garnet-bearing gneiss. The relationship of metamorphic rock to plate tectonics is also covered." Go to the Earth Revealed site and scroll to "Metamorphic Rocks". One-time, free registration may be required to view film.

"Sedimentary Rocks": The Key to Past Environments *Earth Revealed* video series (Annenberg/CPB) This program returns to the Grand Canyon: its exposed layers of sedimentary rock allow scientists to peer into the geologic past. The movement of sediment and its deposition are covered, and the processes of lithification, compaction, and cementation that produce sedimentary rocks are explained. Organic components of rock are also discussed. Go to the Earth Revealed site and scroll to "Sedimentary Rocks: The Key to Past Environments". One-time, free registration may be required to view film.

Readings

Uncovering Hidden Hazards in the Mississippi Valley (USGS)

The Mississippi Valley-"Whole Lotta Shakin' Goin' On" (USGS)

CHAPTER OVERVIEW

15: Tectonics and Landforms

Learning Objectives

By the end of this chapter you should be able to:

- Describe the theory of plate tectonics and the evidence used to support it.
- Compare and contrast the environmental setting of the four types of plate boundaries.
- Explain the relationship between earthquakes, volcanoes, and plate boundaries.
- Draw simple diagrams showing the effect of stress on rock materials.
- Describe the movement associated with faulting.
- Describe landform features resulting from folding.

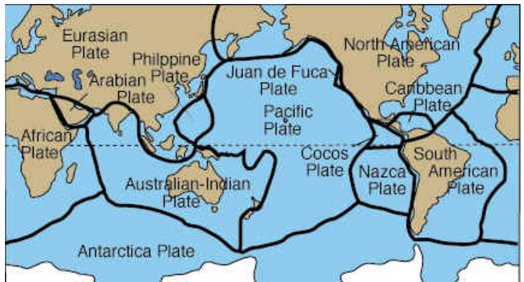
In this chapter you'll travel back to a distant time when the geography of the Earth's crust was much different than it is today. The search for answers to Earth's dynamic nature will set the context for explaining modern day tectonic activity. **Tectonics** is study of the processes that control the structure and properties of Earth's lithosphere. Plate tectonics is the process of plate formation, movement, and destruction. It explains the evolution of Earth's surface through time, the building of mountains, formation of deep valleys, and the movements of lithospheric plates that have impacted climate, human evolution and the distribution of plant and animal species. By the conclusion of the chapter you should be able to explain how plate movement has created many of the surface features of our present day Earth.

15.1: Plate Tectonics and Continental Drift
15.2: Plate Boundaries
15.3: Crustal Deformation
15.3.1: Folding and Faulting
15.3.2: Types and Geographic Patterns of Faults
15.3.3: Tsunamis
15.4: Review and Additional Resources

15.1: Plate Tectonics and Continental Drift

Introduction

The surface of the lithosphere is fractured into a number of ***tectonic plates*** (also known as lithospheric or crustal plates) which are in constant motion. As these plates move and collide, the lithosphere buckles, warps, and is torn apart. When this occurs, the Earth's surface shakes with great force, like that which accompanies earthquakes. Volcanoes are common along many plate boundaries as well.

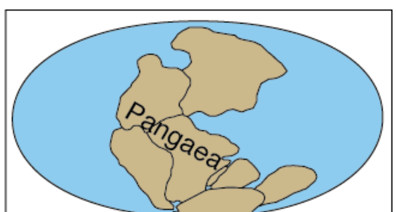


Major tectonic plates of the world.

Figure 15.1.1: Major Tectonic plates of the world (Diagram Courtesy of USGS)

Plate Tectonics

Plate tectonics refers to the process of plate formation, movement, and destruction. It finds its foundations in two theories, continental drift and sea-floor spreading. ***Continental drift*** describes the movements of continents over the Earth's surface. Sea-floor spreading refers to the creation new oceanic plate material and movement away from the mid-ocean ridge. It was Alfred Wegener in the early 1900's who brought forth the concept that the "shell" of the Earth's surface was fractured, and these "pieces" drifted about. Blasphemy in the minds of scientists of Wegener's day, some 50 years later his ideas were finally accepted. Wegener was able to piece together (pardon the pun) several bits of information which led to his conclusion that the present configuration of the continents is not the same as it was in the past. In fact, the continents were one "super-continent" called ***Pangea***.



200 million years ago all of the present-day continents combined to form a single supercontinent called Pangaea.

Figure 15.1.2: The supercontinent of Pangea (Diagram Courtesy of USGS)

Look at a map of the Earth like that in Figure 15.1.3. Carefully examine the east coast of South America and then let your eyes drift to the west coast of Africa. It looks like you could "fit" South America up against Africa like a puzzle. The same can be said for the fit between North America, Africa, and Europe (Figure 15.1.4)

Figure 15.1.3: Present location of world land masses.

Figure 15.1.4: Fit of continental land masses

When we slide the continents together, some over lap between the land masses occurs. This is possibly due to the creation of ***exotic terrain***, new land that has been formed somewhere else and moved to its present location. This remarkable correspondence provides circumstantial evidence for the theory of continental drift.

Looking for the evidence

If the continents were in one piece at some time in the past, we should find similar fossils and rocks on both continents which is precisely what Wegener discovered. By studying the geologic record, the fossil record, and climatic record, he found remarkable similarities between Africa and South America.

Figure 15.1.5: Fossil Glossopteris leaf, Ellsworth Land, Antarctica. Click image to enlarge (Photo Credit USGS DDS21)

Fossils of the same species of plants and animals were found in similar geologic formations in different parts of the world, most notably South America, Africa, and India. For example, fossils of the Glossopteris, an ancient fern, are found in South America, Africa, Antarctica, India, and Australia. It was hypothesized that such a distribution could only come about if the continents were all part of the one super-continent.

Examining the stratigraphy (vertical sequences) of the rock record, Wegener could point to further evidence for Pangea and continental drift. Wegener noted that the rock sequences in South America, Africa, India, and Australia are very similar. Wegener showed that the same three bottoms layers occurred on each of the continents. The bottom layer, called tillite, was thought to be of glacial origin. The middle layer composed of coal beds, shale and sandstone contained Glossopteris fossils, as did the bottom tillite layer. The top most and youngest layer is lava flows. Such a strong similarity in the rock record of these localities, now separated by great geographic distance, lent credence to Wegener's notion of continental drift.

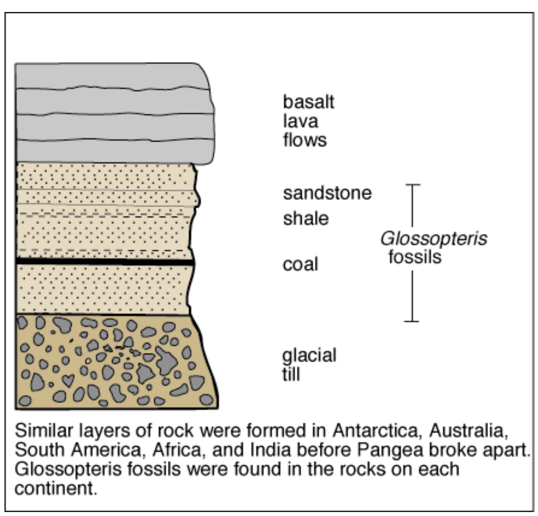


Figure 15.1.6: Simplified stratigraphic profile for portions of South America, Antarctica, Australia, Africa and India (Courtesy of USGS)

The occurrence of glacial features (Figure 15.1.7) in the geologic record of South America, Africa, India ,and Australia provides further evidence for the notion of continental drift. Glaciers affected all or part of these continents at the same time in Earth history.

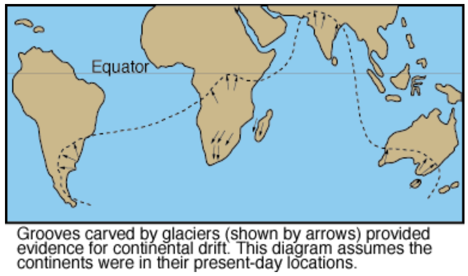


Figure 15.1.7: Evidence of glaciation to support continental drift (Courtesy of USGS)

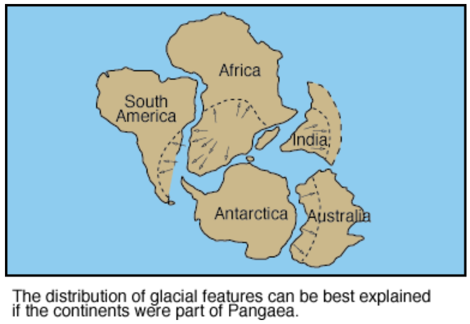


Figure 15.1.8: Past glaciation explained by continental drift (Courtesy of USGS)

Video: Pangea (Courtesy Khan Academy)

The Mobile Crust

Wegener's ideas were not readily accepted during his day because he did not offer a plausible mechanism for the movement of the continents. Wegener suggested it was the spin of the Earth that caused plates to "plow" their way through the mantle beneath (Figure 15.1.9).

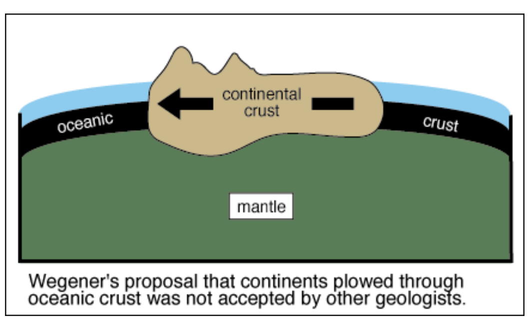


Figure 15.1.9: Wegener's proposed movement of plates (Courtesy of USGS)

Interestingly, there appeared to be a split in the scientific community in a geographical sense at the time. Geologists in the Northern hemisphere were less accepting as those living in the Southern hemisphere who were familiar with the rocks Wegener used to support his hypothesis. It wasn't until 1928 that a Scottish geologist proposed a mechanism to drive continental drift. Arthur Holmes believed a fluid mantle possessed ***convection currents*** created by heat trapped beneath the Earth's surface. Holmes hypothesized that convection currents welled up toward the surface and then drug continents across the surface.

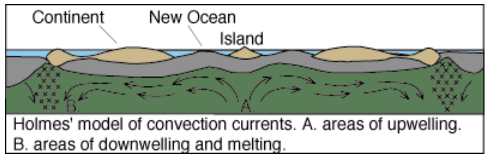


Figure 15.1.10: Holmes' convection current model. (Courtesy of USGS)

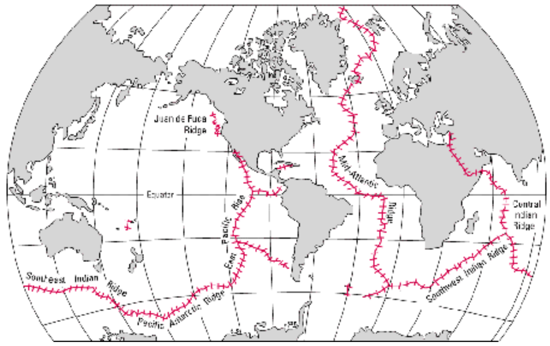


Figure 15.1.11: Mid-ocean Ridge (Courtesy USGS) (Click image to enlarge)

In the late 1950's and early 1960's oceanographic research was opening the final frontier on Earth, the mysteries of the ocean floor. During the 1950's seismologists showed that earthquake activity was concentrated along the longest continuous mountain system on Earth, the mid-ocean ridge. Known for over a century, the mid-ocean ridge system in the Atlantic Ocean rises some 6,500 feet above the surrounding ocean floor and extends for more that 37,500 miles (60,000 km) in all the world's oceans. At the crest of the ridge system lies a trough or rift. These rifts are about 20 miles wide (30 km) and 6,500 feet (2,900 m) deep and are a site where lava is expelled on to the ocean floor. The youngest material is found near the ridge with rocks of increasing age further away. It appears that the mid-ocean ridge is the site of sea floor spreading leading to plate movement. The key to sea floor spreading was found in the magnetic properties of rock lying on the sea floor.

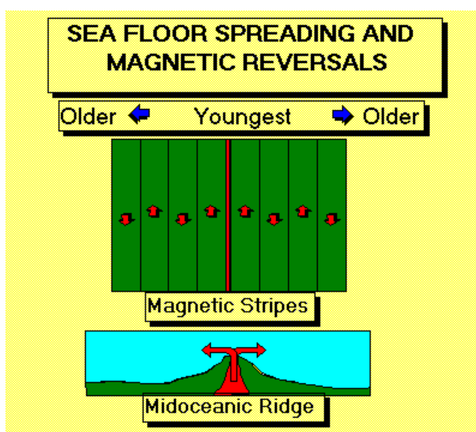
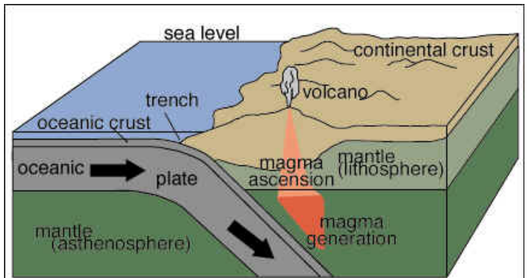


Figure 15.1.12: Sea floor spreading and magnetic stripes

Geoscientists found that as new material is extruded from the mid-ocean ridge onto the ocean floor, the polarity of the rocks is frozen in time. Dragging a magnetometer across the ridge, they noticed that the polarity recorded a series of "flips" when the polarity of the rocks reversed. Parallel stripes of ***magnetic reversals*** on either side of the ridge was supporting evidence for sea floor spreading. (See animation of magnetic stripe formation - caution large file) (For more details see: North Cascades Geology - Sea Floor spreading" and Magnetic Stripes and isotope clocks (USGS). These ideas set the stage for further research that has given us a plausible explanation for the movement of the crust and the drifting of continents first proposed by Wegener.

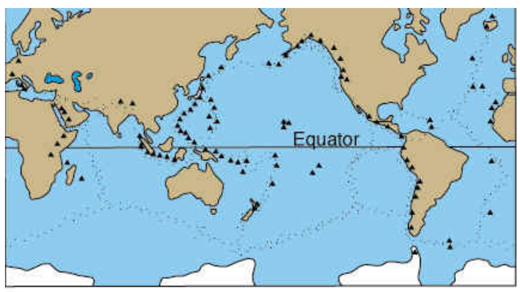
Modern Theory of Plate Movement and Continental Drift

The movement of lithospheric plates referred to as ***continental drift***, is believed to be caused by the radioactive decay of elements in the core and mantle that produces heat. The heat in turn creates convection currents in the mantle which "drive" the plates along their path of movement. When plates collide, heavier, more dense plates dive beneath lighter, less dense crustal plates along ***subduction zones***. As the heavier plate moves downward into the mantle, the increase in temperature and pressure drive water and other volatile fluids ("dewatering") from the oceanic crust. At a depth of 100 kilometers (60 miles), the water-rich fluids decrease the melting point of mantle rock causing it to melt. The magma that slowly moves upwards and may be extruded onto the surface as ***lava*** (Figure 15.1.13). Some plates slip past one another, creating earthquakes, (Figure 15.1.13) like what happens along the San Andreas fault in California. In many places the crust is separating and moving away in opposite directions, or diverging as happened to create the Great Rift Valley of Africa.



Magma is generated at subduction zones where dense oceanic plates are pushed under lighter continental plates.

Figure 15.1.13: Sea floor movement and plate tectonics (Courtesy of USGS)



Global distribution of volcanoes (▲) and earthquakes ( ) based on Simkin and others (1989).

Figure 15.1.14: Global distribution of earthquakes and volcanoes (Courtesy of USGS)

Though many earthquakes seemingly occur along plate boundaries, they can occur far away from the edges of plates too. One of the most well-known seismic regions is the New Madrid Seismic Zone located in the Mississippi Valley of the central United States. Investigate the New Madrid Seismic Zone by reading The Mississippi Valley - "Whole Lotta Shakin' Goin' On" . Then return here to continue.

Video: Plate tectonics: Evidence of plate movement (Courtesy of Khan Academy)

15.2: Plate Boundaries

Along the boundary of the Earth's tectonic plates a fiery drama of catastrophic proportions is played out. Movement of the Earth's crust creates earthquake activity and in some places great outpourings of lava extrude onto the surface.

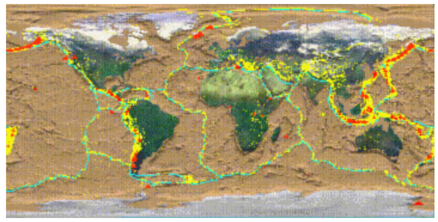


Figure 15.2.1: Earth's Lithospheric plates (Courtesy: NASA Goddard Space Flight Center)

Four types of plate boundaries are recognized and are depicted in Figure 15.2.1***A spreading or divergent boundary*** occurs where plates are moving away (diverging) from one another, like that occuring along the midocean ridge where new crust is formed. ***Convergent*** boundaries are located where subduction is active and the lithosphere is being "consumed". This occurs where two plates collide with one another. ***Transform*** boundaries occur where plates are grinding past one another, like the San Andreas fault. ***Plate boundary zones*** are broad belts in which boundaries are not well defined and the effects of plate interaction are unclear. Understanding plate motions (USGS) is important in deciphering land forming processes that occur along plate boundaries.

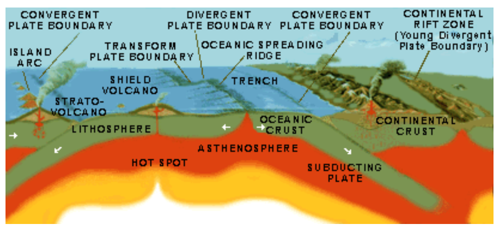


Figure 15.2.2: Tectonic Settings (Courtesy of USGS)

Video: Plate tectonics: Geological features of divergent plate boundaries (Courtesy Khan Academy)

Video: Plate tectonics: Geological features of convergent plate boundaries (Courtesy Khan Academy)

Plate Boundaries and Earthquakes

An ***earthquake*** is the shaking of the Earth as a result of crustal movement. Earthquakes emanate from faults, or fractures in the Earth where movement occurs. Most earthquakes occur at the boundaries where plates meet. Submarine earthquakes create *seismic ocean waves* that travel long distances across the ocean. They often strike land with devastating consequences. [For an animation of how earthquakes are propagated see "The Savage Earth" - The Restless Planet: Earthquakes animation , NOVA, PBS].The location of earthquakes and the ruptures associated with them are what scientists use to define plate edges.

There are several different kinds of faults classified according to the type of movement that occurs. Where plates move horizontally past one another, transform faults occur. Such is the case of the San Andreas Fault in California. Where the crust is spreading apart, like the mid-ocean ridge, shallow earthquakes (within 30 kilometers of the surface) are common. Shallow to deep earthquakes occur along subduction zones where one plate overrides another, like that which occurs along the northwest coast of the United States, western Canada and southern Alaska.

Figure 15.2.3: San Andreas Fault, California, is where numerous earthquakes occur due to slippage along two plate boundaries. (Source: USGS Used with permission)

Plate Boundaries and Volcanoes

Looking at a map of lithospheric plate boundaries shows volcanic activity along the boundaries of some lithospheric plates. Convergent plate boundaries where subduction occurs commonly experience volcanic activity. The "***Ring of Fire***" that extends from the west coast of the United States toward the Aleutian Islands and over to Japan is a good example of volcano activity associated with the margins of plates. Mt. St. Helens (Washington), Mt. Shishaldin (Alaska), and Mt. Fujiyama (Japan) were born from the collision and associated melting of plates beneath the surface of the Earth. These "stratovolcanoes" are built by enormous eruptions of viscous lava and ash created from magma rich in silica.

Figure 15.2.4: Shishaldin Volcano, Alaska is a volcano found on the "Ring of Fire" (Source: Volcano Hazards Program, USGS Used with permission)

Volcanoes are also found along spreading plate boundaries. Here, basaltic magma is extruded onto the floor of the ocean. In some places, the magma solidifies into great volcanic cones rising from the ocean floor. Iceland's Heimaey volcano is a good example of volcanic activity along the midocean ridge.

One of the most well-known locations for volcanic activity, the Hawaiian Islands, is not a product of plate margin processes. The Hawaiian Islands have formed over a "hot spot" or mantle plume where magma rises to the surface and flows out onto the ocean floor. The chain of islands were created as the Pacific Plate moves over the mantle plume creating a succession of volcanoes oriented in a northwest (oldest) to southeast direction (youngest).

15.3: Crustal Deformation

Enormous stress is imposed on the crust at the boundaries of the lithospheric plates and where convection currents in the mantle tug and tear at the crust above. When a stress is imposed on rock material it will deform (change shape) and often volume. The change in shape as a result of imposing a stress is called strain.

Figure 15.3.1: Folds in quartzite due to compression (Courtesy USGS; Source)

There are three basic kinds of stress. ***Compression*** occurs when rock masses are pushed together like that which occurs when plates collide. Rocks tend to shorten laterally and thicken vertically when exposed to compressional stress. Compression often creates great folds in rock. ***Tension***, or tensional stress, pulls the crust apart, like that which occurs along diverging plate boundaries. Tension extends the crust causing it to thin and lengthen. Rifting, like that which created the Great Rift Valley of Africa, is a result of tension. When plates slide past one another in opposite directions along transform plate boundaries, a shearing stress is created. ***Shearing stress*** cuts the crust into parallel blocks displacing them horizontally relative to one another. Shearing takes place along the San Andreas Fault where the Pacific Plate is moving past the North American Plate.

Digging Deeper into the Behavior of Rock Material

Rocks behave in a variety of ways when stress is imposed on them. The relationship between stress and deformation is shown in stress-strain diagrams like those below. The reaction of rock material to an imposed stress depends on the temperature and pressure conditions. As stress is imposed on rock it starts to deform up to its ***yield point***. Before it gets to the yield point, the rock will undergo ***elastic deformation*** (Figure 15.3.2). Like a rubber band, if the stress is released before reaching the yield point, the rock material will return to its original shape. However, *under low temperature and pressure conditions*, once the rock reaches its yield point it will break, called ***brittle failure*** (Figure 15.3.3). Brittle failure may occur if stress is imposed suddenly as well.

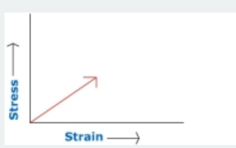


Figure 15.3.2: Elastic Deformation (Click image to enlarge)

Figure 15.3.3: Brittle Failure (Click image to enlarge)

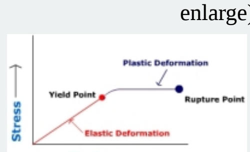


Figure 15.3.4: Plastic Deformation (Click image to enlarge)

Upon reaching the yield point *under high pressure and temperature conditions*, the rock may undergo ***plastic deformation*** (Figure 15.3.4). In this case, once the rock changes shape and if stress is released, it will not return to its original form. During plastic deformation mineral bonds adjust to the stress by breaking, moving about, and then reforming. Once it reaches its ***rupture point***, the material will break.

15.3.1: Folding and Faulting

15.3.2: Types and Geographic Patterns of Faults

15.3.3: Tsunamis

15.3.1: Folding and Faulting

Folding

When rocks deform by plastic deformation they can bend and fold. The process of ***folding*** occurs when rock is compressed, as it is along colliding plate boundaries. Upturned folds are called ***anticlines*** and down turned folds are called ***synclines***. Anticlines and synclines are geologic structures, that is, they are folds in rock material. They give expression to the surface as linear ridges (anticlines) and troughs (synclines). The sides of the fold are called the ***limbs***. Each fold has an ***axial plane***, an imaginary plane that runs down its length and divides the fold in half.

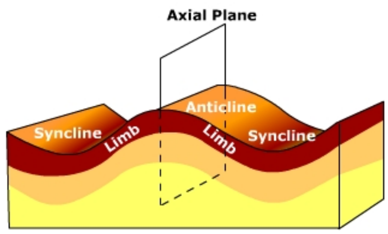


Figure 15.3.1.1: Components of a Fold

Symmetrical or open folds with their near-vertical axial planes and gently dipping limbs of about the same angle are a product of gentle compression. Symmetrical folds are found near the margins of mountain systems where tectonic activity is relatively quiet. If the compression is more pronounced from one direction, an ***overturned fold*** may occur. Extreme directed pressure may lay the fold over with its axial plane nearly horizontal with the surface producing a ***recumbent fold***. Sometimes the length of the folds are tilted creating ***plunging folds***. One of the best examples of folded topography is the Appalachian mountains found in the Ridge and Valley physiographic province of North America.

Figure 15.3.1.2: Teton Anticline, Utah (Photo credit: USGS Digital Data Series DDS-21)

Figure 15.3.1.3: Syncline in Lockhart Basin, Utah (Photo credit: USGS Digital Data Series DDS-21)

Faulting

When enormous stresses build and push large intact rock masses beyond their yield limit, faulting of the surface is likely to occur. A ***fault*** is a fracture along which movement occurs. The plane that extends into the earth and along which slippage occurs is called the ***fault plane***. The ***fault dip*** is the angle from horizontal that the fault plane makes. The map direction that the fault takes is called the ***strike***, measured east or west of true north. Generally, two walls are distinguished, the footwall and hanging wall. The ***hanging wall*** moves horizontally, vertically, or in both directions relative to the ***footwall***. We identify the hanging and foot walls relative to the fault plane. The hanging wall is above the fault plane while the foot wall is below. The steep face of an exposed block is called the ***fault scarp***. The ***fault line*** is the trace of the fault along the surface.

Figure 15.3.1.4: Red Canyon fault scarp near Red Canyon Creek, Montana (Courtesy USGS). Click image to enlarge

Faults can be traced for thousands of kilometers across the surface at tens of kilometers in depth. The sudden slippage of rock masses past one another results in shock waves that we feel as an ***earthquake***. For information about earthquakes see "How Earthquakes Occur" by the USGS.

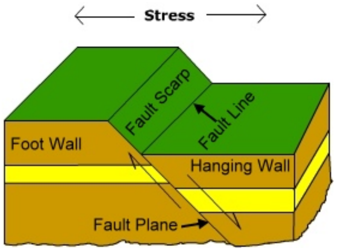
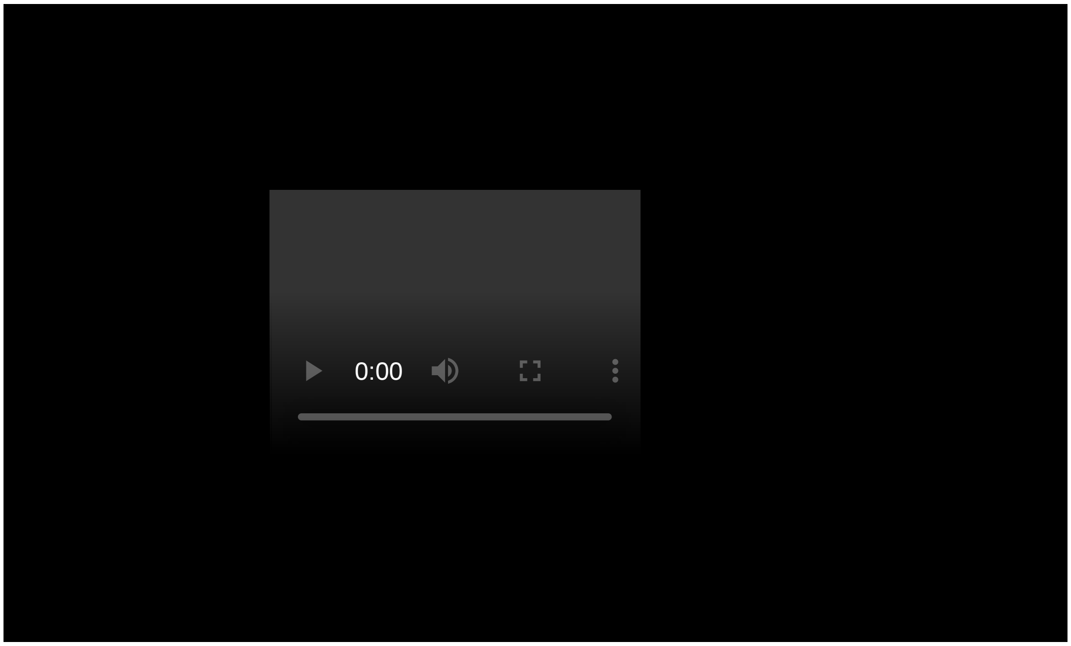


Figure 15.3.1.1: Features of Faults (normal fault depicted). Click image to enlarge.

15.3.2: Types and Geographic Patterns of Faults

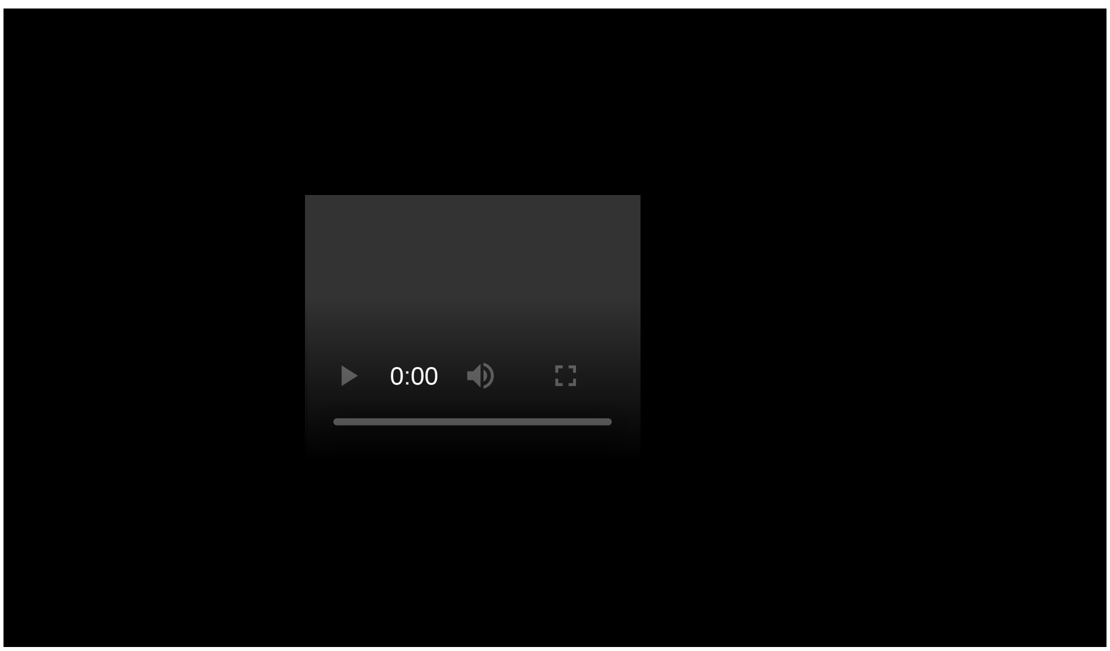
Types of Faults

Faults are distinguished on the basis of the movement of the footwall relative to the hanging wall. ***Dip slip faults*** are those in which vertical displacement primarily occurs.

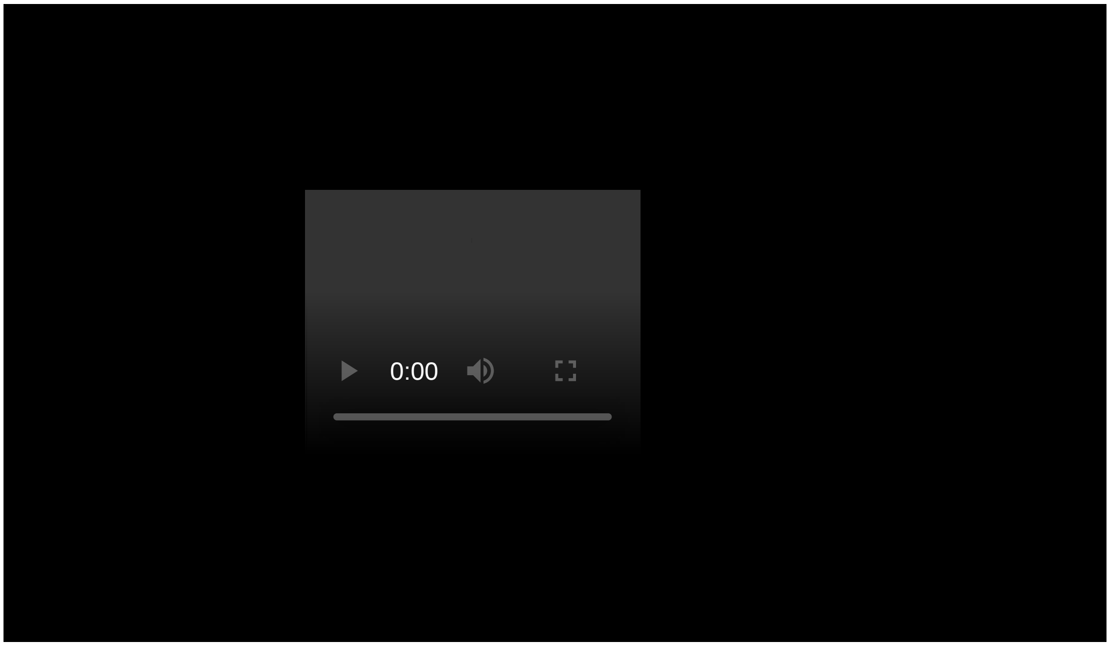


Video: Normal Fault (Courtesy USGS)

A ***normal fault*** is one in which the hanging wall *falls down* relative to the foot wall due to tensional stress. The Teton Mountains in North America are a result of normal faulting. A ***reverse fault*** is one in which the hanging wall *moves up* relative to the foot wall due to compression. A **thrust fault** is a reverse fault at 45^{o} angle.

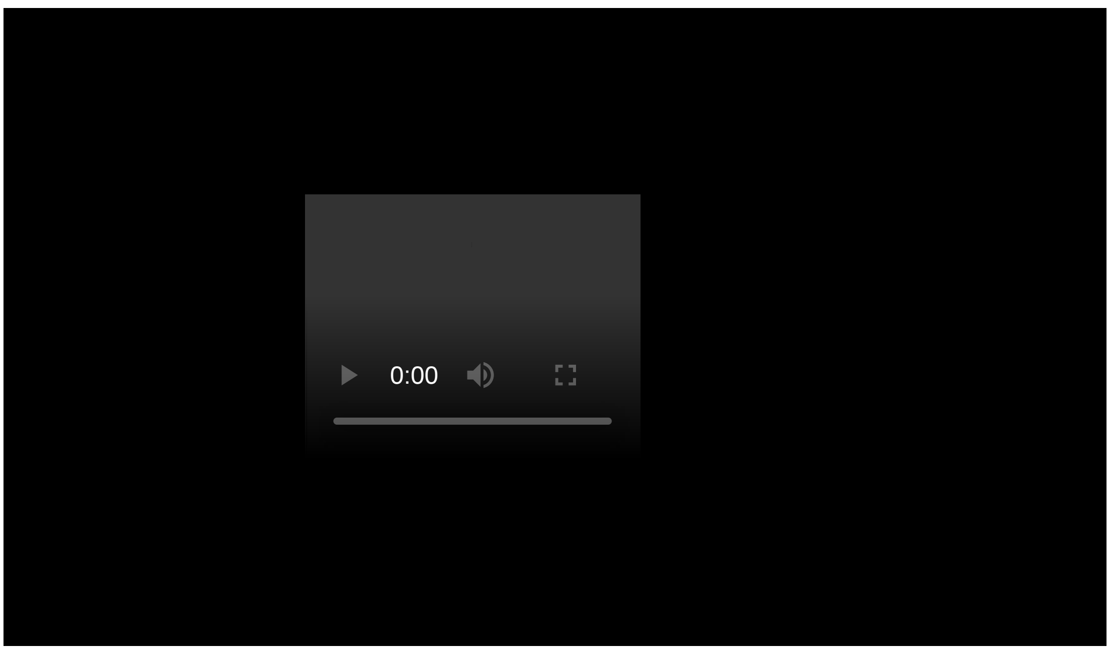


Video: Thrust Fault (a reverse fault at 45^{o} angle) (Courtesy USGS)



Video: Horst and Graben (Courtesy USGS)

A ***horst*** forms between two normal faults when a block of rock in the middle remains stationary and the blocks on either side subside. A ***graben*** forms when a block of rock falls between two faults. Huge, relatively flat bottomed valleys, like Death Valley in California, are created in this way. The Basin and Range physiographic province of North America is noted for its faulted mountains (horsts) and flat-bottomed valleys (grabens). Large plateau surfaces form in this fashion. The Basin and Range Province of North America is noted for its faulted mountains and flat-bottomed valleys.



Video: Strike slip / Transform Fault

Strike slip or transform faults are those that primarily exhibit horizontal movement . Such activity can be discerned from surface features like offset streams. The San Andreas fault is a well-known strike slip fault caused by the Pacific Plate sliding past the North American Plate. (View a segment of the San Andreas fault in Google Earth)

Oblique faults exhibit both horizontal and vertical movement.

Geographic Patterns of Faults and Earthquakes

The fracturing and movement of the Earth's surface have been linked to stresses created by movements of molten rock within the asthenosphere. Convection currents within this subsurface region tug at crustal plates, driving them into or past one another, or pulling them apart. Thus, the patterns of earthquakes and faults are closely associated with the boundaries of plates.

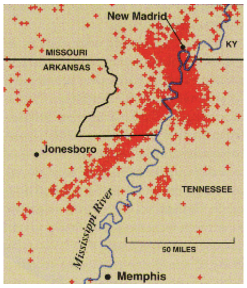


Figure 15.3.2.1: New Madrid Seismic Zone (Courtesy USGS; Source)

Though faulting and earthquakes are common along plate boundaries, they also occur in zones of weakness within the interior of a plate. The New Madrid Seismic Zone is the site of one of the largest earthquakes to strike North America (1811-1812). Though it had relatively little effect on human populations due to its location in a sparsely populated area at the time, it had a significant impact on the natural environment. The largest earthquakes caused the Mississippi River to flow backwards and low water falls were formed from the fracturing of the earth. 150,000 acres of forest ere destroyed and Reelfoot Lake, KY was formed. Now, several large population centers could be affected by the seismic zone (Note: this links to pdf).

15.3.3: Tsunamis

A **tsunami** is a fast moving, long wavelength water wave generated by a sudden displacement of water by undersea landslides, earthquakes, or volcanic activity. They are commonly called "tidal waves", but are by no means created by the tides. The sudden slippage of the ocean floor near the source of an earthquake can send a train of seismic waves across the ocean. When an overriding plate along a subduction zone suddenly breaks free it moves upward raising the sea floor and the water above. The waves move outward in ever-expanding circles, nearly imperceptible in deep ocean water. As they approach land, water recedes from the shore. This dramatic action often entices the curious to investigate. But very shortly a water wave rises rapidly from the ocean surface, crashing onto shore and rushing landward.

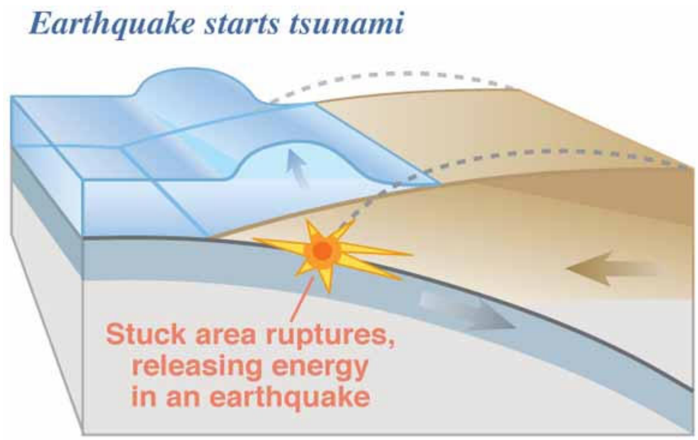


Figure 15.3.3.1: Formation of a tsunami (Courtesy USGS; Source: Surviving a Tsunami—Lessons from Chile, Hawaii, and Japan, USGS Circular 1187 https://pubs.usgs.gov/circ/c1187/

On December 26th, 2004 subduction between the Indian and Eurasian (more specifically the Burma) plates off the coast off the coast of Indonesia resulted in a magnitude 9 earthquake and large tsunami that devastated South Asia. [Watch "Violent Earth" from National Geographic.] The earthquake was a result of stresses being released when the Indian plate slid beneath the Burma plate. The resulting vertical movement of the ocean floor displaced hundreds of cubic meters of water and large waves propagated outward from the focus of the quake. The massive tsunami devastated coastal regions of South Asia as it crashed ashore.

Video: "Killer Tsunamis" from National Geographic

One of the largest earthquakes to occur in recent memory occurred March 11, 2011 off the coast of Japan. The huge tsunami it created devasted the northeast coast of Japan, destroying towns and infrastructure. Learn more about this magnitude 9 earthquake and its aftermath by "Digging Deeper: The Great East Japan Earthquake of 2011", or skip and continue reading.

Digging Deeper: The Great East Japan Earthquake of 2011

On March 11, 2011 the Island of Japan was rocked by a violent earthquake. The magnitude 9 Tōhoku earthquake, officially named the Great East Japan Earthquake, originated 129 km (80 miles) offshore east of Sendai, Honshu, Japan, at a depth of 30 km. It was the fourth largest earthquake in the world since 1900. Honshu lies near the junction of the North American, Eurasian, Pacific, and Phillippine Sea plates. The massive earthquake radiated from plates slipping along the subduction zone, actually moving the entire country. Areas near Ishinomaki moved southeast by 5.3 meters (17 feet), while parts of Tokyo moved 9 inches.

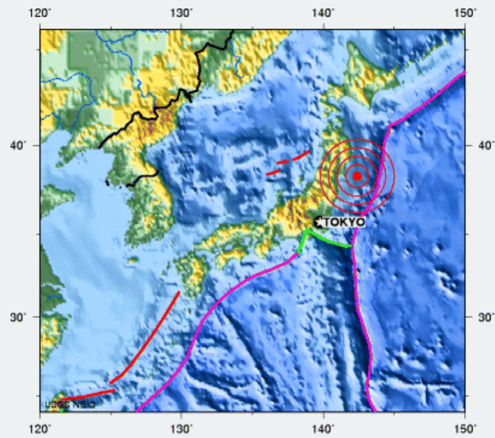


Figure 15.3.3.2: Location of the Tōhoku earthquake. (Courtesy USGS; Source)

As the North American plate slid upward over the Pacific plate, a 16 foot bulge of water rose and swept across the Pacific at an estimated 500 mph. As the water approached land the wave increased to incredible heights. A huge tsunami washed across the northern coast of Japan within moments. Sendai airport was inundated by a wall of water 12 m(39 ft) high. An estimated tsunami height of 37.9 m (124 ft) swept across the slope of a mountain 200 m (656 ft) from the coast. Flooded fields several kilometers inland remained so after more than a week due in part to coastal subsidence. Land subsidence at Oshika Peninsula Miyagi was as much as 1.2 m (3.93 ft). Those coast locations suffering from subsidence are now more susceptible to flooding during high tides.

Video: Tōhoku earthquake tsunami propagation (Courtesy NOAA)

The effects of the tsunami were far more deadly than the earthquake itself. Nearly 15,000 people were killed and 10,000 missing. Hundreds of thousands were left homeless as whole towns were devastated. The earthquake and subsequent tsunami severely damaged the Fukushima nuclear reactor station in the towns of Okuma and Futaba, leaking radioactivity into the air and water. Large evacuations of the surrounding area and contamination of food and water supplies resulted from the leakage.

Figure 15.3.3.1: The flooded Port of Sendai, Japan. (Courtesy US Navy; Source)

Damage from the tsunami was not confined to Japan. Tens of millions of dollars in damage to public infrastructure and private property occurred in Hawaii. Along the west coast of North America docks and harbor facilities were damaged as a tsunami surge of up to 2.4 m (8 ft) struck portions of California and Oregon. An California man attempting to photograph the rising water was swept out to sea and died.

Figure 15.3.3.1: Achi, Japan. Large ferry boat washed ashore sits amid the ruins of houses. (Courtesy US Navy; Source)

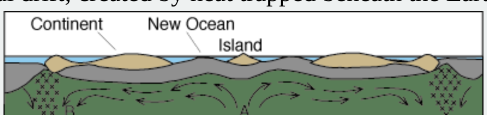
15.4: Review and Additional Resources

Review

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the module and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the module. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **tectonic plates**
  aka lithospheric or crustal plates; make up the surface of the lithosphere
- **plate tectonics**
  the process of plate formation, movement, and destruction
- **continental drift**
  the movements of continents over the Earth's surface
- **sea-floor spreading**
  the creation new oceanic plate material and movement away from the midocean ridge
- **Pangea**
  the one "super-continent"; the past configuration of the continents
- **exotic terrain**
  new land that has been formed somewhere else and moved to its present location
- **midocean ridge**
  the longest continuous mountain system on Earth
- **mantle convection currents**
  the mechanism that drives continental drift; created by heat trapped beneath the Earth's surface



Holmes' model of convection currents. A. areas of upwelling. B. areas of downwelling and melting.

- **magnetic reversal**
  a series of "flips" when the polarity of the rocks reversed
- **subduction zone**
  where more dense plates dive beneath lighter, less dense crustal plates
- **spreading boundary**
  occurs where plates are moving away (diverging) from one another
- **convergent boundary**
  located where subduction is active and the lithosphere is being "consumed". This occurs where two plates collide with one another
- **transform boundary**
  where plates are grinding past one another, like the San Andreas fault

- **plate boundary zone**
  broad belts in which boundaries are not well defined and the effects of plate interaction are unclear
- **Ring of fire**
  extends from the west coast of the United States toward the Aleutian Islands and over to Japan; a good example of volcano activity associated with the margins of plates
- **strain**
  change in shape as a result of imposing a stress
- **elastic deformation**
  Like a rubber band, if the stress is released before reaching the yield point, the rock material will return to its original shape
- **brittle failure**
  under low temperature and pressure conditions, once the rock reaches its yield point it will break; or if stress is imposed suddenly
- **plastic deformation**
  once the rock changes shape and if stress is released, it will not return to its original form
- **folding**
  occurs when rock is compressed, as it is along colliding plate boundaries
- **anticline**
  Upturned folds
- **syncline**
  down turned folds
- **symmetrical fold**
  near-vertical axial planes and gently dipping limbs of about the same angle are a product of gentle compression
- **overturned fold**
  If the compression is more pronounced from one direction
- **recumbent fold**
  When extreme directed pressure lay the fold over with its axial plane nearly horizontal with the surface
- **fault**
  a fracture along which movement occurs
- **fault Plane**
  The plane that extends into the earth and along which slippage occurs
- **fault dip**
  the angle from horizontal that the fault plane makes
- **strike**
  The map direction that the fault takes
- **fault scarp**
  The steep face of an exposed block

- **fault line**
  the trace of the fault along the surface
- **strike slip fault**
  aka transform fault; those that primarily exhibit horizontal movement
- **dip slip fault**
  those in which vertical displacement primarily occurs
- **transform fault**
  aka strike slip fault; those that primarily exhibit horizontal movement
- **normal fault**
  one in which the hanging wall falls down relative to the foot wall due to tensional stress
- **reverse fault**
  the hanging wall moves up relative to the foot wall due to compression
- **graben**
  forms when a block of rock falls between two faults
- **horst**
  forms between two normal faults when a block of rock in the middle remains stationary and the blocks on either side subside
- **thrust fault**
  a reverse fault at 45^{o} angle

? Review Questions 15.4.1

What is plate tectonics.

Answer

Plate tectonics is the theory that the surface is broken into several tectonic plates that are moving and interacting with one another to produce relief features of the Earth.

Courtesy USGS

What evidence was used to confirm the notion of continental drift?

Answer

Similar configuration of continents, fossils, and geologic deposits widely separated from one another.

Where does sea flooring spreading occur? How have scientists confirmed that sea floor spreading is taking place?

Answer

Sea floor spreading occurs along the midocean ridge where new rock material is extruded onto the ocean floor. Magnetic stripes indicate similar polarity in rocks on either side of the ridge. The age of rocks increases away from the midocean ridge.

What drives the movement of tectonic plates?

Answer

It is thought that convection currents in the mantle, the push of crustal rock as it is extruded along the midocean ridge, and the pull of slabs of crust at subduction zones are responsible for the movement of plates.

What is occurring along the midocean ridge?

Answer

The midocean ridge is a primary site for sea floor spreading. As a result, earthquakes and volcanic activity is common.

Sea floor spreading (Courtesy USGS)

What is a subduction zone, where do you find them, and what kinds of geological activity occurs there?

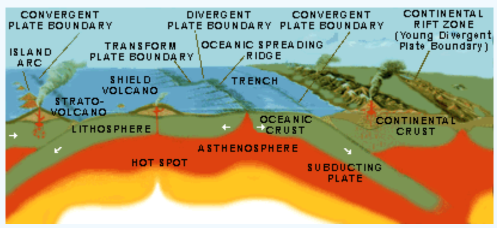
Answer

A subduction zone is where crustal rocks are forced beneath the surface. Subduction is common where heavier, more dense ocean plates collide with lighter, less dense continental plates.

Compare and contrast the four main types of plate boundaries. Give examples of where they occur.

Answer

A ***spreading boundary*** occurs where plates are moving away (diverging) from one another, like along the midocean ridge . Here, new crust is formed by accretion. A ***convergent boundary*** is found where subduction is active and the lithosphere is being "consumed". A ***transform boundary*** forms where plates are grinding past one another, like the San Andreas fault. ***A plate boundary zone*** is a broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.

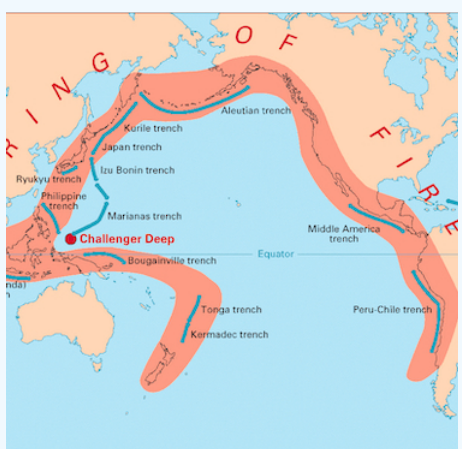


Tectonic Settings (Courtesy USGS)

What is the "Ring of Fire"?

Answer

The "Ring of Fire" is "ring" of volcanoes encircling most of the Pacific ocean.



Ring of Fire (Courtesy USGS)

Describe elastic deformation, brittle failure, and plastic deformation.

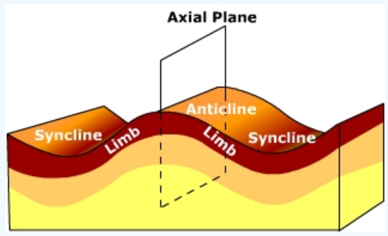
Answer

Elastic deformation: when stress is imposed on rock it deformed, when released it returns to its original shape. ***Brittle failure***: breakage caused when stress is imposed beyond the rupture point of brittle materials. ***Plastic deformation***: when stress is imposed on rock it deformed, when released it remains in its deformed shaped.

How does folding occur and what is the result?

Answer

Folding occurs by compression of rock material. An up-turn fold is called an anticline while a down-turn fold is a syncline.



Compare and contrast the different kinds of faults.

Answer

A ***dip slip fault*** exhibits vertical displacement. ***A normal fault*** is one in which the hanging wall falls down relative to the foot wall due to tensional stress. ***A reverse fault*** is one in which the hanging wall moves up relative to the foot wall due to compression. ***A thrust fault*** occurs when the hanging wall is pushed up and then over the foot wall at a low angle.

? Self-Assessment Quiz 15.4.1

1. The original "super continent" was called
   A. Pangea
   B. Gondwanaland
   C. Nortreland
   D. none of the above
2. Wegener proposed that continental crust "plowed" through _____ as it moved from one place to the next.
   A. oceanic crust
   B. the mantle
   C. the Moho
   D. none of the above
3. In the late 1920's until the present, the movement of plates is thought to be due to
   A. convection currents in the crust
   B. convection currents in the mantle
   C. convection currents in the core
   D. earthquakes along subduction zones
4. Along the Mid-ocean ridge
   A. earthquakes occur
   B. sea floor spreading occurs
   C. volcanism occurs
   D. all the above occurs
5. Subduction zones are mostly likely found where
   A. ocean crust collides with ocean crust
   B. ocean crust collides with continental crust
   C. continental crust collides with continental crust

D. where continental crust divergence takes place

6. Which of the following boundaries characterize the San Andreas Fault?
   A. Spreading
   B. Convergent
   C. Transform
   D. None of the above
7. Volcanism in Iceland is due to which of the following plate boundaries?
   A. Spreading
   B. Convergent
   C. Transform
   D. None of the above
8. Volcanism on the Hawaiian Islands is due to which of the following plate boundaries?
   A. Spreading
   B. Convergent
   C. Transform
   D. None of the above
9. The "Ring of Fire" is due to
   A. ocean crust colliding with ocean crust
   B. ocean crust colliding with continental crust
   C. continental crust colliding with continental crust
   D. where continental crust divergence takes place
10. The longest continuous chain of mountains formed by tectonic processes is found
    A. in North America
    B. in South America
    C. in Asia
    D. on the ocean floor

Answer

1. A
2. B
3. B
4. D
5. B
6. C
7. A
8. D
9. B
10. D

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "Earth's Deadliest Earthquakes" (NOVA PBS)

Connections: "South Asia Disaster" News Hour with Jim Lehrer. See "Tsunami Warnings" at the site.

Physical Geography Today: Earthquakes Hazard Program - USGS

Multimedia

San Francisco 1906 Earthquake *Science Friday* (NPR) April 21, 2006 hour one. "One hundred years ago ..., San Francisco's ground began to shake. After the massive quake came the fire -- and when it was all over, the city lay in ruins, with thousands dead."

"Living with the Earth I" The Earth Revealed (Annenberg/CPB) (30:00) Go to the Earth Revealed site and scroll to "Living with the Earth I". One-time, free registration may be required to view film.

"Exotic Terrane" from the Open Video Project. "A geologic history of the Pacific Northwest that explains how islands near China accreted, or welded, themselves to the North American continent. Animations of the formation of North America explain the process. The video also visits Hells Canyon in Idaho. On-location interviews with an expert geologist add to the viewer's experience". File must be downloaded to view - 245 megabytes

"Faces of Earth: Assembling America" (American Geosciences Institute). "From the Pacific Northwest to the shores of the Atlantic seaboard, the breadth and scope of America is like no other place on Earth. Travel with geoscientists and explore how time and the forces of nature have shaped the continent and influence the life in the United States"

"Southern Appalachians" (USGS) Geology of the Southern Appalachians (24:34)

"The Seattle Earthquake" *The News Hour with Jim Lehrer* (PBS). A magnitude 6.8 earthquake shook the Pacific Northwest February 28, 2001, rattling windows from Vancouver to Salt Lake City. Read the transcript or watch the clip.

"Earthquakes" *Science Friday* (NPR) June 24, 2005 episode discusses a recent swarm of earthquakes in California and new studies of the New Madrid Seismic Zone. (17:44)

"Colliding Continents: - *Naked Science*. How were the continents formed?

Readings

"Plate Tectonics and People" (USGS)

"On the Shoulders of Giants - Alfred Wegener" (NASA)

CHAPTER OVERVIEW

16: Volcanic Processes and Landforms

Learning Objectives

By the end of this chapter you should be able to:

- Draw and label a simple diagram of the features associated with a volcanic cone.
- Explain the distribution of volcanic activity across the Earth.
- Describe the features of effusive and explosive eruptions.
- Describe the hazards associated with volcanism.

Volcanoes are a window into the heart of the Earth's dynamic interior. Born of molten rock from deep within, volcanoes represent the ever recycling nature of the solid Earth. Awesome displays of fiery fountains of molten rock and massive eruptions of gases and ash impose a significant danger to human habitation in volcanically active regions. In this chapter we'll explore where volcanoes occur, how they are formed, and hazards they pose to humans.

16.1: Features of Volcanoes
16.2: Distribution of Volcanoes
16.3: Types of Volcanoes and Landscapes
16.4: Volcanic Hazards
16.5: Review and Additional Resources

16.1: Features of Volcanoes

A **volcano** is an opening in the surface of the Earth from which **magma** (molten subsurface rock) and associated gases and ash erupt; also, the form or structure, sometimes conical, that is produced by the ejected material. Volcanic activity may create vast plateaus where flood basalts emerge from cracks, covering the surface with massive flows of **lava** (molten rock above the surface) and subsequently dissected by streams.

Common to all volcanoes is a **magma chamber** 📷. The magma chamber is a huge, subterranean caldron of molten rock that is less dense than the surrounding rock and rises buoyantly, sometimes under great pressure to the surface. The main conduit through which magma moves toward the surface is the **central vent**. A **crater** sits at the top of a volcano and is the location where much of the lava, gas, rock fragments and ash are ejected from.

Figure 16.1.1: Mt. St. Helens last major eruption left the huge crater seen in the center of the photograph. (Courtesy USGS CVO)

Lateral vents are found on the sides of some volcanoes where lava is extruded. An extremely large crater is some times found at the summit of a volcano. These massive craters called **calderas**, are created when pressure builds inside the volcano until the top is literally blown off, magma drains back into the central vent and the top of the cone collapses in. Crater lake formed in the caldera of Mount Mazama.

Video: "Crater Lake" courtesy of Britannica

Explore Crater Lake with Google Earth

Outpourings of magma can occur as a fluid-like **lava** 📷 or as fiery clouds of ash and rock fragments. The ability of lava to flow depends on its viscosity or "stickiness". The viscosity of magma depends on temperature, silica content, and incorporated gases. Basaltic magma has approximately 50% SiO^2, the smallest amount of incorporated gas and readily flows across the surface. Andesitic magma contains 60% SiO^2 and has a substantial content of incorporated gas, giving it a moderate viscosity. Rhyolytic magma is 70% SiO^2 and contains the largest amount of gas. Rhyolytic magma produces the highest viscosity lava and is responsible for violent eruptions.

Figure 16.1.2: Hydrocholoric acid steam rises from the ocean as a Pu`u `O`o lava flow reaches sea water. (Photo credit: M. Ritter)

Volcanic eruptions, especially explosive eruptions, eject fragments of volcanic rocks and lava collectively called **tephra** . Ground-hugging **pyroclastic flows** of fast-moving gas and fragments of rock having temperatures of 500 oC can rush down the flanks of a volcano at speeds reaching 100 km/hr, carbonizing all in their path.

Volcanic eruptions are accompanied by the release of noxious and sometimes lethal gases. Steam makes up the majority of gas that is released by a volcano followed by carbon dioxide, sulfur dioxide, and hydrogen chloride. When lava spills into the ocean, the intense heating of salt water produces a noxious steam cloud of hydrochloric acid. Sulfur dioxide combines with water in the atmosphere to produce acid rain. Naturally produced acid deposition around the top of Mauna Loa has devastated the local vegetation.

16.2: Distribution of Volcanoes

Volcanic activity is widespread over the earth, but tends to be concentrated in specific locations. Volcanoes are most likely to occur along the margins of tectonic plates, especially in subduction zones where oceanic plates dive under continental plates. As the oceanic plate subducts beneath the surface, intense heat and pressure melts the rock. Molten rock material, magma, can then ooze its way toward the surface where it accumulates at the surface to create a volcano. Volcanic activity can be found along the **Mid-ocean ridge system** as well. Here, oceanic plates are diverging and magma spreads across the ocean floor, ultimately being exposed at the surface. Crustal spreading long the ridge is partly responsible for the volcanic activity of Iceland. It is also thought that a "hot spot" lies beneath the island that contributes to volcanism.

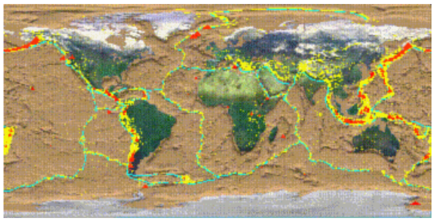


Figure 16.2.1: Distribution of Volcanic Activity. Note the close correlation between the site of volcanic activity (in red) and lithospheric plate boundaries. Click image to enlarge (Source: NASA GSFC)

Hot spots are places where a chamber of magma has accumulated at depth beneath the surface. The volcanic islands of Hawaii are a notable example of this. The Hawaiian Islands ride atop the Pacific plate as it moves in a northwesterly direction over the hot spot that creates the volcanoes. Therefore, the oldest volcanic island is found at the northwest end of the chain and the youngest to the southeast. Volcanic activity ceases as the older islands move off the hot spot.

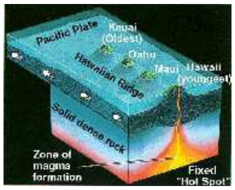


Figure 16.2.2: Hawaiian islands forming over hot spot (Source: USGS; Used with permission)

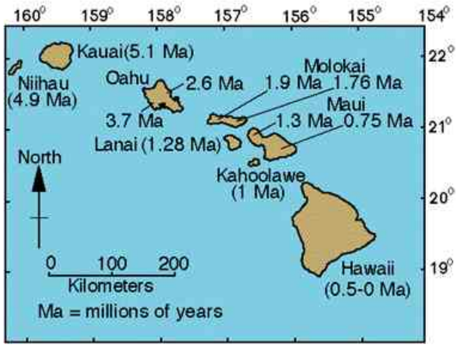


Figure 16.2.3: Age of Hawaiian Islands (Source: USGS; Used with permission)

Figure 16.2.4: Lava fountain of the Pu`u `O`o cinder and spatter cone on Kilauea Volcano, Hawaii. (Source: USGS Used with permission)

Rather than forming a mountain like the volcanoes in the Hawaiian Islands, some places have been covered by massive flows of basaltic lava due to volcanic activity. One of the best known sites in North America is the Columbia Plateau. The Columbia Plateau is located in the eastern Washington, south through eastern Oregon and most of southern Idaho.

16.3: Types of Volcanoes and Landscapes

Types of Volcanoes

Volcanoes are classified by the types of eruption they produce. Broadly speaking, eruptions can be either effusive or explosive. **Effusive eruptions** are sometimes called "quiet" eruptions (if eruptions can be quiet!). Effusive eruptions are noted for their vast outpourings of very fluid type lava that easily runs across the surface. **Explosive eruptions** occur as violent explosions of lava and rock fragments that gets stuck in the vent of the volcano. Gases released from the hot magma build to incredible pressure and are released, along with lava, ash and other pyroclastic material, during an explosive eruption. These two types of eruptions create different types of volcanic cones.

Effusive Eruptions

Effusive eruptions are those that create vast lava flows of low viscosity, fluid lava. Magma associated with effusive-type eruptions is relatively low in silica and thus "easily" flows up the vent and spreads across the surface. Moving across the land, these lava flows can take on two different forms. **Pahoehoe** (a Hawaiian term) lava has a glistening, ropy like appearance as it moves and cools. **AA** lava is more pasty than pahoehoe and forms a sharp, clinkery, rough surface. As the core of the flow moves across the surface, the rough "clinkers" are carried along the top of the flow. At the leading edge of the flow, the clinkers tumble forward into a heap.

Figure 16.3.1: View NNW of Mauna Loa, a shield volcano. (USGS; Click image to enlarge)

Shield volcanoes are a product of effusive eruptions. As the fluid lava flows out onto the surface, it spreads out and cools into a broad, low-angled slope. The final shape looks much like a warrior's shield with the convex side pointing towards the sky. The Hawaiian Islands are an example of shield volcanoes. Though much lava pours from the summit caldera, flank eruptions from lateral vents spreads molten lava along the sides of the volcano. As the lava flow cools, tubes may form in the flow. These are conduits through which lava flows beneath a skin of solidified lava. Occasionally lava will accumulate as a lava pond or lake too.

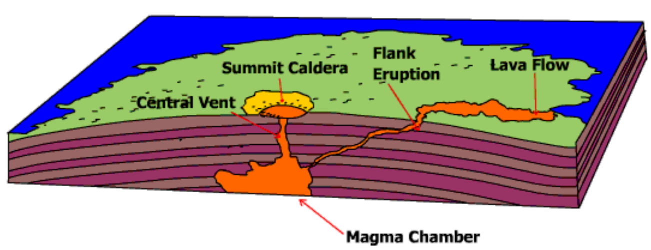


Figure 16.3.2: Shield volcano similar to those found in the Hawaiian Islands

Explosive Eruptions

A second category of volcanoes are those characterized by explosive eruptions. **Explosive eruptions** are common to volcanoes with very viscous lava and high amounts of gas under pressure. The viscosity, or stickiness, of the lava relates to the silica content. Magma high in silica is more viscous than lavas low in silica. Explosive eruptions are common to volcanoes along the "Ring of Fire", a string of volcanoes extending from the northwest coast of the United States, up through the Aleutian Islands, and into Japan . As the magma rises through the central vent, it gets stuck and gases build to high pressures until an eruption of great force occurs.

Figure 16.3.3: Mt. St. Helens, a composite volcano (Source: USGS)

Vast amount of ash and pyroclastic material can be ejected from these kinds of volcanoes. Accompanying many of these eruptions are vast outpourings of noxious gases and fine particulate matter called "**Nuees Ardentees**" or "glowing clouds or avalanches". These clouds can rush down the flanks of a volcano at speeds reaching 60 mph. Escape from such clouds is virtually impossible (See Volcanic Hazards and Episodes: Mt Pelee.)

Figure 16.3.4: A nearly perfect cinder cone in the *Cinder Cones and Lava Beds Natural Landmark Area* in the north-central portion of the Mojave National Preserve. (Courtesy USGS; Source: "Our Dynamic Desert")

Two types of volcanoes characteristically produce explosive eruptions, cinder cones and composite volcanoes. **Cinder cones** are primarily composed of layers of pyroclastic material built from rock fragments once lodged in the central vent of the volcano. Mt. Paricutin is one of the most famous cinder cones erupting from a Mexican farmer's field in 1943.

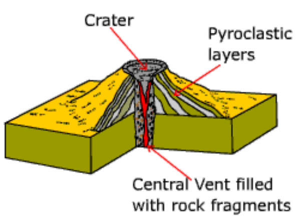


Figure 16.3.5: Cinder Cone; Example: Mt. Paricutin

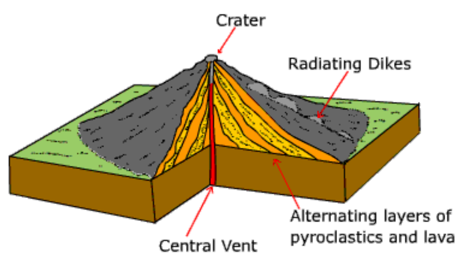


Figure 16.3.6: Composite or Stratovolcano; Example: Mt. Rainier & Mt. St. Helens

Composite, or stratovolcanoes also produce explosive eruptions. As shown in Figure 16.3.6, composite volcanoes form from alternating eruptions dominated by pyroclastics or lava. As a result, composite volcanoes display layers of these alternating flows. Composite volcanoes are among the tallest volcanoes on earth, with Mt. Fuji, Mt. St. Helens, and Mt. Kilimanjaro being examples. Composite volcanoes are often associated with convergent plate boundaries where subduction is occurring.

Volcanic Landscapes

Landscapes created by volcanism contain a unique set of landforms. As volcanic activity subsides, magma may cool in the central vent and, over thousands of years, the overlying cone is worn away to expose the harden rock inside called a **volcanic neck**. Radiating away from the central vent may be nearly vertical fractures into which magma can intrude and cool. Erosion of the overlying surface reveals a linear, fin-like ridge radiating away from the volcano called a **dike**. Shiprock, New Mexico, is an example of a volcanic neck with prominent dikes radiating away from it.

In Earth's geologic past, large areas have been inundated by massive floods of basaltic lava. A **flood basalt** of 170,000 cubic kilometers known as the Columbia River basalts covered a large portion of southeastern Washington, eastern Oregon and southern Idaho. The outpouring of 1100º C lava raced across the surface at an estimated average speed of 5 km/hour. When the eruptions ceased, over 500,000 km^2 of the Earth's surface was covered. As streams carved the massive accumulation of lava, a **lava plateau** formed that we today call the Columbia Plateau.

Figure 16.3.7: Shiprock, New Mexico in background with dikes in left foreground. (Source USGS DDS21)

16.4: Volcanic Hazards

Volcanic activity and the landscape that results are both part of a natural and rejuvenating process in which lava flows build new land. Ash becomes the parent material for soil. However, volcanic activity can be a hazard to humans. Figure 16.4.1 illustrates several volcanic hazards described below.

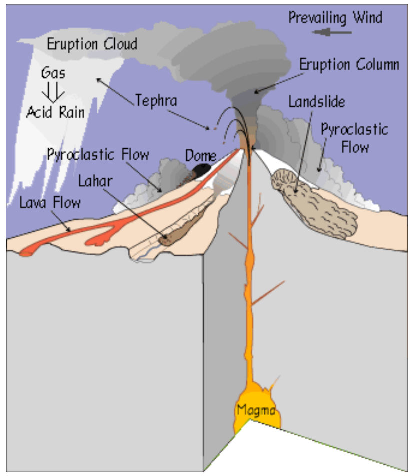


Figure 16.4.1: Volcano Hazards

Hot ash and gas shoot upward as an **eruption column** from the top of a volcanic cone during an explosive eruption. In extreme cases, an eruption column may penetrate the stratosphere, spreading aerosols and particulates that affect weather. An explosive eruption column may collapse sending hot ash, gas, and fragments of rock rushing down a volcano as a **pyroclastic flow**. The collapse of a dome may also produce a pyroclastic flow. Reaching temperatures of 1500 F and speeds of 700 km/h (450 mph, pyroclastic flows are extremely dangerous. *Nuée ardente* (French for "burning cloud") refers to a glowing red pyroclastic flow. An **eruption cloud** may drift for hundreds of kilometers downwind of the volcano spreading ash and tephra over a large region.

Figure 16.4.2: Ascending eruption cloud from Redoubt Volcano as viewed to the west from the Kenai Peninsula. (Source: R. Clucas, U.S. Geological Survey and the Alaska Volcano Observatory)

Lava flows are generally slow enough that people can evacuate before the flows pose a threat to life. Lava flows do however, cause significant property damage. Lava flows block highways and turn structures into cinders (Figure 16.4.3). Diversion barriers have been used with some success to redirect fluid lava flows. Spraying seawater on a flow to cool and solidify it has also been attempted.

Figure 16.4.3: Geologist photographing lava outbreak (Source: USGS)

Mudflows or debris flows called **lahars** result when hot pyroclastic material melts snowpacks, or fresh pyroclastic deposits are mobilized by heavy rains. Having the consistency of wet cement, a lahar can rush down mountain slopes or along a river valley at speeds of 22 mph or more. Sadly, nearly 22,000 people lost their lives when a lahar, produced by the melting of a summit glacier, buried the town of Aremero on the slopes of Nevado del Ruiz. Nearly 220 kilometers (135 miles) of river channels surrounding Mt. Saint. Helens were affected by the lahars from the May 18, 1980 (Figure 16.4.4).

Figure 16.4.4: A mudline left behind on trees shows depths reached by the mud from a lahar generated by the 1980 eruption of Mt. Saint Helens. A scientist (middle right) gives scale. (Source: USGS)

Tiny, jagged particles of volcanic ash are hard and abrasive. Short-term exposure to ash causes irritation of the eyes and respiratory issues, especially for those with diseases like asthma. Heavy ash fall, especially when wet, can collapse buildings. Air travel is rerouted around eruptions to keep ash from being sucked into jet aircraft engines. The April 2010 eruption of Iceland's Eyjafjallajökull volcano closed the air space in several European countries for over a week as aircraft were rerouted away from the ash cloud.

Sulfur dioxide is a common gas expelled from volcanoes and when combines with moisture in air, it produces acid rain or **volcanic fog** called “vog”. Acid rain destroys vegetation and contaminates water supplies. Vog causes respiratory problems and kills crops.

Significant Volcanic Events

Volcanoes have played a significant role on Earth's physical geography as well as human activities. Let's dig a little deeper by highlighting several examples significant volcanic events through human history. Use Figure 16.4.5 a sample of notable volcanic events.

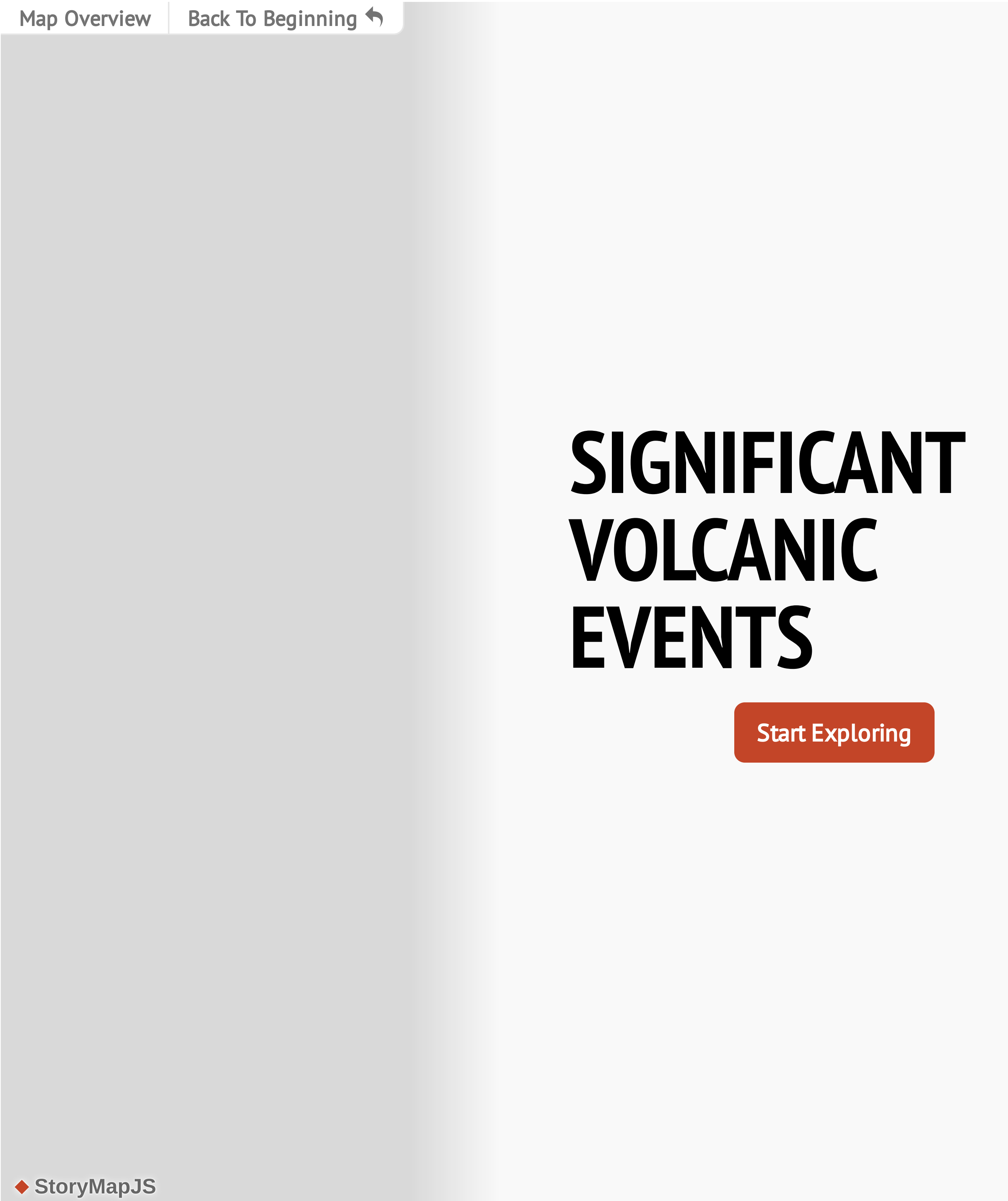


Figure 16.4.5 Significant historical volcanic events. Click the arrow. (If having difficulty use link and/or try a different browser)

16.5: Review and Additional Resources

Review

Figure 16.5.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **volcano**
  an opening in the surface of the Earth from which magma and associated gases and ash erupt; also, the form or structure, sometimes conical, that is produced by the ejected material.
- **central vent**
  The main conduit through which magma moves toward the surface
- **crater**
  sits at the top of a volcano and is the location where much of the lava, gas, rock fragments and ash are ejected from
- **caldera**
  massive craters created when pressure builds inside the volcano until the top is literally blown off, magma drains back into the central vent and the top of the cone collapses in
- **magma chamber**
  a huge, subterranean caldron of molten rock that is less dense than the surrounding rock and rises to the surface
- **lava**
  molten rock above the surface
- **lateral vent**
  found on the sides of some volcanoes where lava is extruded
- **pyroclastic flow**
  fast-moving gas and fragments of rock having temperatures of 500 ^{o}C rushing down the flanks of a volcano at speeds reaching 100 km/hr, carbonizing all in their path.
- **hot spot**
  places where a chamber of magma has accumulated at depth beneath the surface
- **midocean Ridge**
  oceanic plates are diverging and magma spreads across the ocean floor, ultimately being exposed at the surface
- **effusive eruption**

those that create vast lava flows of low viscosity, fluid lava. Magma associated with effusive-type eruptions is relatively low in silica and thus "easily" flows up the vent and spreads across the surface

- **shield volcano**

  a product of effusive eruptions; as the fluid lava flows out onto the surface, it spreads out and cools into a broad, low-angled slope.

- **Pahoehoe lava**

  has a glistening, ropy like appearance as it moves and cools

- **AA lava**

  more pasty than pahoehoe and forms a sharp, clinkery, rough surface

- **explosive eruption**

  common to volcanoes with very viscous lava and high amounts of gas under pressure. Magma is high in silica, thus more viscous

- **cinder cone**

  primarily composed of layers of pyroclastic material built from rock fragments once lodged in the central vent of the volcano

- **composite (Stratovolcano)**

  produce explosive eruptions; form from alternating eruptions dominated by pyroclastics or lava; display layers of alternating flows

- **lahar**

  Mudflows or debris flows resulting from when hot pyroclastic material melts snowpacks, or fresh pyroclastic deposits are mobilized by heavy rains

- **Nuees Ardentees**

  noxious gases and fine particulate matter; aka "glowing clouds or avalanches"

Review Questions 16.5.1

Compare and contrast shield, composite, and cinder cone volcanoes.

Answer

Shield volcanoes have broad, low-angled slopes and built layer on layer of fluid lava. Composite volcanoes are steep-sided cones built from alternating flows of lava and pyroclastics. Cinder cones are smaller cones built primarily from explosive eruptions of pyroclastics.

Shield Volcano (Photograph: D. Little; Courtesy USGS)

Composite Volcano (Photograph: R. McGimsey; Courtesy USGS)

Cinder Cone (Photograph: J.P. Lockwood; Courtesy USGS

Where do volcanoes occur?

Answer

In subduction zones, along the midocean ridge, and over hot spots.

What is the basic difference between eruptions from shield and composite volcanoes?

Answer

Eruptions from shield volcanoes tend to be dominated by effusive eruptions of fluid lava. Composite volcanoes produces explosive eruptions from stickier magma.

What is a lahar?

Answer

Mudflows called lahars are caused by the rapid melting and runoff of snow mixing with ash and soil.

What is a pyroclastic flow?

Answer

Hot ash, pumice, rock fragments and noxious gas that moves rapidly down the side of a volcano.

What are the principal gases emitted by a volcano?

Answer

The most common gas released by magma is steam (H_2O), followed by CO_2 (carbon dioxide), SO_2 (sulfur dioxide), (HCl) hydrogen chloride and other compounds.

How do calderas form?

Answer

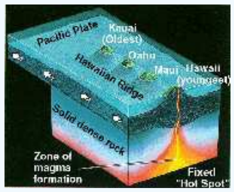
By the volcano blowing the summit off or magma draining from the central vent removing support for the summit causing it to collapse in.

Mt. Saint Helens, Courtesy USGS

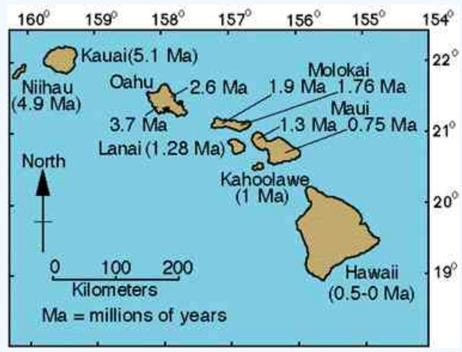
Explain how the Hawaiian Islands formed.

Answer

The Hawaiian islands were formed by volcanic activity over a hot spot. The youngest island in the chain lies toward the southeast as the Pacific Plate moves toward the northwest.



Hawaiian islands forming over hot spot (Source: USGS)



Age of Hawaiian Islands (Source: USGS)

How was the Columbia Plateau formed?

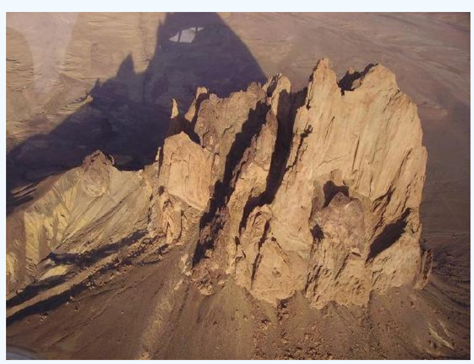
Answer

A flood basalt of 170,000 cubic kilometers known as the Columbia River basalts covered a large portion of southeastern Washington, eastern Oregon and southern Idaho creating the plateau.

What is a volcanic neck?

Answer

A volcanic neck is the "mold" of the central vent. Magma stuck in the central vent cools. Removal of the overlying rock exposes the plug-like shape within. Shiprock, NM (below) is a notable example of a volcanic neck.



? Self-Assessment Quiz 16.5.1

1. Volcanoes are found

   A. along the midocean ridge

   B. near subduction zones

C. hot spots (mantle plumes)
D. all of the above

2. A volcano built by alternating flows of lava and accumulation of pyroclastics is called

A. a shield volcano
B. a cinder cones
C. a composite volcano (stratovolcano)
D. any of the above

3. A caldera

A. is a lateral vent on the side of a volcano
B. a huge crater at the top of the volcano
C. a tube where lava pours into the ocean
D. none of the above

4. The oldest island in the Hawaiian chain is located towards the ______ end of the chain.

A. northwest
B. northeast
C. southwest
D. southeast

5. The volcanoes that comprise the Hawaiian Islands are

A. shield volcanoes
B. composite volcanoes
C. cinder cones
D. none of the above

6. Shield volcanoes

A. are associated with effusive eruptions
B. have very steep sides
C. mostly emit pyroclastic material from their central vent
D. are associated with all the above

7. ______ are mudflows due to rapid melting of snow packs along the sides of snow covered mountains.

A. Pyroclastic avalanche
B. Pahoehoe
C. AA
D. Lahars

8. Devil's Tower is a

A. dike
B. lava plateau
C. a landing site for alien spacecraft
D. volcanic neck

9. A lava that has a glistening, ropy-like appearance associated with effusive eruptions is known as

A. AA
B. Pahoehoe
C. Nuees Ardentees
D. Pu' u' O'o

10. The Columbia River Plateau is was built from

A. limestone
B. granite
C. basalt
D. none of the above

Answer

1. D
2. C
3. B
4. A
5. A
6. A
7. D
8. D
9. A
10. C

Additional Resources

Focus on The Physical Environment: "Cascades Volcanoes: When Sleeping Giants Wake" (KSPS Public TV)

Physical Geography Today: Weekly Volcanic Activity (Smithsonian & USGS)

Multimedia

Volcanism *Earth Revealed* (Annenberg/CPB) *from the site*: "Volcanoes provide clues about what is going on inside Earth. Animations illustrate volcanic processes and how plate boundaries are related to volcanism. The program also surveys the various types of eruptions, craters, cones and vents, lava domes, magma, and volcanic rock. The 1980 eruption of Mount St. Helens serves as one example." Go to the Earth Revealed site and scroll to "Volcanism". One-time, free registration may be required to view film.

"Volcanoes" - *Talk of the Nation - Science Friday* (NPR) segment from August 2, 1996 explores how and where volcanoes form and how to predict eruptions with geologists from the Cascade Volcano Observatory and others. (RealAudio required)

Underwater Lava "Host Noah Adams talks with Christopher Fox, of the National Oceanic and Atmospheric Administration (NOAA) about underwater equipment that was monitoring a nearby volcano. It got covered with molten lava, but is still working. The instrument records pressure and temperature variations -- it also has a camera, and captured the eruption in movie form, viewable under the title 'lava flow animation' on https://www.pmel.noaa.gov/vents/nemo/explorer/rumble.html". (4:00)

Readings

Tracking a Volcano (NASA EOS) Volcanologists use satellites to measure the average temperature of lava flows and determine the rate at which the magma is coming out of the ground.

Web Sites

Anatomy of Nyriragongo (NOVA - PBS) Explore the main features of Nyiragongo and learn what risks it poses to the 500,000 people who live in its shadow.

Cascades Volcano Observatory (USGS) Wealth of information, photos, data and other reference materials related to volcanoes.

Deadly Volcanoes (NOVA - PBS) Revisit some of the worst volcanic disasters of the past 400 years.

Volcanoes of the World - wealth of information, QTVR, video clips, virtual field trips to volcanoes.

Volcano World - the Web's premier volcano site.

CHAPTER OVERVIEW

17: Weathering, Erosion, and Mass Movement

Figure 17.1: Landslide in Venezuela (Courtesy USGS)

Movement of earth material can be so slow that it is imperceptible to the human eye, or move at tremendous speeds, covering or destroying all in its path. Here you will investigate the processes that mobilize earth materials and the surface changes that result from weathering, erosion, and mass movement.

Learning Objectives

By the end of this chapter you should be able to:

- Compare and contrast chemical and physical weathering.
- Explain how mass movement occurs and the landform features created by it.
- Explain how splash, sheet, rill and gully erosion occurs.

17.1: Weathering
17.2: Mass Movement
17.3: Water Erosion
17.4: Review and Additional Resources

17.1: Weathering

Slopes

A **slope** is an inclined ground surface. Most slopes are mantled with unconsolidated regolith, the product of weathering. Regolith serves as parent material for soil above and grades downward into unaltered bedrock below. Loose regolith serves as a source of **colluvium**, sediment that has been eroded, transported and deposited down slope. In order to do so, the erosional forces must overcome the forces of resistance: friction, inertia (the resistance to movement), and particle cohesion.

The land surface constantly responds to endogenic and exogenic forces that shape the Earth. Being an open system, a slope seeks a state of balance between the forces of resistance and those of change. The surface attains a state of **dynamic equilibrium**, a condition where the system constantly adjusts to processes that raise the surface (e.g. tectonic uplift) and those that wear it down (e.g. erosion by water). The system fluctuates around a stable average state unless the driving forces of change exceed a geomorphic threshold, such as a massive earthquake, tsunami, volcanism. Once this occurs, a period of system adjustment occurs, finally ending in a new stable state.

Weathering

Weathering is the breakdown and decomposition of earth material, namely rocks. Weathering is an important mechanism to destabilize surface materials for their eventual removal by erosive processes. Weathering of rock-forming minerals can create new products from pre-existing rocks. The physical disintegration of rocks affects soil development and texture. Weathering releases chemical compounds that become available for biological processes. The weathering of carbonate minerals releases carbon to the atmosphere which impacts atmospheric chemistry and temperature. And the list goes on. Weathering, needless to say, is an important environmental process that bridges all elements of our physical environment and sustains the notion of a changing Earth.

Figure 17.1.1: Talus slopes created by physical weathering. (Courtesy USGS DDS21)

Weathering occurs in two ways. **Physical weathering**, also called mechanical weathering, involves the disintegration of rock materials. Physical weathering incurs no change in the chemistry of the material being altered. Instead, it simply breaks large pieces into smaller ones. **Chemical weathering** involves the decomposition of rocks and sediment. In this case, a chemical change occurs and a new product is created from the material that has undergone weathering. Weathering processes are determined by the climate and vegetation of a place. Dry locations tend to be dominated by physical weathering and moist places by chemical weathering.

Physical weathering

The result of physical weathering is to simply make smaller pieces out of larger ones. In so doing, physical weathering makes it easier for surface materials to chemically decompose and be eroded. When a large block of material is broken into smaller pieces additional surface area for chemical weathering to act is exposed. Examine Figure 17.1.2 below. On the left is a block whose length, width and height is equal to one centimeter. This means that the volume of the block is equal to 1 cubic centimeter and the total surface area is equal to 6 square centimeters. If we split the block in length and width wise (dashed lines) we create eight smaller pieces, each with a height, width, and depth of .5 centimeters. Though the volume of all eight pieces taken together is still 1 cubic centimeter, the total amount of surface area is greatly increased to 12 cm^2.

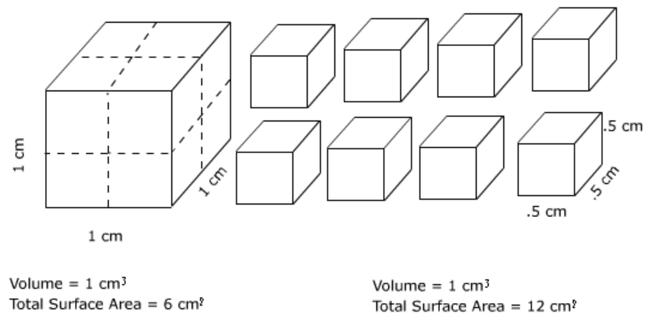


Figure 17.1.2: Effect of particle size and surface area.

Physical weathering processes

There are a number of physical weathering processes that break earth materials apart, a very common one is called ***root wedging***. Plant roots work their way into rock crevices called ***joints***. As they grow, roots create pressure on the sides of the crack enlarging it until the rock breaks apart. This is a common problem for home owners where trees are grow too close to a house. Tree roots can force their way into the foundation, breaking it apart, and let water seep into the owner's basement.

Figure 17.1.3: Tree roots growing into bedrock. (Courtesy USGS DDS21)

Frost wedging occurs when water freezes in rock fractures. As the water freezes it expands putting pressure on the sides of the crack, enlarging it until the rock breaks apart. ***Thermal expansion and contraction*** can weaken rock and cause it to disintegrate. In deserts, surface materials get exceedingly hot during the day and be exposed to cold temperatures at night. The expansion upon heating and contraction during cooling weakens rock breaking it apart. ***Alternate wetting and drying*** causes material to expand and contract, thus weakening rocks and inducing them to break as well. Regardless of process, the result is a mass of unconsolidated material.

Chemical weathering

The minerals in rocks formed beneath the surface are in equilibrium with the temperature and pressure conditions at time of their formation and thus are quite stable. However, many minerals are no longer in equilibrium with their environmental conditions when exposed at the surface and are susceptible to weathering. ***Chemical weathering*** results in the formation and retention of minerals in equilibrium with environmental conditions at the Earth's surface. The least stable minerals in igneous and metamorphic rocks are olivine and plagioclase, the most stable is quartz.

The interlocking and spacing of mineral grains controls the tendency towards weathering. Rocks with loosely interlocking mineral grains allow agents of chemical weathering to penetrate, thus speeding their decomposition. Limestone is primarily composed of calcite, a mineral that is quite soluble under surface conditions and easily dissolves in humid environments. In dry regions, the tight texture of limestone prevents it from disintegration and thus is a relatively resistant rock when found in deserts.

The process of chemical weathering tends to:

- increase bulk creating stress within rocks
- lower the density minerals
- decreased particle size resulting in increased surface area
- creates more mobile materials

- creates more stable minerals

Chemical weathering processes

Oxidation takes place when oxygen reacts with earth materials. Oxygen dissolved in water combines with atoms of metallic elements abundant in silicate minerals. Attacking metals in the soil, oxidation causes them to rust leaving the soil a brownish red to red color. When oxygen combines with iron, the reddish iron oxide *hematite* (Fe_2O_3) is formed:

$$4Fe^{+3} + 3O_2 \rightarrow 2Fe_2O_3$$

Hydrolysis is an exchange reaction involving minerals and water. Free hydrogen (H^+) and hydroxide ($(OH)^-$) ions in water are able to replace mineral ions and drive them into solution. As a result, the mineral's atomic structure is changed into a new form. It is a process whereby silicate minerals like potassium feldspar are weathered and a clay mineral is formed.

$$2KAlSi_3O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2K^{2+}$$

Hydration involves the absorption of water like which occurs during the conversion of hematite to limonite:

$$2Fe_2O_3 + 3H_20 \rightarrow 2Fe_2O_3 \cdot 3H_20$$

Some geoscientists question whether hydration is a true chemical weathering process because the process is readily reversible and the new product is not chemically different from its precursor. Some would rather call hydration a physical weathering process.

Carbonic acid action involves combination of carbon dioxide and water. Though present in pure water, carbon dioxide dissolved in water provides ions that produces free hydrogen. Carbon dioxide in the atmosphere combines with rain water to form carbonic acid (H_2CO_3):

$$H_2O + CO_2 \rightarrow H_2CO_3$$

Though weak, when carbonic acid is combined with a mineral like calcite ($CaCO_3$) common to limestone, calcium and bicarbonate ions are released and carried off by groundwater.

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{+2} + 2HCO_{-3}$$

Rock resistance to weathering

Rocks react differently to weathering due to the differences in mineral content and structure. Some minerals are unstable under surface conditions and are readily soluble. Others are stable and resist the agents of weathering. Some rock-forming minerals are physically soft, being easily crushed and split while harder minerals are less easily broken apart. The arrangement and size of mineral grains control weathering processes. Water has a difficult time penetrating intricately locked and closely spaced mineral grains to promote weathering. Larger, loosely cemented minerals disintegrate and decompose more readily. Minerals in the form of poorly joined sheets readily break apart.

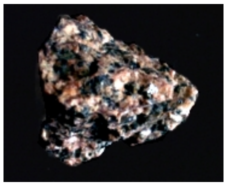


Figure 17.1.4: Granite, a predominate rock type that composes the continental land masses.

Granite is a coarse grained rock composed of quartz and feldspar. Both quartz and feldspar are hard minerals, but feldspar is less stable under surface conditions than quartz. The feldspar readily weathers to become clay in humid conditions. The feldspar will weather in dry climates as the somewhat porous granite allows moisture to penetrate. As the feldspar decomposes it weakens the bonds holding the rock together and it disintegrates

Karst Landscapes

The chemical weathering of carbonate-rich rocks creates a unique landscape abounding in caves, disappearing streams, and springs. **Karst**, a Yugoslavian term that comes from a narrow strip of limestone plateau noted for the assemblage of solution landforms. Karst develops in regions underlain by limestone and to a lesser extent dolomite. Chemical solution of the limestone, especially when fractured, wears away the bedrock leaving fissures and possibly undermining the surface. Some of the most spectacular cave complexes are found in such areas. Significant karst regions are found in Jamaica, the northern Yucatan, New South Wales, northern Puerto Rico, the Great Valley Region of Pennsylvania, Maryland, Virginia, and Tennessee, central Kentucky and central Florida in the United States

Figure 17.1.5: Stalactites hang from the ceiling and stalagmites grow from the floor of Carlsbad Caverns, NM (Photo Credit: National Park Service)

Generally four conditions are important for karst development. First, there must be limestone at or near the surface. Though karst is found in areas underlain by dolomite, it usually far less soluble than limestone. Second, the limestone must be dense, highly jointed, and thinly bedded. If the rock is too porous, water will be rapidly absorbed throughout the entire mass and not be concentrated along restricted flow lines. Third, the existence of entrenched valleys below uplands underlain by soluble and well jointed rocks ensures downward movement of groundwater, favorable for the development of karst. Finally, at least moderate precipitation must fall in the region. Few arid or semi-arid regions exhibit karst features, though some relic features may exist from a previous moist period in the past.

Karst Landforms

One of the most common features of areas underlain by limestone are sinkholes. ***Sinkholes*** form either from beneath the surface or from the surface down. Collapse sinkholes form when the limestone is dissolved away from below, removing the support for the surface and it collapses in. Collapse sinks can be particularly dangerous because one might not know that the support for the surface under their feet is being slowly eaten way. Sinkholes can also be created where water infiltrates into the surface widen the fissure into which it flows. These sinkholes are called **dolines**.

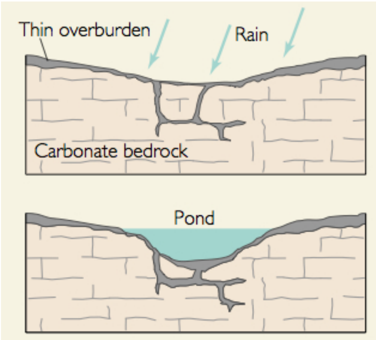


Figure 17.1.6: Sinkholes from dissolution (Courtesy USGS)

Sinkholes are commonly funnel-shaped and broadly open upward. They may be a few feet to more than 100 feet in depth, though usually ranging from 10 to 30 feet. Sinkhole diameter sizes range from a few square yards to several acres in area.

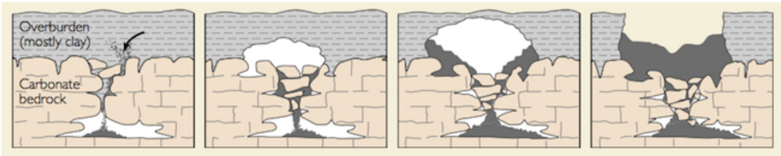


Figure 17.1.7: Collapse sinkhole (Courtesy USGS)

Streams flowing along the surface may enter a sinkhole as a "**disappearing stream**" and flow underground for some distance to reappear at the surface. A **karst window** forms when the roof above the underground stream collapses in. **Cavern systems** are carved by these underground streams over time.

Figure 17.1.8: Sinkhole, Cape Breton, Canada (Image courtesy Geological Survey Canada)

17.2: Mass Movement

Mass movement is the down slope movement of earth materials under the influence of gravity. The detachment and movement of earth materials occurs if the stress imposed is greater than the strength of the material to hold it in place. ***Shear strength*** is a measure if the resistance of earth materials to be moved. The interlocking of soil particles increases the ability of material to stay in place. Plant roots also help bind soil particles together. ***Shear stress*** is primarily a function of the force exerted by the weight of the material under the influence of gravity acting in the down slope direction. The slope of the surface determines the amount of stress that occurs on earth materials. Water destabilizes hill slopes by creating pressure in the pore spaces of earth materials. Water infiltrating into slope materials saturates the soil particles at depth by filling the pore spaces between. The weight of water lying above creates water pressure that drives soil particles apart. This lessens the friction between them and enables them to slip past one another. Material is mobilized when the shear stress imposed on a surface exceeds the shear strength. The movement, especially in the case of slides and slumps, is along a failure plane. The failure plane may be a well-defined layer of clay or rock upon which sets the destabilized surface material. Humans induce mass movement when subjecting a slope to a load that exceeds its ability to resist movement. People building houses on scenic hill slopes often find their homes threatened by a landslide. Undercutting of hillsides during road construction commonly creates unstable slopes making them prone to failure.

Types of mass movement

Soil creep is nearly imperceptible to the naked eye as it is the slowest of all types of mass movement. Soil creep generally occurs in the top few meters of the surface and is accomplished by expansion and contraction of the soil. For instance, when water in the soil freezes the ice pushes soil particles outward perpendicular to the slope. Upon warming, the ice melts and the soil is pulled down slope under the influence of gravity. Over many freeze-thaw cycles soil moves slowly down slope. In many cases one might not be able to tell that soil creep is occurring by just examining the surface. However, trees growing on surfaces undergoing creep will have curved trunks or roots that are curved. Broken retaining walls and curved railroad tracks also indicate creep in action.

A ***slide*** is a sheet of material that slips over a failure plane ending anywhere from a meter to a kilometer down slope. Slides produce concave scars while slumps tend to produce a scarp or cliff exposure. Trees are broken and bent and the slide can bury the soil down slope. Digging into buried soils and analyzing their contents can tell us about the age and what the environment was like when the slide occurred.

Figure 17.2.1: La Conchita, CA 2005 landslide (Courtesy USGS; Source)

La Conchita, California has experienced devastating landslides in recent years. Unstable slopes mobilized by rain water caused a landslide and debris flow seen in Figure 17.2.1. The city lies on a narrow strip of coast 250m (800ft) wide between the shoreline and a 180 m (600ft) bluff above it. Extraordinary rains and rising groundwater levels caused the slope to fail, fortunately no one was killed. However, in 2005, another year of abnormally high rain fall caused the slope to fail again, this time burying structures and killing 10 people.

Video: "Landslides" (Courtesy National Geographic)

Slumps are characterized by a backward rotation of the earth material as it moves along a curved failure plane resulting in a reverse slope. Slumps take place as an intermittent movement of earth or rock material, often as several independent units, creating a number of step-like "terracettes." Undercutting of slopes by stream erosion, waves, and road building are common causes of slumping.

Figure 17.2.2: Slump on hill side. Notice the step-like appearance of terracettes (Courtesy USGS DDS21) (Click image to enlarge)

Solifluction is the down slope movement of soil over a permanently frozen subsurface. Solifluction is common on slopes underlain by permafrost. During the summer when the upper permafrost is activated, the waterlogged soil mass slowly moves down slope to form solifluction lobes or terraces.

Figure 17.2.3: Solifluction terraces, Niwot Ridge, Colorado

A **flow** is the down slope movement of water-saturated soil, regolith, weak shale, or weak clay layers. *Earth flows* are fairly slow, occurring over a few hours or so slow that they are almost imperceptible. Earth flows are accompanied with slumping, but unlike slumping, there is no backward rotation. Earth flows differ from mudflows in that they (1) tend to be slower, (2) are not confined to channels, (3) are more common in humid areas than dry, and (4) have a lower water content.

Figure 17.2.4: Mudflow, Pacific Palisades, CA. (Courtesy USGS DDS21) Click image to enlarge

A *mudflow* is the rapid down slope movement of water-saturated water- saturated soil, regolith. The higher water content creates a flow rapid enough to be perceptible to the eye. Conditions favorable for the development of mudflows are: (1) unconsolidated surface materials, (2) steep slopes abundant but intermittent precipitation, and (3) sparse cover of vegetation. Mudflows tend to be more prevalent in dry regions where vegetation is sparse and heavy rains may form. When set in motion, they occupy stream-cut channels rushing along in a torrential flow of mud.

Figure 17.2.5: Talus slope, Isabelle Valley, Colorado

Rock fall is one of the most sudden forms of mass movement. Rock fall occurs when blocks of rock shed from a cliff face and collect at the base. **Talus** is a term that is applied to an accumulation of rock by rock fall.

Video:"Riding the Storm - Landslide Danger in San Francisco" (Courtesy USGS)

17.3: Water Erosion

Erosion is the detachment of earth material from the surface. Once detached, agents like water or wind transport the material to a new location where it is deposited. The most ubiquitous form of erosion is that done by water.

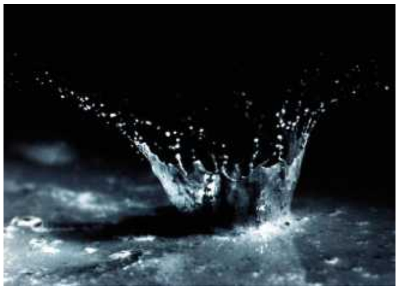


Figure 17.3.1: Rain drop impact causing splash erosion (Image courtesy NRCS)

Rain splash erosion is caused by the impact of water striking the surface. Rain splash erosion generally takes place in two steps. As precipitation is absorbed by the surface it fills the pore spaces, loosening soil particles and driving them apart. The impact of subsequent rain drops hitting the surface splash the particle away from the point of impact. The effect is to give the surface a dimpled-like appearance.

Figure 17.3.2: Severe sheet erosion on a field (Image courtesy NRCS)

Surface runoff forms when the rainfall intensity of a storm exceeds the infiltration capacity of the soil. ***Sheet erosion*** is caused by the unconfined flow of water running across the surface. The effects of sheet erosion are often hard to distinguish because such thin layers of soil are being removed. It isn't until several years later that significant degradation is perceived.

Figure 17.3.3: NRCS personnel inspecting rill erosion on a field (Image courtesy NRCS)

Rill erosion is caused by water concentrating into innumerable, closely-spaced small channels. Left unchecked, rills can cut vertically and horizontally and when joined form gullies.

Figure 17.3.4: Severe gully erosion on a field in Iowa (Image courtesy NRCS)

Gullies are steep-sided trenches formed by the coalescence of many rills. Once started they are difficult to stop.

17.4: Review and Additional Resources

Review

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the module and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the module. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **weathering**
  the breakdown and decomposition of earth material, namely rocks
- **physical weathering**
  involves the disintegration of rock materials; breaks large pieces into smaller ones
- **chemical weathering**
  decomposition of rocks and sediment.a chemical change occurs and a new product is created from the material that has undergone weathering
- **root wedging**
  Plant roots work their way into joints; as they grow, roots create pressure on the sides of the crack enlarging it until the rock breaks apart
- **joints**
  rock crevices
- **frost wedging**
  occurs when water freezes in rock fractures. As the water freezes it expands putting pressure on the sides of the crack, enlarging it until the rock breaks apart
- **thermal expansion and contraction**
  can weaken rock and cause it to disintegrate; expansion upon heating and contraction during cooling weakens rock breaking it apart
- **regolith**
  the product of weathering
- **oxidation**
  takes place when oxygen reacts with earth materials. Oxygen dissolved in water combines with atoms of metallic elements abundant in silicate minerals.
- **hydrolysis**
  an exchange reaction involving minerals and water. Free hydrogen (H^+) and hydroxide $(OH)^-$ ions in water are able to replace mineral ions and drive them into solution
- **karst**
  a Yugoslavian term that comes from a narrow strip of limestone plateau noted for the assemblage of solution landforms
- **sinkhole**
  form either from beneath the surface or from the surface down
- **karst window**

forms when the roof above the underground stream collapses in

- **mass movement**
  the down slope movement of earth materials under the influence of gravity
- **shear stress**
  primarily a function of the force exerted by the weight of the material under the influence of gravity acting in the down slope direction
- **shear strength**
  a measure of the resistance of earth materials to being moved
- **creep**
  occurs in the top few meters of the surface and is accomplished by expansion and contraction of the soil; slowest of all types of mass movement
- **slide**
  a sheet of material that slips over a failure plane ending anywhere from a meter to a kilometer down slope
- **slump**
  characterized by a backward rotation of the earth material as it moves along a curved failure plane resulting in a reverse slope
- **earth flow**
  fairly slow, occurring over a few hours or so slow that they are almost imperceptible. Accompanied with slumping; no backward rotation; are not confined to channels; are more common in humid areas
- **mud flow**
  is the rapid down slope movement of water-saturated water- saturated soil, regolith. The higher water content creates a flow rapid enough to be perceptible to the eye.
- **rock fall**
  occurs when blocks of rock shed from a cliff face and collect at the base
- **erosion**
  the detachment of earth material from the surface
- **rain splash erosion**
  caused by the impact of water striking the surface
- **sheet erosion**
  caused by the unconfined flow of water running across the surface
- **rill erosion**
  caused by water concentrating into innumerable, closely-spaced small channels
- **gully erosion**
  steep-sided trenches formed by the coalescence of many rills

Review Questions 17.4.1

What is the difference between physical and chemical weathering?

Answer

Physical weathering processes are those that break rocks into smaller pieces (disintegration). Chemical weathering chemically alters rock-forming minerals into a product (decomposition).

List the effects of chemical weathering on minerals and rocks.

Answer

- increase bulk creating stress within rocks
- lower the density minerals
- decreased particle size resulting in increased surface area
- creates more mobile materials
- creates more stable minerals

Compare and contrast hydration and hydrolysis as it relates to rock weathering.

Answer

Hydration and hydrolysis involve the absorption of water into the molecular structure of a mineral. Hydration is a reversible process and hydrolysis is not.

What is soil creep and what features of the landscape can be used to tell creep has taken place?

Answer

Soil creep is the slow down slope movement of earth material. The process is imperceptible to the human eye. Terracettes, broken retaining walls, curved tree roots, deformed railroad tracks result from creep.

Compare and contrast slumps and slides.

Answer

Slumps take place on well-defined failure planes, exhibit rotation of the failed mass, and often form terraces. Slides occur along irregular failure planes with the mass sliding down slope burying the overlying surface with debris.

Explain the process of mass movement.

Answer

Mass movement is the down slope movement of earth material under the influence of gravity. Movement occurs when the shearing stress imposed on material is greater than the shearing strength.

What does erosion mean?

Answer

Erosion is the detachment of material from the surface.

Describe the process of rain drop erosion.

Answer

Rain drop erosion occurs in a series of steps. Initial rain drops soak the surface driving soil particles apart. Subsequent rain drops detach soil particles upon impact. A dimpled surface often results from rain splash erosion.

What is particularly harmful about sheet erosion?

Answer

Sheet erosion occurs when the unconfined flow of water across the surface strips thin layers of top soil. It can be imperceptible to the human eye.

Compare and contrast rill and gully erosion.

Answer

Rill erosion occurs when moving water is confined to small channels. A gulley is a much larger channel formed from the coalescence of rills

Self-Assessment Quiz 17.4.1

1. Backward rotation of a mass of earth material when mobilized is typical of
   - A. slides
   - B. slumps
   - C. rock fall
   - D. creep
2. Another term that describes chemical weathering is
   - A. disintegration
   - B. decomposition
   - C. rotting
   - D. fragmentation
3. Curved tree trunks, fractured retaining walls, curved roots are typical features of
   - A. slides
   - B. slumps
   - C. rock fall
   - D. creep
4. Talus is a deposit associated with
   - A. slides
   - B. slumps
   - C. rock fall
   - D. creep
5. Physical weathering
   - A. is typical of warm and wet environments
   - B. results in new mineral products being formed
   - C. increases surface area
   - D. all the above
6. Solifluction is a mass movement process in
   - A. the rain forest
   - B. the desert
   - C. the tundra
   - D. the steppe
7. _______ erosion occurs when water is confined to small channels.
   - A. rain splash
   - B. sheet
   - C. rill
   - D. gully
8. Sheet erosion
   - A. occurs as channeled flow
   - B. in some cases is nearly imperceptible
   - C. occurs when the infiltration capacity of the soil exceeds the rainfall intensity

D. all the above

9. Karst landscapes develop over __________ bedrock
   A. sandstone
   B. limestone
   C. granite
   D. basalt
10. Conditions favorable for mudflows include
   A. unconsolidated surface materials
   B. steep slopes abundant but intermittent precipitation
   C. sparse cover of vegetation
   D. all the above

Answer

1. B
2. B
3. D
4. C
5. C
6. C
7. C
8. B
9. B
10. D

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "Killer Landslides" (NOVA PBS). (29:00)

Connections: When Land Slides (*NASA Earth Observatory*)

Physical Geography Today: "Real-Time" Monitoring of an Active Landslide above Highway 50, California - USGS

Readings

When Land Slides (NASA EOS)

CHAPTER OVERVIEW

18: Fluvial Systems

Figure 18.1

> "Wild rivers are Earth's renegades, defying gravity, dancing to their own tunes, resisting the authority of humans, always chipping away, and eventually always winning."
>
> ~ Richard Bangs, River Gods ~

Fluvial processes are those associated with the work of streams. Among all the various land forming agents, the work of running water is the most ubiquitous. Nearly every part of the Earth has seen, at sometime in its geologic past, the imprint of fluvial processes.

Learning Objectives

By the end of this chapter you should be able to:

- Describe the features of a drainage basin.
- Explain how the features of a drainage basin control runoff and discharge from streams in it.
- Explain how drainage patterns within a drainage basin form.
- Describe the factors that control and explain the processes of fluvial erosion, transportation, and deposition.
- Describe channel geometry and explain its role in stream flow.
- Describe to components of a hydrograph and explain the controlling factors over its shape.
  Explain how floods occur.
- Compare and contrast the several types of deltas.
- Identify fluvial landforms from a topographic map.
- Describe the processes and feature formed from fluvial processes in dry regions.
- Describe the impact of climate change on fluvial processes and landforms.

18.1: The Stream System

18.2: Channel Geometry and Flow Characteristics

18.3: Geologic Work of Streams

18.4: Stream Gradation

18.5: Landforms of Alluvial Rivers

18.6: Fluvial Processes in Dry Regions

18.7: Review and Additional Resources

18.1: The Stream System

The fundamental unit of study for fluvial processes is the **drainage basin** or **watershed**. A drainage basin is a portion of the Earth's surface that contains a main stream and its tributaries and is bounded by a drainage divide. The **drainage divide** represents the boundary between adjacent drainage basins and determines into which basin precipitation flows. There is no upper or lower limit to the size of a drainage basin. We can delimit the drainage basin of the Mississippi River as most of the area east of the Rocky Mountains. The main stream is the Mississippi River and its tributaries are rivers like the Missouri, Arkansas, and Wisconsin to name just a few. Or, at a more local scale we can delimit the Wolf River basin found in central Wisconsin.

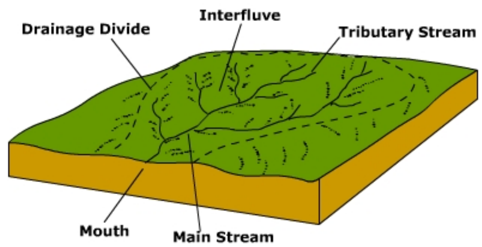


Figure 18.1.1: The Drainage Basin

Streams within the drainage basin are either perennial or intermittent in flow. **Perennial streams** flow all year. The base flow of these streams is provided by groundwater seepage into the channel. **Tributary streams** are small streams that enter into the main stream. Tributary streams, especially the smaller ones around the periphery of the basin, are intermittent. **Intermittent streams** only flow during wetter times of the year. Much of their flow is provided by surface runoff and when the water table is higher as a result of moist conditions. The upland between tributaries is called an **interfluve**.

Figure 18.1.2: Mississippi River Basin (Courtesy NOAA; Source)

The famous geographer John Wesley Powell recognized the value of the watershed concept in environmental planning. In 1878 Powell published his *Report on the Lands of the Arid Region*, which propose a strategy for settling the western United States without fighting over limited water resources. *All Things Considered's* Howard Berkes reports "Powell's knowledge of the region convinced him that water, or the lack of it, would be a major and ongoing problem in America's westward expansion." ► Powell proposed to organize settlements around water and watersheds because overuse or pollution would impact everyone in the watershed.

Figure 18.1.3: The Victoria Nile, near Murchison Falls in northern Uganda. (Courtesy K. Dunn, FAO_17389)

Some streams are classified as **exotic streams**. Exotic streams are those that originate in a humid region but flow through an arid region. Such is the case of the Nile and Colorado Rivers. The headwaters of the Nile River is in the wet Ethiopian Highlands, and travels through the eastern portion of the Sahara Desert on its way to the Mediterranean Sea. Along its route, the river loses substantial amounts of water to evaporation. The same is true for the Colorado River. With its headwaters in the Rocky Mountains, it flows south and west towards the southwest desert of the United States. During its journey it loses nearly half its flow to evaporation. The Colorado used to flow to the ocean, astonishingly it no longer does. The reason is that the remaining water has been diverted for agriculture and municipal water use.

Drainage Patterns

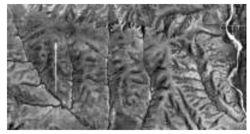


Figure 18.1.4: Aerial photograph illustrating typical dendritic drainage pattern developed in an area underlain by Gila conglomerate. Gila County, Arizona. (Courtesy USGS DDS21) Click image to enlarge

Over time, a stream system achieves a particular **drainage pattern** to its network of stream channels and tributaries as determined by local geologic factors. Drainage patterns or *nets* are classified on the basis of their form and texture. Their shape or pattern develops in response to the local topography and subsurface geology. Drainage channels develop where surface runoff is enhanced and earth materials provide the least resistance to erosion. The texture is governed by soil infiltration, and the volume of water available in a given period of time to enter the surface. If the soil has only a moderate infiltration capacity and a small amount of precipitation strikes the surface over a given period of time, the water will likely soak in rather than evaporate away. If a large amount of water strikes the surface then more water will evaporate, soaks into the surface, or ponds *on level ground. On sloping surfaces* this excess water will runoff. Fewer drainage channels will develop where the surface is flat and the soil infiltration is high because the water will soak into the surface. The fewer number of channels, the coarser will be the drainage pattern.

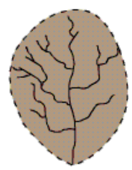


Figure 18.1.5: Dendritic drainage pattern

A **dendritic drainage pattern** is the most common form and looks like the branching pattern of tree roots. It develops in regions underlain by homogeneous material. That is, the subsurface geology has a similar resistance to weathering so there is no apparent control over the direction the tributaries take. Tributaries joining larger streams at acute angle (less than 90 degrees).

Figure 18.1.6: Parallel drainage pattern

Parallel drainage patterns form where there is a pronounced slope to the surface. A parallel pattern also develops in regions of parallel, elongate landforms like outcropping resistant rock bands. Tributary streams tend to stretch out in a parallel-like fashion following the slope of the surface. A parallel pattern sometimes indicates the presence of a major fault that cuts across an area of steeply folded bedrock. All forms of transitions can occur between parallel, dendritic, and trellis patterns.

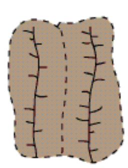


Figure 18.1.7: Trellis Drainage Pattern

Trellis drainage patterns look similar to their namesake, the common garden trellis. Trellis drainage develops in folded topography like that found in the Appalachian Mountains of North America. Down-turned folds called synclines form valleys in which resides the main channel of the stream. Short tributary streams enter the main channel at sharp angles as they run down sides of parallel ridges called anticlines. Tributaries join the main stream at nearly right angles.

Figure 18.1.8: Rectangular Drainage Pattern

The **rectangular drainage pattern** is found in regions that have undergone faulting. Streams follow the path of least resistance and thus are concentrated in places were exposed rock is the weakest. Movement of the surface due to faulting off-sets the direction of the stream. As a result, the tributary streams make sharp bends and enter the main stream at high angles.

View an offset stream along the San Andreas Fault in Google Earth.

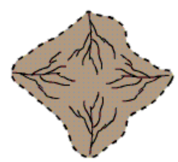


Figure 18.1.9: Radial Drainage Pattern

The **radial drainage pattern** develops around a central elevated point. This pattern is common to such conically shaped features as volcanoes. The tributary streams extend the headward reaches upslope toward the top of the volcano. 

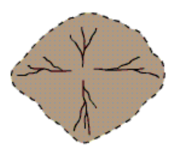


Figure 18.1.10: Centripetal Drainage Pattern

The **centripetal drainage pattern** is just the opposite of the radial as streams flow toward a central depression. This pattern is typical in the western and southwestern portions of the United States where basins exhibit interior drainage. During wetter portions of the year, these streams feed ephemeral lakes, which evaporate away during dry periods. Salt flats are created in these dry lake beds as salt dissolved in the lake water precipitates out of solution and is left behind when the water evaporates away.

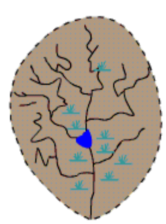


Figure 18.1.11: Deranged Drainage Pattern

Deranged or contorted patterns develop from the disruption of a pre-existing drainage pattern. Figure 18.1.11 began as a dendritic pattern but was altered when overrun by glacier. After receding, the glacier left behind fine grain material that form wetlands and deposits that dammed the stream to impound a small lake. The tributary streams appear significantly more contorted than they were prior to glaciation. 

The patterns described above are **accordant**, or correlated with the structure and relief over which they flow. Those streams that are **discordant** with the rocks over which they flow are either antecedent or superimposed. For instance, **antecedent** streams flowed across bedrock structures prior to uplift. Slow mountain building permitted stream erosion to keep pace with uplift. Such appears to be the case for the Columbia River that cuts across the Cascade Mountains. Streams in portions of the Appalachian Mountains have formed in weaker rock that through time has eroded away. These streams appear to be **superimposed** over the rock layers that they presently flow over. The Cumberland Gap is a famous water gap formed in this way as it cuts through the folds of the Appalachians.

18.2: Channel Geometry and Flow Characteristics

Channel Geometry

Channel geometry and characteristics of stream flow are inherently related. Changes in the geometry of the channel can impact stream velocity and discharge.

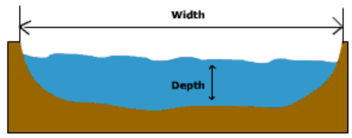


Figure 18.2.1: Cross-sectional area.

The **cross-sectional area** of the stream is determined by multiplying channel depth by channel width along a transverse section of the stream. For a hypothetical stream with a rectangular cross-sectional shape (a stream with a flat bottom and vertical sides) the cross-sectional area (A) is simply the width multiplied by the depth:

$$A = (W * D)$$

The **wetted perimeter** is the portion of the channel that is "wet". The wetted perimeter (WP) is the width plus twice the depth that the water touches:

$$WP= W + 2D$$

The greater the cross-sectional area in comparison to the wetted perimeter, the more freely flowing will the stream be because less of the water is in proximity to the frictional bed. So as hydraulic radius increases so will velocity (all other factors being equal).

Studies have shown that width and depth tend to vary regularly with stream discharge. If discharge is held constant and width decreases, then the channel should deepen by scouring. This occurs as a result of the increased velocity and transportation power which accompanies the narrowing of a channel. Studies have also shown that as mean discharge of a stream increases downstream so do channel width, depth, and average current velocity.

The flow velocity is directly related to the **hydraulic radius** (cross-sectional area divided by the wetted perimeter) and channel slope, and inversely related to channel roughness.

Channel slope or gradient is the difference in elevation between two points on a stream divided by the distance between them measured along the stream channel. The flow velocity, and thus power of the stream to do work is also directly related to the slope of the channel, the steeper the slope, the faster the velocity of flow.

Stream Flow

Sources of Stream Flow

There are four basic sources of stream flow. *Groundwater flow* into the channel is what provides for the base flow, or normal flow of the stream. For perennial streams the water table is at the height of the surface of the stream as shown below. The base flow of the stream is augmented by *interflow* from the soil moisture zone. At the surface, *direct channel precipitation* and *surface runoff* as **overland flow** contribute to stream flow during and following storms.

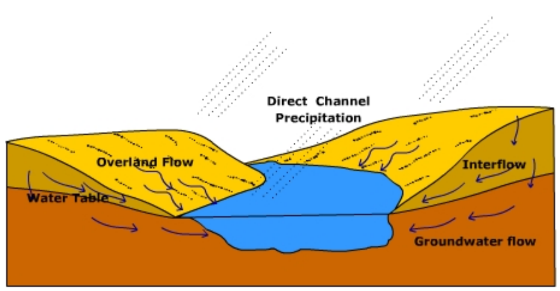


Figure 18.2.2: Sources of Stream Flow

Flow velocity

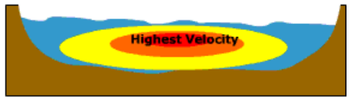


Figure 18.2.3: Flow velocity

The **flow velocity** of a stream is how fast the water is moving through a cross-section. Flow velocity is determined by the balance between the down slope gravitational stress as a result of the slope of the stream, and the loss or expenditure of energy in overcoming the frictional resistance of the channel bed and side. In general, the flow velocity is greatest at the center of the channel, just below the surface. More specifically the highest velocity of flow follows the stream **thalweg**, a line that connects the deepest part of the stream channel. Here, water moving through the stream encounters the least resistance to flow yielding a higher velocity of flow.

Video: Streamgage - The Silent Superhero (Courtesy USGS)

Flow Regimes

Under very low velocities water flows through a stream as smooth sheets running parallel to the bed called **laminar flow**. Laminar flow has an appearance much like that of a deck of cards with the top card jutting forward over those below. The tug of the channel bottom slows the water near the bed with the water nearer the surface flowing somewhat faster. Only the finest particles kind be detached, so laminar flow is basically nonerosive.

Under higher flow velocities, resistance within the flow and that caused by the bed and sides of the channel cause the flow to break down into separate currents. The swirling currents of **turbulent flow** undergo constant variation in speed and direction of flow. The swirls of water created during turbulent flow are more erosive than laminar flow and help suspend material in the stream. Turbulent flow is the "normal" type of flow in most streams.

Stream discharge

Stream discharge is the volume of water passing through a particular cross-section in a unit of time, measured in units like cubic meters per second or cubic feet per second. The discharge of a perennially flowing stream is provided by the influx of groundwater into the channel. This influx provides what is called the "**base flow**" of the stream. Water is added to the stream by runoff from the surrounding terrain during storm events.

Discharge(Q) can be expressed as

$$Q = A \text{ X } V$$

where,

A= cross-sectional area

V= velocity

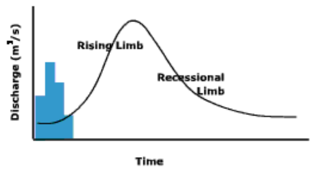


Figure 18.2.4: A stream hydrograph

The **hydrograph** is a graphical way of portraying the change in discharge over time, and how it relates to inputs of water and the environment in which the stream is located. The Y-axis of the hydrograph is scaled for discharge, and when investigating the influence of a storm event, precipitation. The X-axis is scaled for time. Discharge is plotted as a line and precipitation as a bar graph. The hydrograph shows discharge starting at its base flow, rising to a peak (the rising limb) and then declining (recessional limb) back to its base flow. Notice how the peak in precipitation does not occur at the same time as the peak in discharge. In other words, there is a lag period between the time when the most precipitation occurs and when the most discharge is recorded.

A number of factors influence the shape of the hydrograph and the length of the lag period. Elongate basins tend to exhibit flatter hydrographs because it takes a longer time for water to move from the head to the recording station at the mouth of the basin. Travel time is less for circular basins resulting in a more peaked hydrograph.

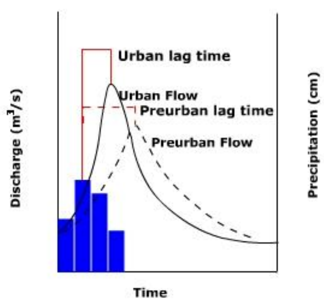


Figure 18.2.5: Comparison of pre-urban and post-urban watershed discharge.

Land cover is another important control over the shape of a stream hydrograph. Under natural conditions, vegetation slows surface runoff and encourages infiltration. As a result, the hydrograph is less peaked and the lag time is longer than a basin with little vegetation. Urbanization of a watershed can have a drastic effect on runoff, discharge, and the resulting hydrograph. Urbanization replaces permeable surface with impermeable ones, streets, parking lots, buildings etc. Water runs off the surface more efficiently and is diverted to nearby streams by the construction of storm sewers. Storm sewers effectively increase the urbanized watershed drainage density. As a result, urbanized watersheds tend to exhibit more peaked hydrographs with shorter lag periods.

Stream energy

The energy that a stream possesses is closely related to its discharge because discharge determines flow velocity. Flow velocity controls the stream's capacity to erode and transport sediment through its channel. Generally, the larger the discharge, the smoother the channel, greater the stream velocity. Cross-sectional area and discharge increases down stream due to tributary and ground water flow into the channel. As a result, one might expect flow velocity to increase in the down stream direction as well. However, as streams grow larger their down stream slope decreases, preventing a continuous buildup of energy and creating a more uniform distribution of stream energy along its length.

Floods and Flooding

A **flood** occurs when a stream channel can no longer contain the water moving through it. Floods usually are local, short-lived events, others can be catastrophic, happening with little or no warning. Floods are most often caused by prolonged rainfall that saturates the ground causing surface runoff into nearby streams increasing their discharge. Flooding occurs when the water spills out of the channel and on to the adjacent terrain. Though viewed as a "natural hazard" to humans, flooding is a natural, rejuvenating process.

Figure 18.2.6: Flooded USGS gage, Lamprey River near Newmarket, NH (Courtesy USGS; Source)

Causes and Conditions

Generally speaking there are two types of floods, 1) where water slowly rises and spills over the banks of a stream or river and 2) flash floods. Floods can occur at anytime of year, but particular seasonal weather patterns are more conducive to the creation of floods than others in different geographic regions. In the United States, cyclonic storms roaring off the ocean and into the Pacific coast states during the winter and early spring can cause flooding. In the southwest, summer and fall thunderstorms release torrents of water that rush down dry stream beds or arroyos as flash floods. Flooding can occur in the north central states during the winter as rain fall or snow melt runs off the frozen ground surface, or ice jams rivers causing them to flood. Flooding in the mid portion of the United States tends to occur in spring and summer as polar front cyclones march across the North American continent. Hurricanes and large convective complexes create flooding in the late summer and fall along the Gulf coast of the United States.

Figure 18.2.7: Flood Season in the United States (Courtesy USGS; Source)

In tropical regions like Bangla Desh, monsoon rains saturate the ground causing severe flooding. Europe floods from the sea may occur as a result of Atlantic storms pushing water to the coast and can be particularly damaging when occurring at high tide. Deforestation greatly increases the risk for flooding.

Figure 18.2.8: Flooding in Rochester, MN (Source: :cjohnson7 on Flickr)

Some of the worst flooding in decades also occurred during the summer of 2007. Flooding in Britain was caused by a persistent jet stream sitting further south than usual at this time of the year. System after system pounded the British Isles. During August of 2007, widespread flooding occurred in the midwest United States causing damage exceeding $115 million. A warm front advanced northward into Iowa and Illinois during mid-August where it stalled and became a stationary front. Warm, moist air overrunning the front provided the ingredients for showers and thunderstorms. Rainfall over the weekend of August 18-19, 17 inches of precipitation fell in Witoka, MN. Rochester, MN measured 6.9 inches of rainfall. The heavy rain sent streams in the region over their banks. Moisture from Tropical Storm Erin to the south enhanced the stormy conditions.

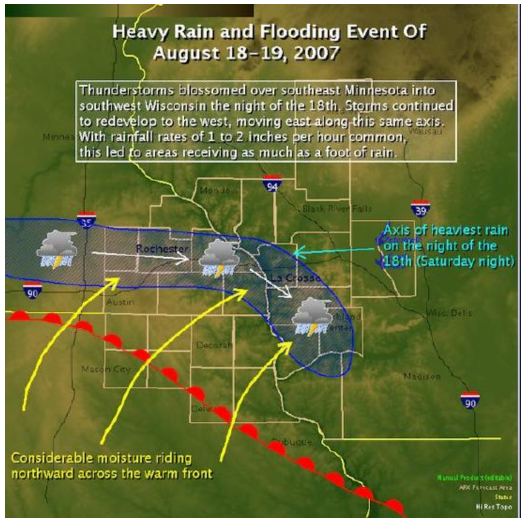


Figure 18.2.9: Weather Conditions during the historic rainfall and flooding event of August 18-20, 2007 (Courtesy NOAA; Source)

Flood Frequency

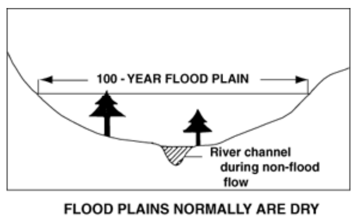


Figure 18.2.10: 100-Year Flood Plain. (Courtesy USGS; Source)

Using frequency analysis, one can estimate the probability of the occurrence of a given flood event The **recurrence interval**, also known as the return period, is based on the probability that the given event will be equaled or exceeded in any given year. For instance, a one hundred year flood has a 1% chance of occurring in any given year. One hundred year floods are rare but can be devastating. The 100-year flood plain is used for flood plain management and insurance purposes. Those living within this zone are often required to have flood insurance in addition to their regular home owner's insurance.

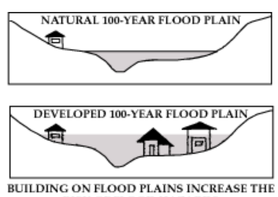


Figure 18.2.11: Development of flood plains increases risk of floods. (Courtesy USGS; Source)

Channel Types

There are three basic types of channels, straight, meandering and braided. Describing a channel by one of the aforementioned terms does not mean that the entire channel is straight or otherwise. It simply means that some portion of the channel can be described in such a way. In fact, portions of a stream may be straight, some meandering and others braided.

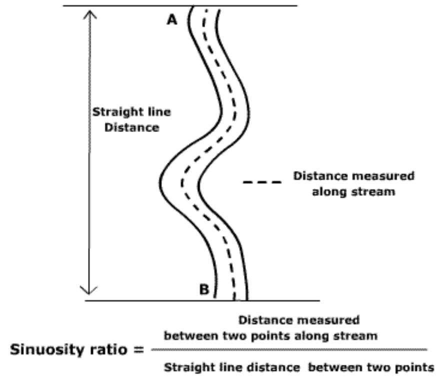


Figure 18.2.12: The sinuosity ratio

Describing a channel as a **straight channel** seems pretty obvious, though rarely is a channel perfectly straight in nature. A **meandering channel** is one that takes twists and turns over its length. Geoscientists use the sinuosity ratio to determine whether a channel is straight or meandering. The **sinuosity ratio** is the distance between two points on the stream measured along the channel divided by the straight line distance between the two points. If the sinuosity ratio is 1.5 or greater the channel is considered to be a meandering one.

Figure 18.2.13: Braided river at junction of Gakona and Copper River, Alaska (Image courtesy USGS DDS-21)

A **braided channel** is created when a stream channel is divided into several smaller ones by the accumulation of in-channel deposits. This occurs when the load of flat stream channel is too great for the velocity or discharge. Or, seasonal fluctuations in discharge expose in-channel deposits. Sand or gravel bars accumulate subdividing the flow of water into many smaller channels. Braided streams are common in glaciated areas where melt water streams choked with sediment is discharged at the snout of the glacier.

Pools and Riffles

We often find a regular sequence of shallow riffles and deeper pools in stream channels, the cause of which is still not well understood. The spacing of the **riffle-pool sequence** is related to the width of the stream. Riffle-pool sequences usually are 5-7 times the width of the channel. Laboratory experiments with artificial channels in noncohesive sand or silt show that riffle and pool sequences in straight channels tend to evolve into meanders. When this happens, a pool becomes a site for a laterally migrating meander. The stream thalweg meanders back and forth between pools, moving toward the outer bank of each successive curve. Erosion is therefore concentrated at the outside banks where the flow is deepest and stream velocity accelerates around meander.

18.3: Geologic Work of Streams

Water flowing through a stream performs three kinds of geologic work. Moving water erodes material from the bed and sides of the channel, it transports the eroded material to a new location, and then deposits it. Material deposited by streams is called **alluvium**. The ability of a stream to do work is a function of stream velocity and discharge.

Erosion

Stream erosion is the detachment of material from the bed or sides of the channel. Approximately 95% of a stream's energy is used to overcome frictional effects imposed by the channel and internal molecular friction. This leaves only 5% of the stream's energy for vertical and lateral cutting. Flowing water erodes in three ways. First, flowing water dissolves materials from the channel contributing to stream's dissolved or, **solution load**. Secondly, the impact of water, or **hydraulic action** on the sides and bed of the channel dislodges materials and makes them available for transport as part of the stream load. Materials too heavy to suspend, scoot and roll across the bed, eroding the channel by **abrasion**.

Figure 18.3.1: Potholes created by scouring bedrock, Devil's Lake, WI. (Courtesy M.Ritter)

Transportation

Once material is detached from the channel it can be transported. Transportation is the movement of earth material, in this case, by water. As particle size increases, so too does the velocity needed to transport it. The material transported through the stream is it's stream load. **Stream load** is composed of dissolved or solution load, suspended load, and bed load. The **dissolved load** comes primarily from groundwater seepage into the stream. Ions in solution also come from the solution of materials that line the channel.

Suspended load is comprised of sediment suspended and transported through the stream. Turbulent flow suspends clay and silt in the stream. Suspended load comes from material eroded from the surface bordering the channel and deposited in the stream, as well as, erosion of the channel itself.

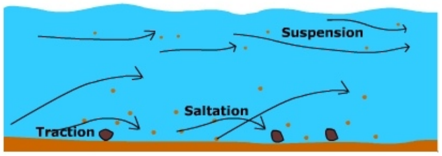


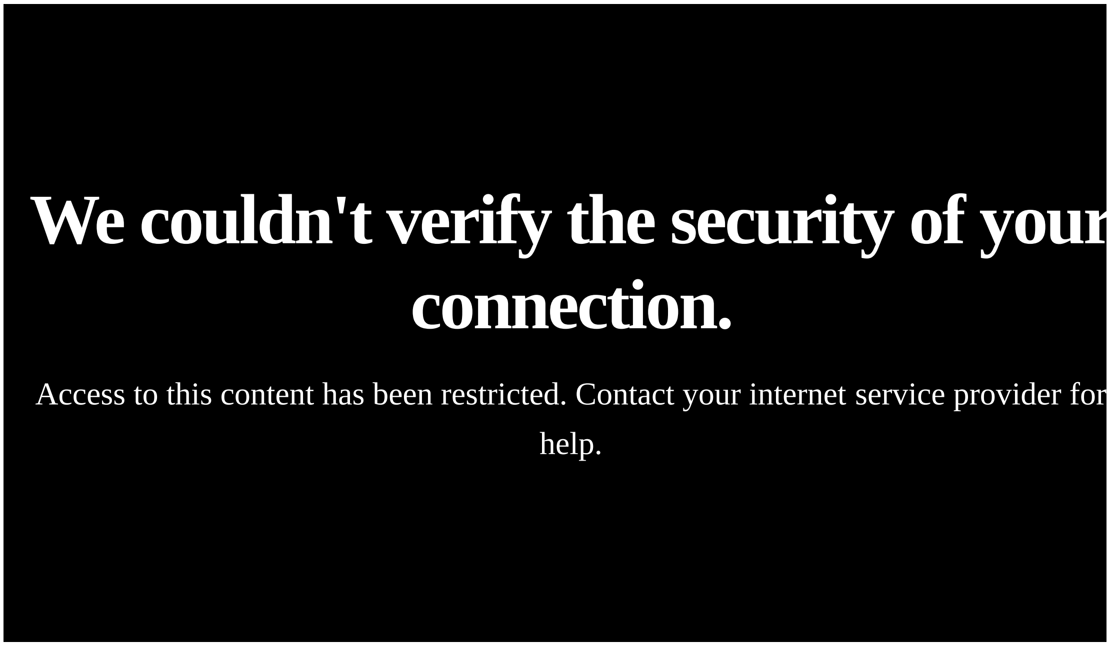
Figure 18.3.2: Stream Load

The **stream capacity** is the maximum load of sediment a stream can carry for a given discharge. As one might expect, stream capacity increases with increasing flow velocity. Increased water velocity imparts a greater frictional drag on bed to erode it. Turbulent flow occurs under higher velocity thus increasing the water's ability to dislodge material from the bed or sides of the stream. **Stream competence** is the largest size material the stream can move under a given discharge.

Bed load is that which is moved across the bed of the channel. Bed load is transported in two ways, **traction**, which is a scooting and rolling of particles along the bed. The second is **saltation**, a bouncing-like movement. Saltation occurs when particles are suspended in the stream for a short distance after which they fall to the bed, dislodging particles from the bed. The dislodged particles move downstream a short distance where they fall to the bed, again dislodging particles upon impact.

Deposition

As velocity and discharge decreases, the ability of the stream to move sediment through it decreases. The heaviest particles deposit on the bed first, with the smaller and lighter particles transported much further before accumulating. **Aggradation** raises the elevation of the bed by the accumulation of sediment in the channel. Deposits of sand and gravel as **bars** can separate the channel into numerous smaller channels resulting in a braided channel.



Video: "Stream Aggradation."

Stream flow and work

Figure $18.3.3$ shows the relationship between particle size and minimum flow velocity for the three types of geologic work performed by water. Examine the minimum flow velocity for erosion. Note that it is much more difficult to erode materials from the channel than it is to transport or deposit them. For the finest particles like clay, a very high velocity of flow is required to dislodge them from the bed of the channel due to their strong molecular bonding. Small particle don't protrude above the bed of the channel so moving water slips over them more easily than larger particle that stand above the bed more. At the other end of the spectrum, the largest particle require high flow velocities to erode them.

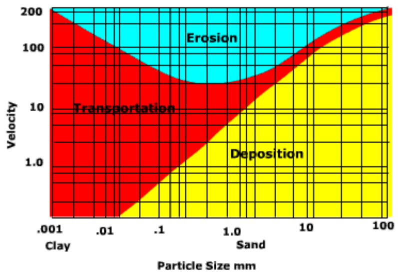


Figure $18.3.3$: Critical velocity (cm/sec) for erosion, transportation and deposition

Examine the area of the graph labeled "Transportation". Note that once clays have been eroded they can be transported over a wide range of velocities, even very slow ones before being deposited. The area of the graph for transportation narrows as you move to larger particle sizes. Larger sized material is harder to transport due to their weight.

Take a look at the area of the graph labeled " Deposition". Notice deposition doesn't extend over to the very smallest size on the left. The very smallest particles are easily transported even under low flow velocity and will not settle out. The minimum velocity for deposition (the line that separates transportation and deposition) climbs steadily to the right. This indicates that as particle size and weight increases, it is more difficult to transport material and deposition will occur with a slight drop in stream velocity.

18.4: Stream Gradation

The characteristics of a stream channel represents a balance between the amount of water flowing through it, the material the channel is located in, and the relief of the region in which the channel has formed. The famous physical geographer William Morris Davis proposed a theory of landscape development that describes a **cycle of erosion** which shapes the land surface. Though an over simplification of the true process, and one that is difficult to apply in many situations, it is nonetheless an interesting way of envisioning how a stream system forms and evolves.

Figure 18.4.1: Vertical cutting is typical of the early stages of stream system development. (Courtesy USGS DDS21) Click image to enlarge

The Davisian Cycle

At the beginning of the **youthful stage**, the region in which the stream system forms has recently been uplifted. Water is concentrated into channel actively that cuts downward toward **base level**, the theoretical limit to which a stream can erode its channel. For streams entering the ocean, base level is sea level. For tributary streams, it is the elevation of the stream into which the tributary joins. During this early stage a maximum amount of relief is created with water falls, narrow channels, and little flood plain area beside the stream.

Once the stream reaches base level, vertical cutting ends and horizontal erosion becomes predominate. During this "**mature stage**" the stream begins to cut away at the sides of the channel, creating a wider floodplain. The channel begins to meander, making broad bends along its length.

As meandering channels wear away at interfluves, the surface is worn down to a plain of low relief called a **peneplain**. The landscape remains in its "**old age**" stage until uplift renews the cycle.

Modern Theories

Modern theories of landscape development suggests that stream system development achieves a **dynamic equilibrium** between the system and its environment. The equilibrium state is determined by the balance between inputs and outputs from the system. Over time, the channel achieves an equilibrium state between inputs (water) and outputs (sediment). Once equilibrium is achieved it remains in this state until a disturbance alters the inputs and outputs of the stream system.

The Graded Stream

In several cases throughout this book we have noted that natural open systems tend toward a state of equilibrium and stream systems are no different. Over a long period of time, the gradient of a stream adjusts so that the average load of sediment is balanced by that which it receives from surrounding slopes and in-flowing channels. For example, if sediment accumulates in stream, the bed of the channel is raised and the slope of the stream increases downstream of the deposit. Increasing the slope results in a higher stream velocity thus increasing the water's ability to move sediment. Eventually, a channel slope is reached that can carry away the accumulated sediment. Conversely, if sediment delivery to the stream is reduced, down cutting of the channel ensues. Channel erosion lowers the stream gradient until the material contributed to the stream is equal to that which is transported through it. Once a stream adjusts its gradient for the local environmental conditions is referred to as a **graded stream**.

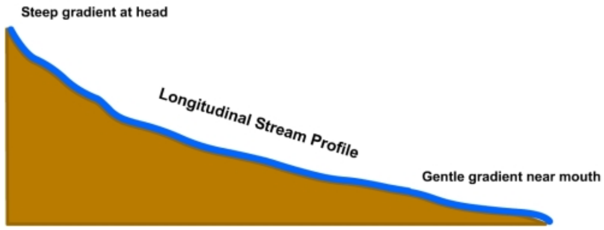


Figure 18.4.2: Longitudinal Stream Profile

The **longitudinal profile** is a depiction of the down slope gradient of a stream. The longitudinal profile of a stream can reveal if a stream has achieved a graded state, whether over a part or the entire stream. The curved profile of a graded stream exhibits a steeper slope upstream giving way to a gentle slope in the down valley direction. Initially stream profiles may be irregular with the stream gradient interrupted by **knickpoints** where waterfalls are found. Knickpoints form where the stream flows over an exposure of resistant bedrock or from tectonic uplift. The knickpoints slowly wear down and migrate upstream as water spills over them. Through time the profile is smoothed to a gentle concave shape.

Figure 18.4.3: Channel bed erosion by upstream progressing knickpoint (Courtesy USDA; Source)

18.5: Landforms of Alluvial Rivers

Rivers that have reached base level develop broad valleys by erosion caused by meandering channels. The stream channel cuts through and redistributes its sediment or **alluvium** that lines the area bordering the stream.

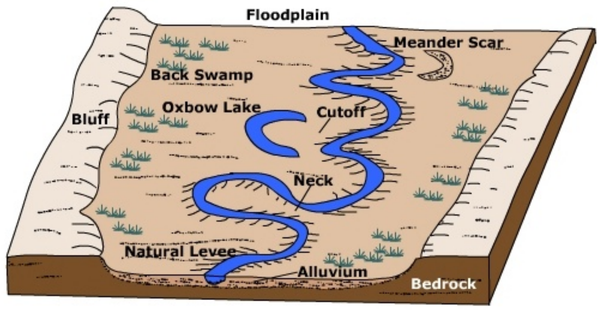


Figure 18.5.1: Alluvial Stream Features

Floodplain

Figure 18.5.2: An alluvial river meanders through its floodplain (Courtesy USGS DDS21)

A **floodplain** is the relatively flat area that borders a stream which is periodically inundated with water during high flow periods. When excess runoff causes the stream discharge to increase beyond the capacity of the channel, water spills out onto the floodplain. Increasing the cross-sectional area of stream flow causes a decrease in stream velocity. The resulting decrease in velocity causes sediment to deposit as alluvium on the floodplain. These alluvial deposits are often rich in nutrients and thus naturally fertilize floodplain soils. Floodplain agriculture has given rise to many of the great world civilizations.

Natural Levee

A **natural levee** is an narrow ridge of alluvium deposited at the side of the channel. During high discharge periods when the stream floods, coarse sediment settles out near the stream channel and grades to finer material further away. The over bank deposits of alluvium are often rich sources of nutrients for soils developed on the floodplain. Because floodplain soils are usually quite fertile, humans have inhabited them for years. To prevent flooding, artificial levees are built close to the channel, typically higher than natural levees. Confining the flood discharge to a small area increases the velocity of flow. The levees of the Mississippi River increase the flow velocity near the mouth as it enters the Gulf of Mexico. As a result, sediment is shot into the Gulf rather than being deposited near the mouth building the river's famous 'bird's foot' delta.

Back swamp

Figure 18.5.3: Draining back swamp of Roanoke River (Courtesy US FWS; Source)

Back swamps are located some distance away from the stream channel on the floodplain. When water spills over onto the floodplain, the heaviest material drops out first and finest material is carried a greater distance. The fine grained alluvium holds much water and drains rather slowly creating wetland areas. Back swamps are important "sponges" that retain water that might cause severe flooding downstream.

Meander

Figure 18.5.4: Meandering channel

A **meander** is a bend in a stream. Vertical channel cutting is typical of the early stages of stream system evolution and hence, meandering channel pattern is negligible. However during later stages as base level is achieved and channel equilibrium is approached, lateral migration of the stream channel is more prevalent. Meanders grow both laterally and in the down stream direction. As water flows into a meander it takes on a *helical or spiral flow* which determines where erosion and deposition is concentrated. Centrifugal force draws water toward the outside bank (cut bank) causing erosion. Sediment eroded from the outside bank is deposited on the inside bank and transported downstream.

Point Bar

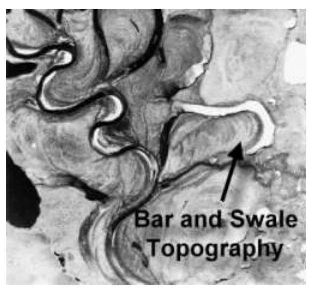


Figure 18.5.5: Point bars (white) and Bar and Swale Topography on a meandering channel (Courtesy USGS DDS21) Click image to enlarge

As water rounds a meander, the water swings toward the outside bank where erosion is concentrated and then spirals toward the inside banks. As the water spirals toward the inside of the meander it is slowed by frictional drag imposed by the bed of the channel. This causes deposition of alluvium on the inside bank to form a bar. A **point bar** forms on the inside bank of a meander and rising from the channel as an accumulation of alluvium. As the channel meander continues to erode laterally, a succession of bars with intervening swales form called **bar and swale topography**.

Neck & Cutoff

A **neck** is the upland between opposing meanders of a stream. A **cutoff** occurs when the neck between river meanders is eroded away and the meanders join to shorten the length of the channel. The slope of the channel increases as well when the river shortens its length.

Mark Twain aptly described the process and effect of river cutoffs when he wrote:

> "The Mississippi is remarkable in another way--its disposition to make prodigious jumps by cutting through narrow necks of land, and thus straightening and shortening itself. More than once it has shortened itself thirty miles at a single jump! These cut-offs have curious effects: they have thrown several river towns into the rural districts, and built up sand bars and forests in front of them. The town of Delta used to be three miles below Vicksburg: a recent cutoff has radically changed the position, and Delta is two miles above Vicksburg."
>
> ~ *Life on the Mississippi* ~

Oxbow lake & meander scar

Figure 18.5.6: Oxbow lake (Courtesy USGS)

A river cut-off results in a portion of the river isolated from the new channel called an **oxbow lake**. Oxbow lakes are typically crescent shaped - like that of an oxbow. Groundwater seeping into the oxbow maintains the lake. Some oxbows will drain or silt up due to deposition during floods. The remnants of the oxbow is identified as a **meander scar**. Wetland and marshes are often found in the scar.

Video: Cut-off and Oxbow Formation on a Stream Table (Courtesy stevekny)
(A stream table is used to model and simulate stream flow.)

Stream terraces

Stream terraces are elevated portions of a floodplain created when the stream down cuts and creates a new floodplain at a lower elevation. Stream terraces are important indicators of environmental change. Down cutting can be initiated by uplift of the land surface due to tectonic activity, increased flow, or a loss of sediment load.

Figure 18.5.7: Stream terraces along Zapato creek, the upper terrace is an important one throughout the hills. Fresno County, California. 1907. USGS Historical photo. (Courtesy USGS)

Deltas

Figure 18.5.8: Satellite image of the bird's foot delta of the Mississippi River (Courtesy USGS)

Deltas form by the deposition of sediment at the mouth of stream when water flows into a lake or the ocean. Stream velocity decreases upon entering the ocean which causes the stream to deposit its load. The shape of a delta depends on a number of factors like the rate of sediment supply, wave action and coastal currents reworking the deposited sediment, and the rate at which the alluvial deposits subsides. For more about deltas see: "*Deltaic Landforms*" Geomorphology From Space, NASA.

18.6: Fluvial Processes in Dry Regions

Though uncommon, when precipitation comes to the desert it can do so in torrential downpours sending a **flash flood** churning down dry streambeds known as **a wash**, **arroyo** or **wadi** depending on region. Salt encrusted soils result as water rapidly evaporates in the desert climate. A **playa** forms as an ephemeral lake in a low region of closed drainage. Permanent lakes and perennially running stream are rare in deserts. Many rivers are *exotic streams*, rivers whose head waters lie in a wetter region and the majority of which flows through a desert.

Figure 18.6.1: Amargosa River flowing through an arroyo, Death Valley National Park. (Courtesy USGS DDS21)

Alluvial fans are another prominent feature of many desert regions. Alluvial fans are fan-shaped alluvial deposits generally found where a mountain stream runs on to a flatter surface at the front of a mountain system. Mountain streams carrying a heavy stream load loses their kinetic energy as they flow out on to the flat plain depositing alluvium. Alluvial fans are quite common in arid regions where water is lost to evaporation and infiltration into coarse surface material when the stream exits the mountain front. Deposition of the sediment cause the channel to migrate horizontally depositing alluvium. Through time the channel migrates back and forth depositing sediment until a fan-shaped deposit is formed. A **bajada** forms when several individual alluvial fans merge into one broadly sloping surface.

Figure 18.6.1: Several alluvial fans merging at the front of a mountain. (Courtesy USGS)

TopoView

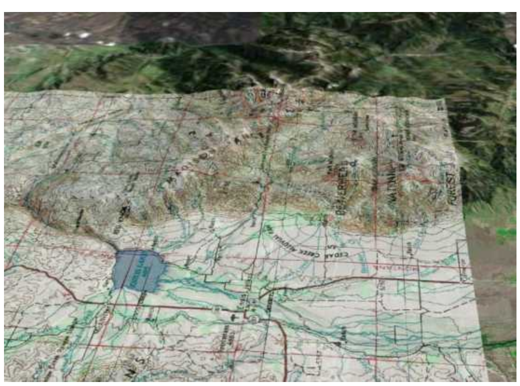


Figure 18.6.1: Ennis, Montana topographic map overlay. (Courtesy Google Earth) Click image to enlarge.

18.7: Review and Additional Resources

Review

Home destroyed during the 1976 Big Thompson Canyon flood, Colorado. Courtesy USGS

Figure 18.7.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **drainage basin**
  fundamental unit of study for fluvial processes
- **watershed**
  fundamental unit of study for fluvial processes
- **perennial stream**
  flow all year
- **tributary stream**
  small streams that enter into the main stream
- **intermittent stream**
  only flow during wetter times of the year
- **interfluve**
  The upland between tributaries
- **drainage divide**
  represents the boundary between adjacent drainage basins and determines into which basin precipitation flows
- **exotic stream**
  those that originate in a humid region but flow through an arid region
- **Davisian Cycle of Erosion**
  a theory of landscape development that describes a cycle of erosion which shapes the land surface
- **Dynamic equilibrium theory**
  equilibrium state is determined by the balance between inputs and outputs from the system. Over time, the channel achieves an equilibrium state between inputs (water) and outputs (sediment)
- **dendritic drainage pattern**
  the most common form and looks like the branching pattern of tree roots

- **parallel drainage pattern**
  form where there is a pronounced slope to the surface. A parallel pattern also develops in regions of parallel, elongate landforms like outcropping resistant rock bands
- **trellis drainage pattern**
  look similar to their namesake, the common garden trellis
- **rectangular drainage pattern**
  found in regions that have undergone faulting. Streams follow the path of least resistance and thus are concentrated in places were exposed rock is the weakest; makes sharp bends and enter the main stream at high angles.
- **radial drainage pattern**
  develops around a central elevated point. This pattern is common to such conically shaped features as volcanoes.
- **centripetal drainage pattern**
  opposite of the radial as streams flow toward a central depression
- **deranged drainage pattern**
  develop from the disruption of a pre-existing drainage pattern
- **accordant stream**
  correlated with the structure and relief over which they flow
- **discordant stream**
  rocks over which they flow are either antecedent or superimposed
- **antecedent stream**
  flowed across bedrock structures prior to uplift
- **superimposed stream**
  appear to be superimposed over the rock layers that they presently flow over
- **cross-sectional area**
  determined by multiplying channel depth by channel width along a transverse section of the stream
- **wetted perimeter**
  the portion of the channel that is "wet"
- **flow velocity**
  how fast the water is moving through a cross-section
- **discharge**
  the volume of water passing through a particular cross-section in a unit of time, measured in units like cubic meters per second or cubic feet per second
- **hydrograph**
  a graphical way of portraying the change in discharge over time, and how it relates to inputs of water and the environment in which the stream is located
- **rising limb (hydrograph)**
  the part of the graph where it rises to a peak
- **recessional limb (hydrograph)**

where the graph declines back to its base flow

- **straight channel**
  relatively straight; rarely is a channel perfectly straight in nature
- **meandering channel**
  one that takes twists and turns over its length
- **braided channel**
  created when a stream channel is divided into several smaller ones by the accumulation of in-channel deposits
- **sinuosity ratio**
  the distance between two points on the stream measured along the channel divided by the straight line distance between the two points
- **stream (channel) slope (gradient)**
  the difference in elevation between two points on a stream divided by the distance between them measured along the stream channel.
- **stream erosion**
  the detachment of material from the bed or sides of the channel
- **stream transportation**
  the movement of earth material by water
- **traction**
  a scooting and rolling of particles along the bed
- **saltation**
  a bouncing-like movement
- **suspended load**
  comprised of sediment suspended and transported through the stream
- **bed load**
  that which is moved across the bed of the channel
- **solution (dissolved) load**
  comes primarily from groundwater seepage into the stream. Ions in solution also come from the solution of materials that line the channel
- **stream deposition**
  sediment moving through the stream accumulate on the bed
- **floodplain**
  the relatively flat area that borders a stream which is periodically inundated with water during high flow periods
- **natural levee**
  a narrow ridge of alluvium deposited at the side of the channel
- **back swamp**
  located some distance away from the stream channel on the floodplain; important "sponges" that retain water that might cause severe flooding downstream.

- **meander**
  a bend in a stream
- **point bar**
  forms on the inside bank of a meander and rising from the channel as an accumulation of alluvium
- **alluvium**
  sediment carried by stream
- **bar and swale topography**
  a succession of bars with intervening swales
- **neck**
  the upland between opposing meanders of a stream
- **cutoff**
  occurs when the neck between river meanders is eroded away and the meanders join to shorten the length of the channel
- **oxbow lake**
  A river cut-off; typically crescent shaped - like that of an oxbow
- **meander scar**
  remnants of the oxbow

? Review Questions 18.7.1

Describe the various stream system features found in a drainage basin.

Answer

The **drainage divide** represents the boundary between adjacent drainage basins and determines into which basin precipitation flows. Streams within the drainage basin are either perennial or intermittent in flow. **Perennial streams** flow all year. The base flow of these streams is provided by groundwater seepage into the channel. **Tributary streams** are small streams that enter into the main stream. Tributary streams, especially the smaller ones around the periphery of the basin, are intermittent. **Intermittent streams** only flow during wetter times of the year. Much of their flow is provided by surface runoff and when the water table is higher as a result of moist conditions. The upland between tributaries is called an **interfluve**.

What is an exotic stream? Give an example.

Answer

A stream that originates in a moist region that flows into and through a drier region. The Nile River is considered an exotic stream.

Explain the basic difference between the Davisian Cycle of erosion and the Dynamic Equilibrium theory.

Answer

The **Davisian theory** begins with the uplift of land or fall of base level, initiating a cycle of erosion from youth characterized by downcutting, to mature (valley widening), and finally old age stage (formation of a peneplain). The cycle is renewed with uplift or a fall in base level. The **dynamic equilibrium theory** describe stream development as constantly adjusting to inputs (water) and outputs (sediment)s to the stream system. Over time, the channel achieves an equilibrium and remains in this state until a disturbance alters the inputs and outputs within the stream system.

Describe the stream network pattern and structural control over dendritic, rectangular, parallel, radial, centripetal, trellis and deranged (contorted) drainage patterns.

Answer

A **dendritic drainage pattern** is the most common form and looks like the branching pattern of tree roots. It develops in regions underlain by homogeneous material. A **parallel drainage pattern** forms where there is a pronounced slope to the surface. A parallel drainage pattern also develops in regions of parallel, elongate landforms like outcropping resistant rock bands. Tributary streams tend to stretch out in a parallel-like fashion following the slope of the surface. A **trellis drainage pattern** looks similar to their namesake, the common garden trellis. Trellis drainage develops in folded topography like that found in the Appalachian Mountains of North America. The **rectangular drainage pattern** is found in regions that have undergone faulting. Faulting off-sets the direction of the stream with tributary streams making sharp bends and entering the main stream at high angles. The **radial drainage pattern** develops around a central elevated point. This pattern is common to such conically shaped features as volcanoes. The **centripetal drainage pattern** is typical of basins in arid regions with interior drainage. During wetter portions of the year streams feed ephemeral lakes, which evaporate away during dry periods leaving salt flats. A **deranged (also know as contorted) pattern** develops from the disruption of a pre-existing drainage pattern.

Compare and contrast antecedent and superimposed streams.

Answer

Antecedent streams flowed across bedrock structures prior to uplift. Slow mountain building permitted stream erosion to keep pace with uplift. The Columbia River that cuts across the Cascade Mountains is an example of an antecedent stream. **Superimposed streams** expose buried geologic structures and cut through them.

Define cross-sectional area, channel slope, and wetted perimeter.

Answer

The **cross-sectional area** of the stream is determined by multiplying channel depth by channel width along a transverse section of the stream. **Channel slope** is the difference in elevation between two points on a stream divided by the distance between them measured along the stream channel. The wetted perimeter is the portion of the channel that is "wet". The **wetted perimeter** is the width plus twice the depth that the water touches.

Describe how cross sectional area related to stream discharge and velocity.

Answer

Generally, the larger the discharge, the smoother the channel, greater the stream velocity. Cross-sectional area and discharge increases down stream due to tributary and ground water flow into the channel.

Why doesn't stream velocity progressively increase in the downstream direction?

Answer

As streams grow larger their down stream slope decreases, preventing a continuous buildup of energy and creating a more uniform distribution of stream energy along its length.

Describe how a stream erodes its channel.

Answer

Solution: dissolving rock from the sides and bed of the channel. Hydraulic action: lifting sediment from the sides and bed of the channel through hydraulic action. Abrasion: materials suspended in the water are used to scour the bed and sides of the channel.

What is the sinsuosity ratio and how does it describe stream channel shape

Answer

The sinuosity ratio is used to determine whether a channel is straight or meandering. It is calculated as the distance between two points on the stream measured along the channel divided by the straight line distance between the two points. If the sinuosity ratio is 1.5 or greater the channel is considered to be a meandering one.

Compare and contrast straight, meandering, and braided channels.

Answer

Straight channel exhibit a linear though rarely is a channel perfectly straight in nature. A meandering channel is one that takes twists and turns over its length. Abraided channel is one in which the main channel is separated into several smaller channels by bars.

Self-Assessment Quiz 18.7.1

1. An oxbow lake
   - A. is created by the cutoff of a meander
   - B. is formed by stream aggradation
   - C. is formed by flooding
   - D. none of the above
2. Deposition of alluvium
   - A. takes place on the outside bank of a meander
   - B. occurs when stream velocity increases
   - C. takes place on the inside bank of a meander
   - D. occurs with an increase in discharge
3. Under constant discharge, an increase in the width of a channel
   - A. will decrease the cross-sectional area of the stream
   - B. will likely decrease stream velocity
   - C. will likely increase stream velocity
   - D. will do none of the above
4. Point bar formation is found
   - A. on the inside bank of a meander
   - B. on the outside bank of a meander
   - C. in the middle of the channel
   - D. at any of the above locations
5. The highest velocity of flow is found
   - A. at the side of the channel
   - B. at the floor of the channel
   - C. in the middle of the channel just below the surface
   - D. on the inside bank of a meander
6. Vertical cutting and channel deepening primarily occurs
   - A. prior to reaching equilibrium
   - B. after reaching equilibrium
   - C. occurs once the stream has achieved base level
   - D. during the Old Age stage of Davis's cycle of erosion.
7. Which of the following drainage patterns typify the Ridge and Valley physiographic province of North America?
   - A. Rectangular
   - B. Centripetal
   - C. Radial
   - D. Trellis
8. Which of the following physiographic features would display a rectangular drainage pattern?
   - A. The Appalachian Mountains

B. The San Andreas Fault
C. Mount Rainer
D. The Black Hills of South Dakota

9. The upland between two tributaries is called
   A. an interfluve
   B. a neck
   C. a levee
   D. none of the above
10. A drainage basin that has undergone urbanization
   A. is likely to experience higher peak discharges
   B. decreased infiltration
   C. shorter lag times
   D. all the above

Answer

1. A
2. D
3. B
4. B
5. C
6. A
7. D
8. B
9. A
10. D

Additional Resources

Use these resources to further explore the world of geography

Focus on The Physical Environment: "Floods: Using Satellites to keep Our Heads above Water. (*NASA Earth Observatory*)

Physical Geography Today: Water Watch - USGS

Connections: Army Corps Project Pits Farmland Against Flood Threat. (NPR 2015) Flood protection pits farmland against local communities.

Active Learning: Virtual River (Cal State-LA)

Multimedia

"Running Water I: Rivers, Erosion and Deposition" (Annenberg/CPB:) *Earth Revealed* "Rivers are the most common land feature on Earth and play a vital role in the sculpting of land. This program shows landscapes formed by rivers, the various types of rivers, the basic parts of a river, and how characteristics of rivers — their slope, channel, and discharge — erode and build the surrounding terrain. Aspects of flooding are also discussed." Go to the Earth Revealed site and scroll to "Running Water I: Rivers, Erosion and Deposition". One-time, free registration may be required to view film.

"Running Water II: Landform Evolution" (Annenberg/CPB) *Earth Revealed* "The Colorado River is a powerful geologic agent — powerful enough to have carved the Grand Canyon. This program focuses on how such carving takes place over time, looking at erosion and deposition processes as they relate to river characteristics and type of rock. The evolution of rivers is covered, along with efforts to prevent harmful consequences to humans." Go to the Earth Revealed site and scroll to "Running Water II: Landform Evolution". One-time, free registration may be required to view film.

"Work of Rivers" (National Archives/Google) 1935 video by the Department of Interior. Interesting from a historical perspective on geomorphic theory (eg. Davisian theory) at the time.

Three Gorges" In this July 8, 2002 segment of *All Things Considered* NPR's Rob Gifford reports from the Yangtze River in central China as the Three Goreges Dam was nearing completion. (Real Media)

Readings

Flood: Using Satellites to keep our Head Above Water (NASA EOS)

Web Sites

Water Resources of the United States (USGS)

CHAPTER OVERVIEW

19: Glacial Systems

Figure 19.1: Surprise Glacier (in background), Harriman Fiord, western Prince William Sound. (Source: USGS, Don Becker)

Some of the most magnificent landscapes on Earth are created by the action of glaciers. Throughout much of our geologic history, great sheets of ice have waxed and waned across the Earth's surface. Glaciers in high mountains have created a craggy landscape of sharp ridges, amphitheater-like depressions, and hanging valleys occupied by spectacular waterfalls. Over the flatter plains of the Earth, ice sheets over a mile thick advanced, plowing over and burying the surface in a great thickness of glacial sediment. Once retreated, the glaciers left sinuous ridges, streamlined hills, and a pocked marked surface of depressions and lakes.

Learning Objectives

By the end of this chapter you should be able to:

- Describe the various theories for ice ages.
- Describe the process of glacial ice formation and construct a diagram showing the zones of accumulation and ablation of a glacier.
- Describe how glaciers move.
- Differentiate between continental, alpine, and piedmont glaciers.
- Describe the factors that control and explain the processes of fluvial erosion, transportation, and deposition.
- Describe features formed from continental and alpine glaciers.
- Identify glacial landforms from a topographic map.
- Describe the impact of climate change on glacial processes and landforms.

19.1: Glaciation

19.2: Geologic Work of Glaciers

19.3: Landforms of Continental Glaciation

19.4: Landforms of Alpine Glaciation

19.5: Digging Deeper-The Fate of Permafrost in a Warming World

19.6: Review and Additional Resources

19.1: Glaciation

A ***glacier*** is a natural accumulation of land ice showing movement at some time. Many times during Earth's history, great ice sheets waxed and waned over the surface. What caused these periods of glaciation is still not fully understood and no single reason will probably be found.

Causes of glaciation

The onset of a period or *stage* of glaciation is due to a change in Earth temperature and circulation. It is generally accepted that a global decrease of 4^{o} to 5^{o}C, especially during the summer, and a substantial increase in the amount of snowfall in subarctic and arctic regions is necessary for the onset of a glacial episode. Several theories have been proposed for such a change in climate -- reductions in solar radiation due to meteorite collisions with the Earth, increased volcanism, the shifting location of continents, and the uplift of vast mountain regions. Milutin Milankovitch proposed one of the most significant theories to account for climate change by variations in Earth orbit. Changes in the eccentricity of earth orbit, the degree of deviation of the orbit from a perfect circular path, is thought to cause the necessary change in insolation to decrease global temperatures. Recall that the Earth's orbit is elliptical, but over periods of 100,000 years the shape varies. The changes in orbit have been correlated with ocean sediments that record the history of glacial stages. The cyclical nature of warming and cooling correspond well with the estimated dates of glacial and interglacial periods. In addition to the change in orbit, the Earth "wobbles" on its axis which alters the amount of insolation reaching the surface of the Earth. [For more about the causes and stages of glaciation in earth history.

Video: Milankovitch cycles precession and obliquity: How changes in Earth's rotation can effect Earth's seasons and climate

Video: Is An Ice Age Coming? (Courtesy National Geographic)

Anatomy of a Glacier

Whatever the cause, the main reason glacial advances are initiated is that winter accumulation exceeds the summer loss of snow over a long period of time. Snow metamorphoses into glacial ice under the increasing pressure of accumulated layers of snow. It first changes to a granular form called **firn**, and ultimately into ice. Glacial ice sometimes looks blue because it absorbs all colors of the visible light spectrum except blue, which it transmits and hence its blue appearance. Glacier ice may also appear white because some ice is fractured with pockets of air that indiscriminately scatters the visible light spectrum.

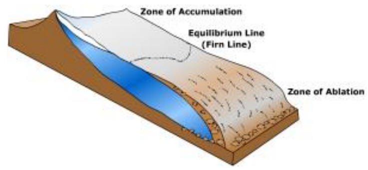


Figure 19.1.1: Regions of a glacier. (Click image to enlarge.)

The mass balance of a glacier determines if it will advance across the surface or not. The mass balance is determined by the amount of gain and loss of ice from the glacier. The mass balance is positive when it accumulates more ice than it loses. A glacier has a negative mass balance if it loses more ice than it gains.

Glaciers form in the ***zone of accumulation***, the portion of the glacier over which accumulation exceeds ablation. ***Ablation*** is the loss of ice (or snow) from the glacier. Ablation includes sublimation, wind erosion, melting, and evaporation. The zone of accumulation for the large continental ice sheets resides at high latitudes. For mountain glaciers, the zone of accumulation is at a high altitude where temperatures are cold prevent complete summertime melt. The ***zone of ablation*** is where loss of ice mass is greater than accumulation. The boundary between these two zones is the ***firn*** or ***equilibrium line***. If accumulation exceeds ablation the glacier will grow. If ablation exceeds accumulation, the glacier will retreat by melting in place. You can approximate the location of the equilibrium line by examining an aerial photograph. The glacier looks dirtier below the equilibrium line as glacial sediment is exposed on top of the ice. Above the line it is more white because fresh snow usually covers the surface. Listen to a glacier refreezing (Antarctica 2000).

Figure 19.1.2: An aerial view of the zone of ablation in Alaska Range (Courtesy USFWS; Source)

Video: "Glacier Power" Go inside a glacier to to help understand power of a glacier (Courtesy of National Geographic)

Glacier Movement

Once the ice reaches a thickness of about 20 meters (66 ft) it will begin to move under the pressure of its weight. Glaciers move across the surface by ***internal deformation*** and ***basal slip***. Under the weight of accumulating ice,the ice is deformed and begins to move by pseudo-plastic flow. Glaciers slip over the surface lubricated by meltwater at their base. Generally speaking, flow velocity in a glacier is greatest near the surface of the ice and decreases towards the bottom. The surface moves faster than the base does due to internal deformation and basal slipping. The actual forward movement of a particle of ice in the glacier is about 1,000 feet per year. A typical glacier will move at about 10 inches a day, though some move more rapidly like Greenland's Jakobshavn glacier. [View "Fastest Glacier" from *Nova scienceNow*] Variations in the speed of the ice caused by surface irregularities results in differential expansion and compression of the ice and the development of ***crevasses***. A deadly situation for hikers, crevasses can open and close with little warning.

Figure 19.1.3: Crevasses on Taku Glacier, Alaska(Image by Melissa Mahon from Pixabay)

A ***glacial surge*** occurs as an abrupt movement that can cover tens of meters per day. The exact cause is not well-known, but may result from water pressure building at the base which "floats" the glacier. In 1986 the Hubbard Glacier surged across the mouth of the Russell fjord in Alaska cutting it off from Yakut Bay. Glacier movement exceeded 112 feet per day, compared to a normal rate of 10 inches per day! The Black Rapids Glacier, AK in 19.1.4is a surging glacier. Tributary glaciers enter the main valley from the left. Massive amounts of glacial sediment have been deposited along the sides of the glacier and up against the valley walls. The tell-tale sign of a surging glacier are the looped moraines that snake their way across the ice.

Figure 19.1.4: Black Rapids Glacier. Alaska (Source: USGS)

Types of glaciers

Two major categories of glaciers are alpine and continental glaciers. **Alpine glaciers** are those that form at high altitudes in mountainous regions where the temperature is favorable for their formation. There are four types of alpine glaciers, cirque, valley, piedmont, and ice field shown. They range from glaciers a few hundred square meters to vast expanses that smother whole mountain ranges. **Cirque glaciers** form in bowl-shaped depressions, called *cirques*, scoured into the side of a mountain. Weathering and erosion Â loosen bedrock at the head of of a preexisting stream valley as ice accumulates. As erosion proceeds, a depression forms in which the cirque glacier continues to grow. **Valley glaciers** fill former stream valleys with ice as they push outward from their zone of accumulation. Cirque glaciers that grow beyond the limits of the depression in which they form spill out to become valley glaciers. **Piedmont glaciers** form when valley glaciers flow out of canyons onto the lowland adjacent to a mountain front. **Ice fields** are confined to large basins or plateaus having tall mountain peaks called **nunataks** protruding above the ice. Ice fields feed alpine valley glaciers.

Figure 19.1.5: An alpine glacier in Togiak National Wildlife Refuge, Alaska (Courtesy USFWS). Click image to enlarge.

Figure 19.1.6: Southern Patagonian Ice Field, Argentina-Chile. (Courtesy NASA JSC.) Click image to enlarge.

Continental glaciers are vast, continuous masses of ice that originate in high latitudes and cover portions of a continent or island Figure 19.1.7). Continental glaciers flow outwards in all directions from thicker ice near the center of the ice mass towards the thinner periphery of the ice mass. Continental glaciers are considered "unconfined glaciers" because they flow over a landscape and generally are not affected by it.

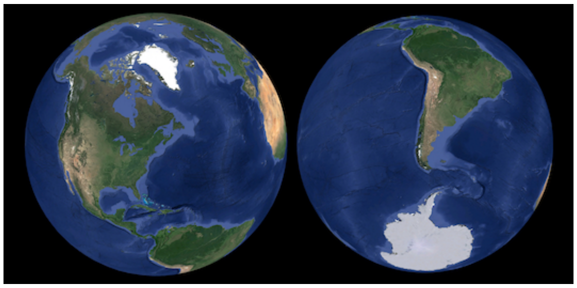


Figure 19.1.7: The only continental glaciersI ice sheets are found in Greenland and Antarctica. (Source: NASA). Click image to enlarge.

There are three types of continental glaciers, ice sheets, ice caps, and outlet. An **ice sheet** covers an area larger than 50,000 square kilometers (19,305 sq. mil.). Greenland and Antarctica and are covered by massive ice sheets today. The Greenland ice sheet occupies 1,710,000 square kilometers (660,000 sq. mi), nearly 80% of Greenland. The ice sheet is over 3 km (1.9 mi) at its thickest point. The Antarctic ice sheet covers nearly 98% of the continent. With almost 14 million square kilometers (5.4 million sq. miles) of ice, the Antarctic ice sheet is the largest single mass of ice on Earth. The ice sheet has a maximum thickness of 4.78 kilometers (2.97 miles).

An **ice cap** is a dome-shaped mass of ice of less than 50,000 square kilometers (approximately 19,000 square miles) and usually covering a highland area. Though covering a mountainous region, an ice cap is categorized as a type of continental glacier because it is not constrained by the topography. Think of an ice cap as a precursor to an ice sheet. The Vatnajokull ice cap in Iceland, the large mass of ice in Figure B, sits on top of three active volcanoes. The bright green lakes and coastal waters are the result of very fine sediment eroded by glaciers and washed out in glacial meltwater. **Outlet glaciers** are similar to valley glaciers as they are confined by the topography but originate from an ice cap.

Video: Antarctica 2009 (Courtesy NASA). The Nov. 4, 2009 Operation Ice Bridge flight criss-crossed the Antarctic Peninsula to survey glaciers flowing down mountain valleys to feed the floating ice shelves.

19.2: Geologic Work of Glaciers

Glacial erosion

Glaciers themselves do relatively little significant erosion because ice is so soft. Under the weight of an ice sheet thousands of feet thick continental glaciers detach material from the surface by ***crushing*** the underlying bedrock. Once the material is loosened from the surface, ice can ***quarry*** (also known as *plucking*) the rock by freezing around and into fractures, then lifting it from the surface. The rock embedded in the ice gouges and smoothes bedrock surfaces by abrasion. ***Striations*** are fine scratches left in bedrock by abrasion. At a larger scale, linear ***grooves*** are ground into the bedrock in the direction of ice movement. Chipping of bedrock leaves crescent-shaped marks called ***chatter marks*** gouged into the bedrock. The constant abrasion of exposed rock also creates ***polished bedrock***.

Figure 19.2.1: Chatter marks in bedrock, Kilarney Provincial Park, Canada. Sun glasses for scale. (Image Courtesy: Michael Ritter)

Figure 19.2.2: Polished bedrock. Kilarney Provincial Park, Canada (Image Courtesy: Michael Ritter)

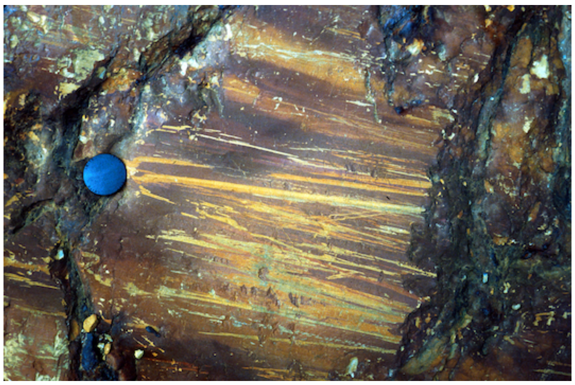


Figure 19.2.3: Glacial Striations. Camera Lense cap for scale. (Image Courtesy USGS)

Figure 19.2.4: Glacial Grooves. Grooves in granite bedrock, Kelly Island, Ohio. (Federal Highway Administration)

Glacier Transport and Deposition

Glacial drift deposited directly by a glacier is called ***till***. Unlike sediment deposited by running water, till is not sorted by sediment size. Till looks like a jumbled mixture of fine and coarse textured material as shown in Figure 19.2.5. Fragments of rock encased in ice tend to retain their angular shape, though occasionally the edges are knocked off when rubbing against the bedrock beneath. Rocks that tumble and roll through a stream are more rounded from striking the bed of a stream channel.

Figure 19.2.5: Glacial till in moraine in Whiteshell Park, Canada. (Source: USGS)

Erratics are boulders whose composition does not match the local bedrock where they are found. Glaciers transported erratics great distances, then deposited them in their current locations as the glaciers retreated.

Figure 19.2.6: Giant erratic in Yellowstone National Park

Water melting from a glacier carries sediment with it. **Outwash** is stratified drift laid down by water issuing off a glacier. The velocity slows as meltwater runs across the surface causing sediment in the water to deposit. The varying water velocity sorts and layers the drift. Streams running off the edge of the glacier overburdened with sediment form braided streams in outwash deposits.

Figure 19.2.7: Sands and fine gravels in stratified glacial outwash near Houghton Lake, Michigan. (Courtesy of Randall Schaetzl, Michgan State University)

Video: "Basal Till and Strations" (Courtesy of UBC Virtual Soil Learning Resources)

Loess is principally wind-deposited silt, much of which was eroded from Pleistocene glacial sediments. Vast deposits of loess are spread across the upper Midwest United States, with significant deposits along major rivers like the Mississippi. The sediment is deposited by glacial meltwater then eroded by strong winds. The Loess Hills of Iowa and Loess Plateau of China are two well-known examples of loess topography.

Figure 19.2.8: CLoess deposit in Pierre Marquette State Park, Illinois (Source: Michael Ritter)

19.3: Landforms of Continental Glaciation

A receding continental glacier exposes a variety of depositional and erosional landforms shown in Figure 19.3.1. Refer to this diagram as you read about the various landforms created by continental glaciers.

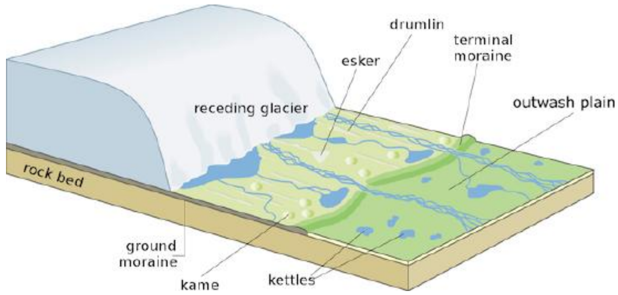


Figure 19.3.1: Glacial landforms created by the effects of continental glaciation. (Source Wikipedia, © Hans Hillewaert / CC BY-SA 4.0 Modified from the original and published here under CC BY-SA 4.0 license.)

A ***moraine*** is a glacially formed accumulation of unconsolidated debris. Moraines often take the form of a belt of low hills composed of till. Those forming at the leading edge of the glacier ***end moraine*** can be found. A ***terminal moraine*** is an end moraine that marks the furthest advance of the ice sheet. A ***recessional moraine*** and end moraine deposited when the ice sheet pauses during retreat.

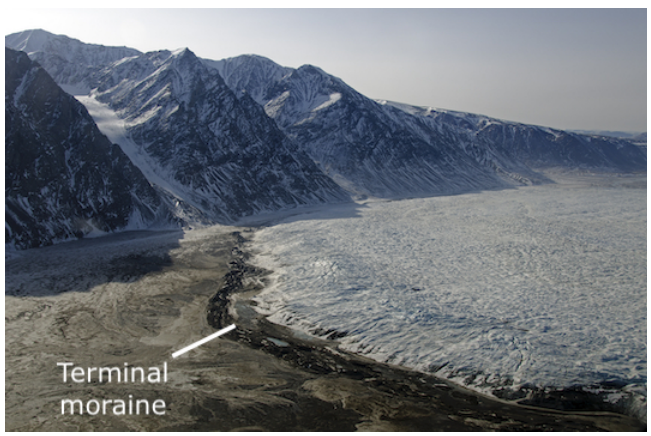


Figure 19.3.2: Terminus of Wordie Glacier in northeast Greenland with small terminal moraine. (Source: NASA)

Often, uplands will cause an ice sheet to separate into lobes. ***Interlobate moraines*** form between lobes of the ice sheet. ***Ground moraine*** is till deposited beneath a steadily retreating glacier that was lodged beneath the glacier and generally found behind the terminal moraine. Ground moraine. Wetland areas are often created in ground moraine which is a convenient way of identifying them from a topographic map.

Figure 19.3.3: Outwash plain, Copper River region, Alaska (Courtesy USGS DDS21)

An ***outwash plain*** forms ahead of the terminal moraine as melt water from the snout of a glacier deposits stratified drift. The outwash plain is a relatively flat surface that may be pock marked with depressions called *kettles*. If numerous kettles are present the surface is called a ***pitted outwash plain***.

Figure 19.3.4: Sinuous form of an esker is seen in this aerial photograph (Courtesy Geological Survey of Canada)

Eskers are sinuous ridges of glacio-fluvial material that form in tunnels in an ice sheet . The sides of the tunnel act as part of the channel for a melt water stream. As the glacier recedes, the support for the stream is removed and the stream deposits its load into a long ridge-like form. Eskers are good sources for sand and gravel, and many of them have been destroyed by mining for these materials.

Figure 19.3.5: Streamline profile of a drumlin in central Wisconsin. Glacier traveled from left to right. (Source: Michael Ritter.)

Drumlins are stream-lined hills that appear separately or in "swarms". Their formation is not well known but form by the deposition of till. As the ice rides over the till it is smoothed into an inverted spoon-shaped feature. The steep side faces the direction the ice sheet came from while the more gentle slope of the tail points toward the direction of ice flow.

Figure 19.3.6: Kame in northern unit of Kettle Moraine State Park, WI (Soure: Michael Ritter)

Kames are steep mounds or conical hills built by the deposition of stratified drift in or around ice. Some kames form in holes in the ice where sediment accumulates. A mound of glacial drift is left behind once the ice melts.

Figure 19.3.7: Kettle lake in moraine. (Courtesy USGS DDS21)

Kettles are pits in the surface that may or may not be occupied by water. They form when an isolated block of ice is surrounded by till or stratified drift. After a period of time the ice block melts away leaving behind a hole in the surface. Kettles are often found on outwash plains or embedded in moraines (hence the name for Kettle Moraine State Forest in Wisconsin).

Video: "Moulin, Kame, and Esker Formation" (Courtesy of UBC Virtual Soil Learning Resources)

19.4: Landforms of Alpine Glaciation

A region altered by an alpine glacier is depicted in Figure 19.4.1. Refer to this diagram as you read about the various landforms created by alpine glaciers.

Figure 19.4.1: Diagram of alpine glacial landforms (Source: Wikipedia, United States National Park Service. Public Domain.)

The headwaters of stream tributaries serve as the birth place for alpine glaciers. The headwaters of tributary valleys lie at the highest elevation in the drainage basin of a mountain stream. Here snow accumulates to great thickness and starts to move down valley. As it moves outward from the zone of accumulation, the glacier scours away at the valley sides. The material eroded from the surface is transported the length of the glacier to the zone of ablation, where it is deposited.

Figure 19.4.2: Pawnee Cirque, Front Range, Colorado (Photo: M. Ritter)

At the zone of accumulation where ice is accumulating, the glacier plucks rock from the head of the valley. The erosion creates a huge, amphitheater-like depression at the valley head called a **cirque**. After the glacier melts away a **tarn**, **or cirque lake** , may be found on the floor. Surrounding the floor are the massive curved side and headwalls of the cirque. A headwall crevasse known as a **bergschrund** forms where snow and compacted firn pull away from ice that remains frozen to the rock of the headwall. As alpine glaciers erode headward, they narrow the upland between ice sheets from opposite directions and a pyramid-shaped peak, called a **horn** is created. When two adjacent cirques on opposite sides of a divide cut back and remove part of it, a sharp-edge notch or pass called a **col** is formed.

Figure 19.4.3: U-shaped trough in the Alps (Photo: M. Ritter)

The massive amount of ice that fills the main valley is from that which accumulates at the head of the valley plus that from all the tributary valleys that enter it. The enormous weight of the ice erodes away at the valley sides. The V-shape of the pre-existing stream valley now takes on the characteristic U-shaped of a **glacial trough.**

Figure 19.4.4: Hanging valley in Yosemite National Park. (Courtesy USGS)

Prior to glaciation, tributary streams entered the main stream at the elevation of the main channel. But during glaciation, tributary glaciers feeding into the main valley are smaller and do not erode their valleys as deep as the glacier that occupies the main valley. Tributary valleys are left hanging at a higher elevation above the main valley floor as a result of more intensive downward cutting by the main valley glacier. These **hanging valleys** create spectacular waterfalls.

Glaciers in adjacent tributary valleys scour away at the upland between them (an interfluve). As erosion of the interfluve continues, it is narrows into a serrated ridge known as an **arête**. As mountain glaciers flow down valley they encounter exposed bed rock of varying resistance to erosion. The glacier will erode down into weaker rock but have to flow over the stronger rock. This creates a series of **rock steps** composed of the more resistant rocks with small depression behind them where the weaker rock is exposed. Often these depressions are occupied with water to form **staircase lakes**. Connected by a small stream these lakes are also know as *paternoster lakes*.

Figure 19.4.5: Niwot Ridge arête, Colorado Front Range (Photo: M. Ritter)

Figure 19.4.6: Staircase lakes, Green Lakes Valley, Colorado Front Range. (Photo: M. Ritter)

Figure 19.4.7: Lateral and end moraine. (Courtesy Geological Survey of Canada)

Glacial till is deposited along the valley sides as **lateral moraine**. Till is transported and deposited at the nose of the glacier as an **end moraine**. The end or terminal moraine marks the furthest advance of the glacier. Behind the terminal moraine are found **recessional moraines** indicating positions of the glacier front during times of retreat. When lateral moraines merge upon entering a main glacial trough, **medial moraines** are formed and run the length of the glacier.

Figure 19.4.8: Medial moraine forming from the merger of lateral moraines (Courtesy USGS)

Video: "Hanging Glaciers" (Courtesy of UBC Virtual Soil Learning Resources)

19.5: Digging Deeper-The Fate of Permafrost in a Warming World

The fate of permafrost in the future is dire. You may not think much about if you live outside the Arctic regions where permafrost is common. Scientists predict that 40 percent of the world's permafrost could thaw if temperatures rise 2^{o}C (3.6^{o}F) due to global warming. Thawing of the permfrost could allow carbon that has been stored for thousands of years to be released into the atmosphere fueling additional warming. In addition, thawing results in land subsidence and mass movement. Buildings and infrastruce-like roads, landing strips, and pipeleines, upon which residents depend have been constructed to account for the expansion and contraction that takes place in the active layer of permafrost. Rising temperature due to climate change threatens structures built under a different permafrost freeze-thaw regime.

The Arctic has experienced a signicant rise in air temperature over the last few decades and the permafrost that undelies much of the surface is undergoing substantial changes. Continuous permafrost on Alaska's North Slope has warmed 2.2^{o}-3.9^{o} C (4^{o} - 7^{o} F) over the last century making it more susceptible to erosion and mass movement. Some places in Alaska have subsided by 4.6 meters (15ft) due to thawing of the permanently frozen subsurface. Accompanied by rising sea level, Alaskan coastal communities near the Arctic Ocean and Bering Sea are being threatened. Figure 19.30 Peeking into Permafrost documents the affects of permafrost thawing on the physical environment of Alaska's Arctic coast.

Video: Peeking Into Permafrost (Courtesy USGS)

19.6: Review and Additional Resources

Review

Crevasses near the terminus of Grinnell Glacier,
Glacier National Park, Montana
Courtesy USGS

Figure 19.6.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

Important Terms and Concepts

- **glaciation**
  great ice sheets waxed and waned over the surface
- **glacier**
  a natural accumulation of land ice showing movement at some time
- **firn**
  granular form; transistion stage between snow and ice
- **zone of accumulation**
  the portion of the glacier over which accumulation exceeds ablation
- **Zone of ablation**
  where loss of ice mass is greater than accumulation
- **equilibrium line**
  boundary between zone of accumulation and zone of ablation
- **crevasse**
  a deep crack, crevice, or fissure found in a glacier
- **internal deformation**
  Under the weight of accumulating ice,the ice is deformed and begins to move by pseudo-plastic flow
- **basal slip**
  Glaciers slip over the surface lubricated by meltwater at their base
- **crushing**
  glaciers detach material from the surface by crushing the underlying bedrock
- **quarry**
  aka plucking; freezing around and into fractures, then lifting it from the surface
- **striations**

fine scratches left in bedrock by abrasion

- **grooves**
  ground into the bedrock in the direction of ice movement
- **chatter marks**
  crescent-shaped marks left by chipping of bedrock
- **polished bedrock**
  caused by the constant abrasion of exposed rock
- **glacial drift**
  sediment transported and deposited by a glacier
- **till**
  deposited directly by a glacier
- **stratified drift**
  sorted sediment deposited by glacier
- **moraine**
  a glacially formed accumulation of unconsolidated debris
- **terminal moraine**
  an end moraine that marks the furthest advance of the ice sheet
- **interlobate moraine**
  form between lobes of the ice sheet
- **ground moraine**
  till deposited beneath a steadily retreating glacier that was lodged beneath the glacier and generally found behind the terminal moraine
- **recessional moraine**
  deposited when the ice sheet pauses during retreat
- **outwash plain**
  forms ahead of the terminal moraine as melt water from the snout of a glacier deposits stratified drift.
- **kettle**
  its in the surface that may or may not be occupied by water. They form when an isolated block of ice is surrounded by till or stratified drift.
- **kame**
  steep mounds or conical hills built by the deposition of stratified drift in or around ice
- **esker**
  sinuous ridges of glacio-fluvial material that form in tunnels in an ice sheet
- **drumlin**
  stream-lined hills that appear separately or in "swarms".
- **cirque**

a huge, amphitheater-like depression at the valley head

- **tarn**

  a small lake formed after a glacier melts away

- **horn**

  a pyramid-shaped peak

- **glacial trough**

  valley takes on the characteristic U-shaped

- **hanging valley**

  When tributary valleys are left hanging at a higher elevation above the main valley floor as a result of more intensive downward cutting by the main valley glacier

- **arête**

  a serrated ridge

- **rock step**

  composed of the more resistant rocks with small depression behind them where the weaker rock is exposed

- **staircase lakes**

  rock steps occupied with water

- **lateral moraine**

  Glacial till deposited along the valley sides

- **medial moraine**

  When lateral moraines merge upon entering a main glacial trough

? Review Questions 19.6.1

Briefly describe the conditions under which glaciers form.

Answer

Glaciation occurs where the winter-time accumulation of snow exceeds the summer loss. Through time, snow accumulates to a sufficient depth to metamorphose into ice. Conditions for glaciation usually occur at high latitudes or high altitudes where temperatures are cool enough to inhibit melting.

Under what conditions will a glacier advance or retreat?

Answer

If the mass balance is positive the glacier will advance. If the mass balance is negative it will retreat.

Describe how a glacier moves across the surface.

Answer

Glaciers move when the weight of ice causes the ice to deform and bulge outwards from the zone of accumulation and bby basal slip, the sliding of ice over the surface on a film of meltwater.

How do glaciers erode the surface?

Answer

Crushing, plucking and abrasion.

Compare and contrast glacial till and stratified drift.

Answer

Till is an unsorted mixture of material deposited by ice. Stratified drift is sorted material deposited by melt water.

How do striations, grooves, and chatter marks indicate the direction of glacier flow?

Answer

Striations and grooves are oriented in the direction of flow, while chatter marks are perpendicular to flow.

Compare and contrast ground, terminal, and recessional moraines.

Answer

A moraine is an accumulation of till producing irregular topography and often taking the form of a belt of low hills. A terminal moraine marks the furthest advance of a glacier. A recessional moraine forms when the glacier recedes and stagnates for a period of time. Ground moraine is an irregular deposit of till spread over the surface beneath the ice.

How do kettles and kames form?

Answer

Kettles are depressions left by melting ice blocks surrounded by till or stratified drift. Kames are steep-sided hills built by the deposition of stratified drift laid down in or around ice.

How do drumlins show the direction of glacier flow?

Answer

The "tail" of the drumlin points in the direction of movement.

What is an esker and how does it form?

Answer

Eskers form by the deposition of glacial drift, composed mostly of glacio-fluvial gravel in a subglacial stream during ice stagnation.

Explain how cirques and tarns form.

Answer

Cirques are bowl-shaped depressions scoured into the side of a mountain by an alpine glacier. Tarns are small depressions filled with water on the cirque floor.

How do hanging valleys form?

Answer

A hanging valley is a tributary valley left hanging at a high elevation above the main valley glacier floor.

What are horns are arêtes and how do they form?

Answer

A horn is a pyramidal peak formed by the headward erosion of cirque glaciers. Arêtes are serrated ridges formed by the erosion of an interfluve by valley glaciers.

How do glacial valleys differ from stream valleys?

Answer

Stream valleys are V-shaped while glaciated valleys are U-shaped.

How do staircase lakes form?

Answer

Staircase lakes form when mountain valley streams are blocked by and fill depressions behind rock steps or moraines.

What relationship do medial moraines have to lateral moraines?

Answer

Medial moraines form by the merger of lateral moraines.

Self-Assessment Quiz 19.6.1

1. Which of the following landforms are most commonly associated with continental glaciation?
   A. cirques
   B. lateral moraine
   C. drumlins
   D. horns
2. Unsorted material laid down by glacial ice is called
   A. till
   B. stratified drift
   C. alluvium
   D. none of the above
3. Stratified drift
   A. is sorted
   B. laid down by melt water
   C. accumulates in layers
   D. all the above
4. Which of the following is a product of glacial deposition?
   A. Striations
   B. A cirque
   C. A horn
   D. A drumlin
5. Which feature is found in the zone of accumulation?
   A. A cirque
   B. A terminal moraine
   C. An outwash plain
   D. None of the above
6. Which of the following features are found on the side of an alpine glacier?
   A. A lateral moraine
   B. A terminal moraine
   C. A medial moraine
   D. None of the above
7. Which of the following features form parallel to the ice front?
   A. Striation
   B. Grooves
   C. Drumlins
   D. Chatter marks

8. What is the ridge-like feature shown below?

   A. A drumlin
   B. An esker
   C. A cirque
   D. A horn

9. Ground moraine
   A. is typically found behind a terminal moraine
   B. has been deposited beneath the ice
   C. is composed of unsorted till
   D. all the above
10. You are hiking in a region that has been created by a continental glacier and see a steep sided, conical shaped hill. You decide that it must be a
   A. kettle
   B. an esker
   C. a drumlin
   D. a kame

Answer

1. C
2. A
3. D
4. D
5. A
6. A
7. D
8. B
9. D
10. D

Additional Resources

Use these resources to further explore the world of geography

Multimedia

"USGS Public Lecture Series: Baked Alaska--What's Happening to the Glaciers in Alaska?" (September, 2009)

"Glaciers" (Annenberg/CPB) *from the site*: "Many of the world's most beautiful landscapes were made by glaciers. This program shows how, explaining glacial formation, structure, movement, and methods of gouging and accumulating earth. The program provides images of glaciers and glacial landforms such as moraines, and discusses how study of glaciers may help us understand ice ages and the greenhouse effect." (30:00) Go to the Earth Revealed site and scroll to "Glaciers". One-time, free registration may be required to view film.
Activity

"What's Happening to Alaska's Glaciers? Their Dynamic Response to Changing Climate and Other Factors" Dr. Bruce Molina (USGS) Descriptive Flyer pdf.

"Snowball Earth" National Geographic

Visualization

- Satellite Image Atlas of Glaciers of the World (USGS)

Readings

- Glaciers on Mt. Rainier (*USGS Open-File Report 92-474*) Brief overview of Mt. Rainier's glaciers including, glacier flow, glaciers and climate, and history of glacier fluctuations.

CHAPTER OVERVIEW

20: Eolian Systems

Learning Objectives

By the end of this chapter you should be able to:

- Describe the factors that control and explain the processes of wind erosion, transportation, and deposition.
- Describe the environment and explain how various dunes form.
- Describe what loess is and explain its formation and distribution.
- Describe the impact of climate change on eolian processes and landforms.

Geomorphic processes performed by the wind are called *eolian processes*, or aeolian after the Greek god of the wind Aeolus. The work of wind shapes the Earth's surface into landforms from the sublime to the spectacular. Though dominating dry climates, eolian processes are also effective in humid regions as well. Here you will become familiar with the processes that create the vast sand seas of the Sahara desert to the wind blown silt-enriched soils of the central United States.

20.1: Eolian Processes
20.2: Depositional Forms
20.3: Review and Additional Resources

20.1: Eolian Processes

Eolian processes are most effective where surface material is fine, dry and loose. Vegetation imposes a frictional force on the wind to reduce its effectiveness. Thus, an environment devoid of vegetation is best. These conditions are met in deserts found on every continent of the world. In most cases, wind erosion predominates over deposition leaving a surface of stones. Only one quarter of Earth's deserts are partially or completely covered by sand.

Figure 20.1.1: Great Sand Dunes National Park. (Courtesy National Park Service)

Though less extensive in area, coastlines of large bodies of water are another eolian environment. Here, waves and currents supply weathered material susceptible to wind action.

Eolian processes have been enhanced by human activity over the past few centuries, especially in Asia and Africa. Overuse of soil and grazing land resources in semi-arid and arid and seasonally dry regions has led to extensive wind erosion and desertification.

Wind Erosion

The entire solid surface of the Earth is subject to wind erosion. It is the balance between the driving force of the wind and the resistance of the surface that ultimately determines whether surface materials are detached and transported away.

Factors affecting wind erosion

The ability of the wind to erode the surface is determined by two factors, air density and wind velocity. The erosive power of the wind (E) is given as:

$$E = V^3 \rho \tag{20.1.1}$$

where V = wind velocity, and ρ = air density. Density has relatively little impact on the power of the wind. The erosive force of the wind is primarily related to its velocity. Its importance is seen as erosive power varies with the third power of velocity. For instance, a doubling of the wind velocity increases the erosive power by 8 fold while a tripling of velocity produces a 27 fold increase.

Figure 20.1.2: Wind erosion on rangeland in New Mexico. (Courtesy NRCS)

The roughness length of the surface (z_0), a parameter based on the size and distance between objects in a group, has a critical control over the velocity of the wind. Grass, shrubs, and trees, all impart a drag on the wind to reduce its erosive force. Vegetation also acts to bind soil particles to the surface. A surface without a cover of vegetation exposes soil to the direct force of the wind making erosion more effective. Thus, dry regions lacking a protective cover of vegetation display the effects of wind erosion more than humid climates.

Table 20.1.1: Roughness Lengths (z_o) for Various Surface

Type of Surface	z_o(cm)

Type of Surface	z_o(cm)
Fir Forest	283.0
Citrus Orchard	198.0
Large City (Tokyo)	165
Corn Field	84.5
Wheat Field	23.0
Grass	10.0
Dry Lake Bed	0.003

The cohesiveness of surface materials affects the resistance of the surface to erosion. Clay particles exhibit a greater degree of cohesiveness than sand. Clay-rich soils tend to resist erosion by wind more than less cohesive materials. Thus, clays require a much higher threshold velocity for detachment than one would expect. Cohesiveness may be provided by a cementing agent as well. Calcium carbonate and other salts common to desert regions deposited in interparticle voids harden and bind particles together.

Features of wind erosion

Landscapes formed from the work of wind result from either the removal of fine particles, or the sculpting effects of material in movement. **Deflation** lifts and removes loose particles from the surface. Deserts where soils of mixed particle size have been eroded of fines leave a cobblestone-like surface behind called **desert lag** or **desert pavement**.The interlocking pavement of stones protects the underlying surface from the wind. If disturbed, the surface becomes subject to erosion. Such has been the result of surface degradation from military activities in the desert regions of North Africa during World War II (as well as later conflicts fought in the desert regions of the Middle East).

Figure 20.1.3: Old Native American road cut through pavement, Death Valley, California. (Courtesy USGS)

Deflation may also result in **blowout depressions**, basins ranging in size from less than a meter to many meters deep. Chemical weathering of cementing materials loosens particles cohesiveness to enable wind erosion. Some extremely large depressions like the Qattara Depression in the western desert of Egypt are partially a result of deflation.

Figure 20.1.4: Rock sculpted by wind, Utah. (Courtesy NRCS)

Sand particles lifted free of the surface can "sand blast" rock surfaces in a process called **abrasion**. Abrasion shapes and polishes exposed bedrock. Abrasion is restricted to a distance of about a meter or two above the surface because sand grains are lifted a short distance. **Ventifacts** are smooth faceted rocks that often have a polished surface that results from abrasion. At a much larger scale, elongate ridges called **yardangs** form by the abrasion and streamlining rock structures oriented parallel to the prevailing wind direction. Abrasion occurs at the windward end while deflation removes material from the leeward end. Archaeologists have suggested that the Great Sphinx of Giza, Egypt is partially formed from a yardang.

Sand transport

Much of our knowledge about sand transport dates back to the 1930s and 1940s when British Brigadier Ralph A. Bagnold conducted experiments while stationed in the desert of North Africa. Sand generally begins to move when the wind achieves a velocity of about 4.5 m/sec. At first, sand exhibits a rolling motion called **traction or surface creep**. Approximately 20 to 25% of total sand transport during sand storms occurs by traction. As wind speed increases, grains are lifted into the air by wind gusts.

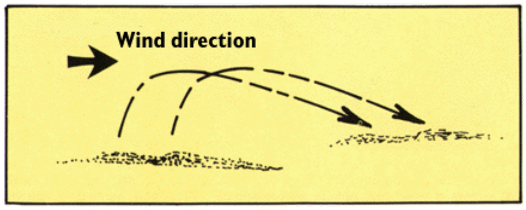


Figure 20.1.5: Saltating sand grains (Courtesy USGS)

Once airborne, sand grains travel downwind and then drop back to the surface several centimeters from their point of origin. Finer dust particles are lifted from the surface and suspended in the air at much greater heights than heavier sand grains. With strong winds and turbulence, sand grains can be lifted as high as 2 meters and travel a distance of 10 meters or more. When a settling sand grain impacts the surface, it sends another grain of sand into the air to travel in the downwind direction. Watching this process in action makes sand appear to be bouncing along the surface. We call this process **saltation** which accounts for 75% to 80% of sand transport over sand dunes. Once saltation begins, transport can continue under somewhat lower wind speeds.

Dust storms are primarily composed of fine material that easily reduce visibilities to a few meters and can persist for hours. During a prolonged dry period, extraordinary amounts of valuable top soil was stripped from the Great Plains during the "Dust Bowl" period of the 1930s. Moister conditions returned and the application of soil conservation techniques have greatly reduced the erosive effects of wind. **Sand storms** are raging systems of blowing, stinging sand traveling a meter or two above the surface.

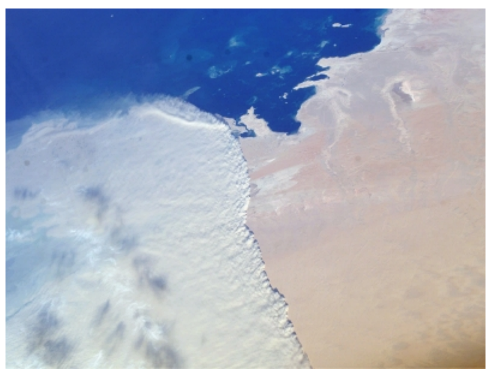


Figure 20.1.6: Sandstorm sweeping over the Persian Gulf state of Qatar racing southward toward southeastern Saudi Arabia and the United Arab Emirates. A major upper-level, low-pressure system over southwestern Asia led to a series of storms that struck the region. Photographed by the crew of the International Space Station on February 15, 2004. (Courtesy NASA Johnson Space Center)

A strange phenomena that has mystified generations is the sound moving sand can make as it is transported across the surface. In approximately 30 places around the world, a sustained hum rings out from this resonating dunes when wind conditions are right. Geoscientist have long wondered what causes "booming dunes". [View "Booming Dunes" from NOVA scienceNow].

20.2: Depositional Forms

Dunes

A ***sand dune*** is an accumulation of loose sand grains piled up by the wind. Dunes are most likely to form where winds are strong and generally blow from the same direction. Some of the most extensive dune fields are found in the world's great deserts like the Sahara. The dune fields of these great sandy deserts are called ***sand seas***. Patches of dunes are found in the southwest desert of the United States. Ancient dune fields are found in regions that were dry in the past but now exhibit a more humid climate. Dune systems are found landward of beaches where sand is blown landward. Beach dunes are common along the coasts of the world's oceans and large lakes like the Great Lakes of North America.

Dune formation

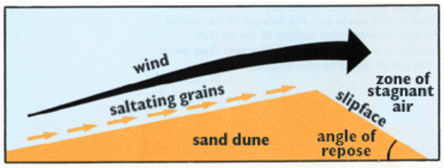


Figure 20.2.1: Sand movement (Courtesy USGS)

Dunes are primarily made up of accumulated sand grains. Finer silt and clay are carried further by the wind leaving the heavier sand grains behind. Generally, a dune forms an asymmetric cross-sectional form with a gentle windward or "stoss" slope and an steep leeward slope called the ***slip face***. Saltating grains move up the windward slope and then come to rest at their angle of repose on the downwind side in a zone of stagnant air.

Dune types

Figure 20.2.2: Barchan dunes, Peru (Courtesy USGS)

A **barchan** or **crescent** dune forms as individual units commonly found in dry regions lacking vegetation. The elongated tips, or horns, point in the downwind direction. Barchans are found moving across a non-sandy surface of gravel or clay up of several tens of meters a year. Symmetrical barchan dunes indicate winds blowing from a constant direction.

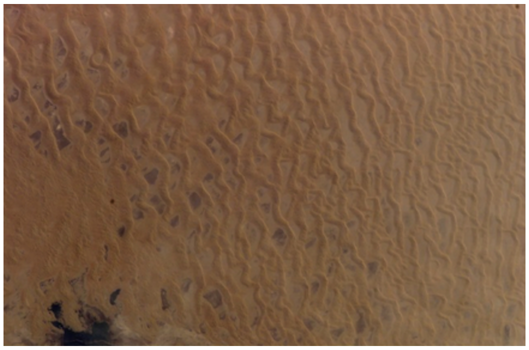


Figure 20.2.3: Transverse dunes in Tikanlik Lake, China (Courtesy Image Science and Analysis Laboratory, NASA-Johnson Space Center. Source)

Transverse dunes form perpendicular to the prevailing wind as accumulations of loose, well-sorted, very fine to medium sand. They have a gentle stoss slope (usually less than 15°) and a steep (32°) slip face.

Individual dunes whose horns point in the upwind direction are parabolic dunes. These hairpin-like dunes form where sand accumulates in a moist environment with a cover of vegetation. Vegetation or dampness in the lower part slows the dune motion there, permitting the dry crest to push ahead of its base causing the horns to be anchored behind.

Figure 20.2.4: Parabolic dunes, White Sands, New Mexico. (Courtesy USGS)

Blowout dunes form from sand deposited at the end of an open-ended deflation hollow. Blowout dunes are common to many sandy coasts (*coastal blowout dunes*). The deflation hollow focuses the wind toward the center of the depression causing the sand to migrate landward as a dune. With little wind energy on the side of the hollow, the tails of the dune move much slower. As a result, beach plants like dune grass, sea oats or sand cherry can find a suitable habitat to flourish in. Once established, the plants help anchor the flanks to promote the formation of the characteristic parabolic shape.

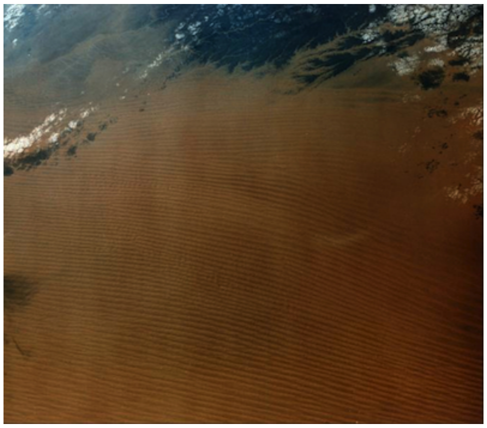


Figure 20.2.5: Seif dunes in Rub-al-Khali, a vast desert in the southern Arabian Peninsula.

Longitudinal dunes form where wind blows from more than one direction in a region with an abundant supply of sand. In some places longitudinal dunes form long smooth "whalebacks', while in other regions they display knife-edged crests. Unlike transverse dunes, these do not migrate, but lengthen in size over time. **Seifs** are elongate dunes that resemble great windrows of sand. They form parallel to the direction of the wind, though are a product of shifting wind direction. The changing wind direction sends sand back and forth across the dune crest leaving a sharp knife-like profile.

Ergs

Individual sand seas are referred to as **ergs**. Small ergs are present in most desert regions. North Africa and the Arabian desert contain the most spectacular forms on Earth with waves of sand covering tens of thousands of square kilometers. Ergs are also found in India, western China, and Australia. **Star dunes** are pyramidal-shaped mounds of sand with slipfaces on three or more arms radiating from the center and common to ergs. They tend to accumulate in areas where the wind comes from several different directions. Star dunes grow vertically rather than laterally.The Sand Hills of Nebraska are remnants of an ancient sand sea.

Figure 20.2.6: Grand Erg Occidental, Algeria. (Courtesy FAO)

Loess

Figure 20.2.7: Loess deposit on bluff above the Illinois River, Pierre Marquette State Park, Illinois. (Courtesy M. Ritter)

Loess is principally wind deposited silt, much of which was eroded from Pleistocene glacial sediments. Vast accumulations are spread across the upper Midwest United States, with significant deposits along major rivers like the Mississippi. As glaciers advanced across North America they ground the underlying rock into a powder-like "glacial flour". This sediment is laid down by glacial melt water and later eroded from the dry deposit by strong wind. The Loess Hills of Iowa and Loess Plateau of China are two well-known examples of loess topography.

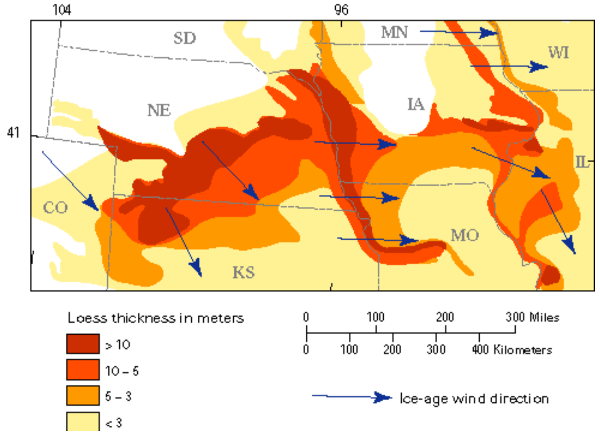


Figure 20.2.8: Loess map of Iowa and surrounding region. (Courtesy USGS; Source: https://pubs.usgs.gov/fs/FS-016-99/index.html#fig3)

20.3: Review and Additional Resources

Review

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

- Important Terms and Concepts (In development)
- Review Questions (In development)
- Self-assessment quiz (In development)

Additional Resources

Use these resources to further explore the world of geography

Connections: "From the Dust Bowl to the Sahel" NASA Earth Observatory

Multimedia

"White Sands" (National Archives/Google) a 1938 National Park Service video describing White Sands National Monument. Interesting (and somewhat comic) from a modern-day perspective.

Readings

"From the Dust Bowl to the Sahel" (NASA Earth Observatory)

Web Sites

FAO Desertification site - "The Web site contains technical and scientific data and information, available at FAO, as well as links to a number of highly informative Web sites on desertification" (Web site)

CHAPTER OVERVIEW

21: Ocean and Coastal Systems

Learning Objectives

Describe the characteristic of water waves and how they travel.

- Explain how tides form.
- Identify characteristic coastal landforms created by erosion and deposition.
- Describe the characteristics of and explain how various coasts are formed.
- Compare and contrast the various types of reefs.

The oceans have a significant impact on the Earth system. Ocean water serves as a reservoir of heat, the source of energy to fuel hurricanes, and constantly sculpts the edges of the continents. Coasts are an interface between the lithosphere and hydrosphere. The erosional and depositional work of ocean water creates spectacular landscapes and habitats for flora and fauna. In this chapter you will investigate the physical properties of oceans and their impact on the physical geography of Earth.

21.1: Water in Motion
21.2: Coastal Landforms and Processes
21.3: Types of Coasts
21.4: Review and Additional Resources

21.1: Water in Motion

Waves and water movement

Waves are undulations in the surface of a water body. Most waves are created when kinetic energy is transferred to water by the frictional stress of wind blowing over it. The resulting transfer causes a rise in water level producing a **wave crest**, followed by the sinking of the surface creating a **wave trough.** The **wave length** is the distance between successive crests. The time required for successive crests to pass a point is the **wave period**. The **wave height** is the distance between the crest of the wave and the still water level. Wave height is determined by (1) wind velocity, (2) duration of the wind, and (3) the fetch. The **fetch** is the distance of uninterrupted flow over an open water surface. An increase in any these factors will increase wave height and length. [See these effects using the "Savage Seas" Wave Machine.]

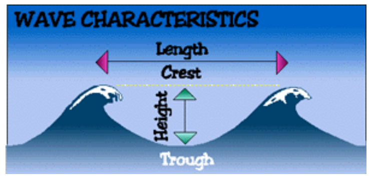


Figure 21.1.1: Wave Characteristics (Courtesy Naval Meteorology Program and Oceanography Command "Restless Sea")

The rise and fall of **oscillatory waves** in an open water reflects the circular motion of water particles. There is relatively little forward motion by a water particle as a wave passes. It is simply the wave form and its energy that is transmitted across the ocean surface. Water particles move in circular orbits that diminish with depth. The radius of the circular path is greatest at the surface and decreases with toward the bottom of the wave. Larger waves exhibit larger orbital radii and extend to a greater depth than smaller waves. At some point in deep water, the wave has no effect on the motion of the water. Thus a *zone of no wave motion* exists from the base of the wave to the ocean floor. "Observe an animation of wave motion" (Courtesy NSF/TERC/McDougall Littell)

Swells are smooth, rounded waves that travel outward from a storm center or continue as broad undulations of the ocean surface after the wind dies down. The wave slope is expressed as the ratio of the wave height to wave length, ranging from 1:25 to 1:50. A wave will become unstable at slopes greater than 1:7 and will fall over itself, or *break*.

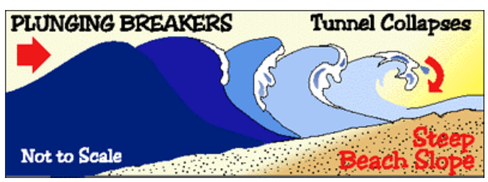


Figure 21.1.2: Plunging breakers. (Courtesy Naval Meteorology Program and Oceanography Command "Restless Sea")

As a wave approaches the coast, a depth is reached offshore where the wave touches the ocean floor. The tug of the ocean floor changes the circular wave motion into an elliptical one; the water moves back and forth over the bottom as each wave passes. The friction imparted from the floor slows the wave base. At a depth of 1.3 times the wave length, the drag causes the top of the wave to rush forward, become unstable and break. Water in the breaking wave is transported toward shore as a **wave of translation**.

Tides

Nearly all marine coastlines experience the rhythmic rise and fall of sea level called **tides**. The daily oscillation in ocean level is a product of the gravitational attraction of the Moon and Sun on Earth's oceans and varies in degree worldwide. Tidal action is an important force behind coastal erosion and deposition as the shoreline migrates landward and seaward.

Causes of Tides

The gravitational attraction of the Sun is about half that of the of the Moon on the Earth. Gravitational attraction is a function of both the mass of the objects and the distance between them. Even though the Moon is much smaller in mass than the Sun it is closer and thus has a greater influence on the Earth than does the Sun. The gravitational pull of the Moon and the Sun stretches both solid and fluid surfaces of the Earth. This creates a tidal bulge in the atmosphere, the oceans and to a very slight extent the Earth's crust.

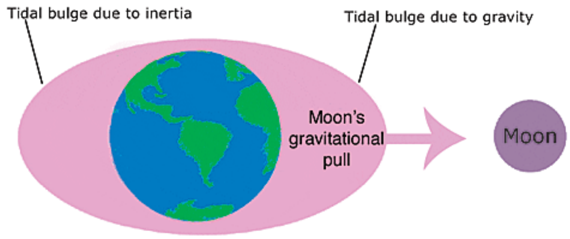


Figure 21.1.3: The two forces that result in tides (Courtesy NOAA; Source)

Gravity is not the only force responsible for a tidal bulge. **Inertia**, the tendency of moving objects to continue moving in a straight line or stay motionless, also affects the tidal bulge. As the gravitational force draws water closer to the Moon the inertial force tries to keep it in place. The tidal bulge forms as the gravitation force exceeds the inertial force on the near side. The gravitational force of the far (opposite) side is less because it is farther away from the Moon. On this side, the inertial force exceeds the gravitational force. Here the water attempts to keep going in a straight line, moving away from the Earth, creating another, smaller bulge. Thus tidal bulge, is greatest on the side of the Earth facing the Moon or Sun ("near side") simply because it's closer than the "far side" of the Earth.

Tidal Currents

Watching the tide "come in" one gets the impression that ocean water is moving in and out along the shoreline. The landward and seaward movement are a result the Earth rotating into and out of a semi-fixed tidal bulge as it changes its position relative to the Sun and Moon. Any point on Earth rotates through two bulges every 24 hours and 50 minutes producing two *high tides* and two *low tides* called each day. The difference in height between consecutive high and low tides is the **tidal range**. During a high tide water moves landward as a **flood current**. During low tide water recedes seaward as an **ebb current**. The two high tides and the two low tides do not have to be of equal height because the angle between the Moon and Earth changes each day. The tidal range is the difference in height between high and low tide.

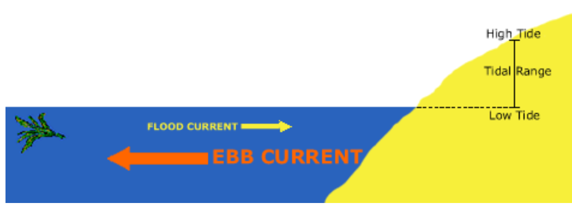


Figure 21.1.4: Flood and Ebb Currents. (Courtesy NOAA; Source))

Spring and Neap Tides

The Sun and Moon are said to be in **conjunction** with they are aligned with the Earth. The highest tides, and greatest gravitational attraction, occur when the Sun and Moon are on the same side of the Earth creating a **spring tide**. This occurs during the new moon phase. A second lower spring tide occurs when the Sun and Moon are on opposite sides of the Earth during the full Moon phase. A **neap tide** results when the Sun and moon are at right angles to the Earth. There are two neap tides, at the first-quarter and second quarter phases of the Moon.

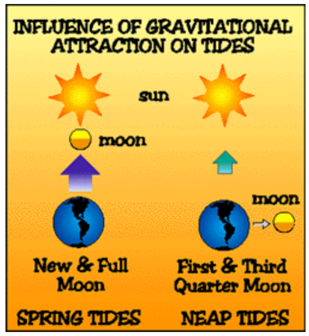


Figure 21.1.5: Spring and neap tides. (Courtesy Naval Meteorology Program and Oceanography Command "Restless Sea")

Located on the northeast end of the Gulf of Maine between New Brunswick and Nova Scotia, the Bay of Fundy is known for its high tidal range, as much as 48 feet (14 meters). Over a 100 billions tons of water passes in and out of the bay every 12 1/2 hours each day. Watch this amazing process occur below.

Video: Bay of Fundy Tides - Halls Harbour, Nova Scotia timelapse (Courtesy: https://www.bayoffundy.com)

21.2: Coastal Landforms and Processes

A ***coast*** or the ***coastal zone*** is a dynamic region where land is sculpted and shaped by wave action and currents. Barring the effects of tectonic uplift and sea level change, erosion is the dominate geomorphic process acting on coasts. Coastal sediments are subject to multiple episodes of erosion, transportation and deposition, though a net seaward transport takes place on a global scale. The deep ocean floor becomes the resting place for terrestrial sediment eroded from the land.

The combined effect of waves, currents and tides result in a variety of gradational processes acting in the coastal zone. Most important is **abrasion**, caused by the scraping or impact of sediment carried by water thrown against shore materials. Breakers are particularly effective at lifting larger rocks and hurling them against the shore.

Hydraulic action caused by the direct impact of waves on the coast can be an effective geomorphic agent. Enormous pressures can build as water and air are compressed into rock fractures. **Solution** is locally important especially where soluble rock is exposed along the shore.

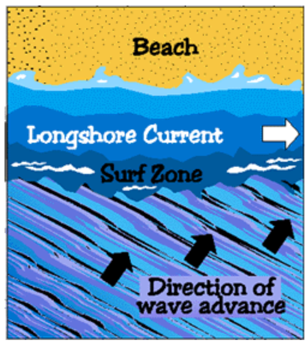


Figure 21.2.1: Longshore current in the surf zone. (Courtesy Naval Meteorology Program and Oceanography Command "Restless Sea")

The water level in the surf zone increases as waves approach shore at an angle. The rising water moves parallel to the shore as a **longshore current. Beach drifting** transports sand grains along the beach as waves strike the shore at an oblique angle. Sediment is carried landward when water rushes across the beach as **swash**. Sediment is carried back toward the ocean as **backwash**. The continual up rush and backwash carries sand in a zig-zag like movement along the shore.

Depositional Coastal Landforms

Beaches

A **beach** is a deposit of loose sediment adjacent to a body of water. Though sand is common to most beaches, a remarkable diversity of sediment size, from boulders to fine silt is found on beaches around the world. Larger particles and steeper slopes are found where wave action is high. Fine particles and gentle slopes are characteristic of beaches exposed to low wave action.

Figure 21.2.2: Black lava beach, Tahiti. (Courtesy NOAA)

Most midlatitude beaches undergo a cycle of erosion and deposition following the seasonal changes in wave action. During the winter, midlatitude storms are more vigorous producing more wave action and erosion. Hence, beaches tend to narrow during the winter. Wave action subsides during the summer as storms weaken somewhat favoring deposition over erosion and producing broader beaches.

Spits and bars

A ***sand spit*** is one of the most common coastal landforms. A sand spit is a linear accumulation of sediment that is attached to land at one end. Sand carried parallel to shore by longshore drift may eventually extend across a bay or between headlands especially where water is relatively calm. Spits are typically elongate, narrow features built to several dozen feet by wind and waves.

Figure 21.2.3: A barrier spit along the South Carolina coast. (Courtesy USGS)

Spits often form when wave energy decreases as a result of wave refraction in a bay. When a coastline turns abruptly, wave energy is dissipated by divergence of wave trajectories, causing sediment to accumulate as the water loses its ability to transport.

Spits can extend across the mouth of a bay, but wave action is usually strong enough to wash sand out to sea or be deposited in the embayment. They may curve into the bay or stretch across connecting to the other side as a ***baymouth bar***. When the bay is closed off by a bar it becomes a ***lagoon***.

Wave energy also dissipates in the lee of large sea stacks or islets. Wave refraction sweeps sediment behind the obstruction from two directions, depositing it as a slender finger called a ***tombolo***.

Barrier Islands

Coastlines paralleled by offshore narrow strips of sand dunes, salt marshes and beaches are known as ***barrier islands***. Barrier island complexes stretch along the southeastern coast of North America from Long Island, New York to the Gulf coast of Texas. Many believe barrier islands originated as offshore bars built by waves breaking on a shallow shore. When waves begin to feel the tug of the ocean floor, they push sand toward shore as they break. The return undertow sweeps sand back to settle on the developing bar. These offshore bars were later exposed when the continent rebounded after ice age glaciers melted.

Figure 21.2.4: Canaveral National Seashore is located along Florida's Central East Coast. The park is situated on a barrier island. (Courtesy NOAA)

Larger barrier islands have been sought as "ideal" places to build vacation homes. Such scenic places are susceptible to the destructive forces of nature such as hurricanes, however. In 1989 Hurricane Hugo hit the U.S. mainland just north of Charleston, South Carolina, with sustained winds of 215 kilometers per hour and a storm surge of more than 6 meters. The barrier islands along the South Carolina coast are generally less than 3 meters above sea level. Most islands were inundated with water and in many places, beaches were severely eroded and dunes were leveled. Much of the sand eroded from the beach was over washed landward or carried offshore. South Carolina suffered $5.9 billion in damage and 29 people died.

Erosional Coastal Landforms

Some of the most spectacular scenery is found along coastlines and produced by the effects of wave erosion. Wave erosion undercuts steep shorelines creating coastal cliffs. A **sea cliff** is a vertical precipice created by waves crashing directly on a steeply inclined slope. Hydraulic action, abrasion, and chemical solution all work to cut a notch at the high water level near the base of the cliff. Constant undercutting and erosion causes the cliffs to retreat landward.

Figure 21.2.5: Sea cliffs with rocky headlands, sea caves, stacks and a pocket beach San Mateo County, California. (Source: USGS Professional Paper 1693)

Sea caves form along lines of weakness in cohesive but well-jointed bedrock. Sea caves are prominent headlands where wave refraction attacks the shore.

Figure 21.2.6: Sea arch and stacks along California coast. (Source: Michael Ritter)

A **sea arch** forms when sea caves merge from opposite sides of a headland. If the arch collapses, a pillar of rock remains behind as a **sea stack**.

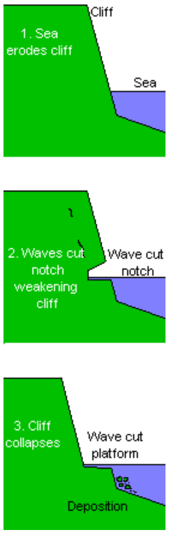


Figure 21.2.7: Development of a wave cut notch. (Source: Wikipedia)

Seaward of the retreating cliffs, wave erosion forms a broad erosional platform called a *wave-cut bench* or **wave-cut platform**. After the constant grinding and battering, eroded material is transported to adjacent bays to become beaches or seaward coming to rest as a **wave-built terrace**. If tectonic forces raise the bench above the water level a marine terrace forms. Some shorelines have several marine terraces creating during various episodes of uplift.

21.3: Types of Coasts

The characteristics of a coast depend on its geologic structure, initial topographic configuration, and shoreline process that shape it. There are several ways and varying scales one can classify these complex systems. ***Submerged coasts*** form when river mouths are flooded due to rising sea level or subsidence of land. A drop in sea level or rise in the land surface creates an ***emergent coast***. ***Depositional coasts*** have abundant depositional features like deltas, bars, spits and reefs where new land has been built. Coral coasts are formed by biological rather than physical processes.

Submerged Coasts

Ria coasts are formed by the submergence of river valleys emptying into the ocean. "Ria" is a Spanish term for coasts with prominent headlands and embayments typical of these coasts. Wave action turns the smooth valley sides into receding cliffs with sand spits and tombolos common. Examples of ria coasts are found in New England and the Atlantic coast of Europe, especially France.

Figure 21.3.1: Kenai Fjord National Park, Alaska. (Courtesy USGS)

Fjord (fiord) coasts are form when glacial troughs are flooded due to a rise in sea level. Fiord coasts are deeply indented, with steep-walled valleys. Sandy beaches are rare as sediment eroded from valley walls collects on the floor. Fjords are common in Scandinavia, British Columbia, Alaska, and Patagonia.

Emergent Coasts

Emergent coasts are a result of forces acting to raise the land surface or drop sea level. The incredible weight of massive ice sheets during the the Pleistocene depressed the continental surfaces beneath them. The continents began to rebound as the ice melted and released the overlying pressure. The rising surface lifted the shoreline above sea level forming **glacial uplift coasts** along continental margins.

Figure 21.3.2: Wave-cut terraces on San Clemente Island, California (Courtesy USGS; Source)

Raised shorelines and erosional features like wave cut terraces are also found along **tectonic coasts** where endogenic forces have uplifted the surface. Such coasts are common along the mountain and island arcs of the Pacific Ocean.

Depositional Coasts

Barrier island coasts are those paralleled by deposits of sand separated from land by a lagoon. There is some controversy over how barrier island coasts form. They begin as offshore bars of submerged sediment that migrate landward unless stabilized. Barrier islands are often cut by tidal inlets, openings that allow water to move landward and seaward with the tides. Barrier islands border the Atlantic coastal plain of North America.

Figure 21.3.3: Birdfoot or Balize delta of the Mississippi River (Courtesy USGS Source: Geomophology From Space)

Delta coasts are those formed by the deposition of sediment at the mouth of a river that enters the ocean. Deposition is caused by the rapid decrease in water velocity as it enters the ocean. Sand and silt are the first to deposit while the mixing of fresh and salt water cause clay particles to bind together forming larger particles that settle to the bottom.

Reefs

Coral is a simple marine animal having a small cylindrical sac-like body called a *polyp* and an exoskeleton of calcium carbonate. As old colonies die new form on top, ultimately forming limestone. There are an estimated 9 million species making it one of the most diverse marine ecosystems. Corals are on the decline in many regions due to human activity.

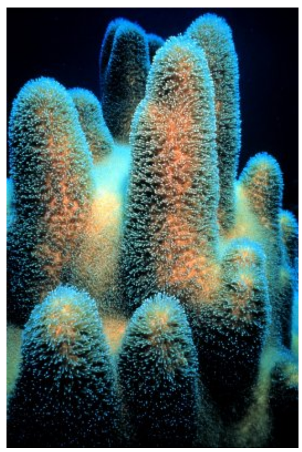


Figure 21.3.4: Pillar coral. (Courtesy NOAA)

Corals thrive in warm tropical water at depths of 10 - 55 m (30 - 18 ft) from about 30^o N to 30^o S. Warm, east coasts encourage their development while few are found in cooler, western coastal environments. Water temperatures range from 18^o to 29^o C (64^o - 85^o F) 27% to 40% salinity. Bleaching and death result when water temperatures rise to high. There are cool water corals found deep, dark ocean water at temperatures as low as 4^o C (39^o F). Corals also require sediment-free water thus few are found near the mouths of rivers discharging in the ocean.

There are three kinds of coral reefs. **Fringing reefs** are platforms of coral attached to land. They tend to be wider where wave action is prominent and the water well aerated. **Barrier reefs** form offshore with lagoon in between. Many form along slowing subsiding islands, growing at a rate that keeps them near sea level. Others form on continental shelves. The largest and one of the most well known is the Great Barrier Reef of Australia at over 2025 km long (1260 m) and 16 - 145 km (10-90 mi) wide. **Atolls** are circular reefs enclosing a lagoon formed from the subsidence and disappearance of a volcanic island cone.

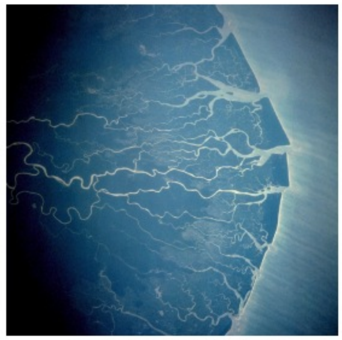
Figure 21.3.5: Triangular atoll in the western Pacific (Courtesy NOAA)

Figure 21.3.6: Great Barrier Reef of Australia (Courtesy NASA/GSFC/LaRC/JPL, MISR Team. Source Visible Earth)

Figure 21.3.7: Fringing reef around Howland Island, Pacific Ocean (Courtesy NASA Astronaut photograph ISS010-E-9287)

21.4: Review and Additional Resources

Review



The fan-shaped Niger River Delta,
the largest delta in Africa.
Courtesy NASA

Figure 21.4.1

Review and assess your learning. Start with the "Important Terms and Concepts" to ensure you know the terminology related to the topic of the chapter and concepts discussed. Move on to the "Review Questions" to answer critical thinking questions about concepts and processes discussed in the chapter. Finally, test your overall understanding by taking the "Self-assessment quiz".

- Important Terms and Concepts (Currently not available)
- Review Questions (Currently not available)
- Self-assessment quiz (Currently not available)

Additional Resources

Use these resources to further explore the world of geography

Connections: "A Dangerous Intersection: Humans and Climate Destroy Reef Ecosystem" *NASA Earth Observatory*

Multimedia

USGS Public Lecture Series: "Hurricanes and Our Changing Coasts" (July, 2009) Description from the site: "In September 2008, Hurricane Ike destroyed nearly every house in the Gulf-front community of Gilchrist, just north of Galveston Texas. In addition to storm surge and battering waves, the land on which the houses were built contributed to the disaster by changing in shape and elevation. Dr. Sallenger will explain how the coast changes during extreme storms—such as Hurricanes Isabel, Katrina, and Ike—and what this means for our coastal developments today and in the future."

"On the Beach" *News Hour with Jim Lehrer* (PBS) August 22, 2003 report on California's coastal erosion problem.

The Sea Floor *The Earth Revealed* (Annenberg/CPB) This segment examines the research submersibles and indirect methods used to study the bottom of the ocean, providing a look at volcanic activity, formations such as the continental shelf and mid-ocean ridges, and life forms living at extreme depths. One-time, free registration may be required to view film. (29:00) Go to the Earth Revealed site and scroll to "The Sea Floor". One-time, free registration may be required to view film.

Conservation Medicine: What the Oceans are Telling Us (WGBH Forum Network) *From the site*: "This talk analyzes how human impacts on the world's oceans have devastated populations, species and ecosystems at a rapid scale, and how methodologies to assess marine ecosystem health are grossly lacking."

Readings

"Amazing Atolls of the Maldives" (NASA Earth Observatory) This report investigates the role of climate and waves in the development of coral reefs that form atolls.

"Shifting Shoals and Shattered Rocks - How Man has Transformed the Floor of West-Central San Francisco Bay" (USGS) 7.9MB

Web Sites

USGS Coastal and Marine Geology Program

Index

A

air mass
8.2: Air Masses
applied classification systems
9.3: Climate Classification

C

clasts
14.5.3: Sedimentary Rocks
climate classification
9.3: Climate Classification
cumulus stage
8.6.1: Thunderstorms

D

deflation
20.1: Eolian Processes
desert lag
20.1: Eolian Processes
desert pavement
20.1: Eolian Processes
desertification
20.1: Eolian Processes
dike
14.5.2: Igneous Rocks
dissipating stage
8.6.1: Thunderstorms
dolomite
14.5.3: Sedimentary Rocks
dunes
20.2: Depositional Forms
dust dome
9.7: Urban Climate
dust storms
20.1: Eolian Processes

E

Erosion
17: Weathering, Erosion, and Mass Movement

G

genetic classification systems
9.3: Climate Classification
greenhouse effect
3.3: Greenhouse Effect

H

humus
11.2: Horizon Development Processes
Hydrologic Cycle
10.2: The Hydrologic Cycle

I

Igneous Rocks
14.5.2: Igneous Rocks

K

Köppen climate classification system
9.3: Climate Classification

L

laccolith
14.5.2: Igneous Rocks

M

magma
14.5.2: Igneous Rocks
mass movement
17: Weathering, Erosion, and Mass Movement
mass wasting
17: Weathering, Erosion, and Mass Movement
minerals
14.4: Minerals
monsoons
9.4.2: Tropical Monsoon Climate

P

pollution plume
9.7: Urban Climate

R

rocks
14.5: Rocks

S

saltation
20.1: Eolian Processes
sand storms
20.1: Eolian Processes
savanna
13.3: Savanna Biome
savanna biome
13.3: Savanna Biome
Sedimentary Rocks
14.5.3: Sedimentary Rocks
sill
14.5.2: Igneous Rocks
soil moisture recharge
10.3.1: Computing a Soil - Moisture Budget
soil profile
11.2: Horizon Development Processes
11.4: Soil Profiles
stratification
14.5.3: Sedimentary Rocks
subarctic cimate
9.6.1: Subarctic Climate

T

thunderstorms
8.6.1: Thunderstorms
tropical monsoon climate
9.4.2: Tropical Monsoon Climate
tropical rain forest
9.4.1: Tropical Rain Forest
13.2.1: Tropical Forests
tropical savanna
13.3: Savanna Biome

U

urban heat island
9.7: Urban Climate

V

ventifacts
20.1: Eolian Processes
volcano
16.1: Features of Volcanoes

W

water cycle
10.2: The Hydrologic Cycle
wave cyclone
8.5: Weather and Wave Cyclones
weathering
17: Weathering, Erosion, and Mass Movement
wind erosion
20.1: Eolian Processes

Glossary

Sample Word 1 | Sample Definition 1

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    - 1.1: Getting Ready for Chapter 1 - *CC BY-SA 4.0*
    - 1.2: The Discipline of Geography - *CC BY-SA 4.0*
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      - 1.4.1: Latitude and Longitude - *CC BY-SA 4.0*
      - 1.4.2: Geographical Zones - *CC BY-SA 4.0*
    - 1.5: Time - *CC BY-SA 4.0*
    - 1.6: Future Geographies - *CC BY-SA 4.0*
    - 1.7: Review and Additional Resources - *CC BY-SA 4.0*
  - 2: The Earth System - *CC BY-SA 4.0*
    - 2.1: The Earth System - *CC BY-SA 4.0*
      - 2.1.1: Birth of the Solar System - *CC BY-SA 4.0*
      - 2.1.2: The Sun - *CC BY-SA 4.0*
      - 2.1.3: Earth Origin - *CC BY-SA 4.0*
      - 2.1.4: Size and Shape - *CC BY-SA 4.0*
      - 2.1.5: The Earth in Space - *CC BY-SA 4.0*
      - 2.1.6: Seasons - *CC BY-SA 4.0*
      - 2.1.7: Day Length and Seasons - *CC BY-SA 4.0*
      - 2.1.8: The Continents - *CC BY-SA 4.0*
      - 2.1.9: The Oceans - *CC BY-SA 4.0*
    - 2.2: Looking Back - The Earth - *CC BY-SA 4.0*
    - 2.3: Natural Systems - *CC BY-SA 4.0*
      - 2.3.1: Components of the Earth System - *CC BY-SA 4.0*
      - 2.3.2: Types of Systems - *CC BY-SA 4.0*
      - 2.3.3: Sources of Energy - *CC BY-SA 4.0*
      - 2.3.4: System Regulation - *CC BY-SA 4.0*
      - 2.3.5: Feedbacks - *CC BY-SA 4.0*
    - 2.4: Looking Back - Natural Systems - *CC BY-SA 4.0*
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      - 2.5.1: Nitrogen Cycle - *CC BY-SA 4.0*
      - 2.5.2: Oxygen Cycle - *CC BY-SA 4.0*
      - 2.5.3: Carbon Cycle - *CC BY-SA 4.0*
      - 2.5.4: The Hydrologic Cycle - *CC BY-SA 4.0*
    - 2.6: Getting Ready for Chapter 2 - *CC BY-SA 4.0*
    - 2.7: Future Geographies- Feedbacks Driving Global Warming and Environmental Change - *CC BY-SA 4.0*
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    - 3.1: Atmospheric Composition - *CC BY-SA 4.0*
    - 3.2: Atmospheric Structure - *CC BY-SA 4.0*
    - 3.3: Greenhouse Effect - *CC BY-SA 4.0*
    - 3.4: Future Geographies - Predicting Atmospheric Composition - *CC BY-SA 4.0*
    - 3.5: Review and Additional Resources - *CC BY-SA 4.0*
    - 3.6: Getting Ready for Chapter 3 - *CC BY-SA 4.0*
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    - 4.1: Energy and Heat - *CC BY-SA 4.0*

- 4.1.1: The Nature of Electromagnetic Radiation - *CC BY-SA 4.0*
- 4.1.2: Radiation as Particles - *CC BY-SA 4.0*
- 4.1.3: Selective Absorption by the Atmosphere - *CC BY-SA 4.0*
- 4.2: Insolation - *CC BY-SA 4.0*
- 4.3: Radiation and Energy Balance of the Earth System - *CC BY-SA 4.0*
  - 4.3.1: The Radiation Balance - *CC BY-SA 4.0*
  - 4.3.2: The Energy Balance - *CC BY-SA 4.0*
- 4.4: Global Patterns of Insolation, Net radiation, and Heat - *CC BY-SA 4.0*
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- 4.6: Global Patterns of Sensible and Latent Heat Transfer - *CC BY-SA 4.0*
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  - 5.2: Controls over Air Temperature - *CC BY-SA 4.0*
  - 5.3: Explaining Patterns of Air Temperature - *CC BY-SA 4.0*
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  - 6.1: Getting Ready for Chapter 6 - *CC BY-SA 4.0*
  - 6.2: Air Pressure - *CC BY-SA 4.0*
  - 6.3: Controls over wind direction and speed - *CC BY-SA 4.0*
  - 6.4: Cyclones and Anticyclones - *CC BY-SA 4.0*
  - 6.5: Local Scale Wind - *CC BY-SA 4.0*
  - 6.6: Regional Scale Winds - The Monsoon - *CC BY-SA 4.0*
  - 6.7: Global Scale Circulation - *CC BY-SA 4.0*
  - 6.8: Wind and Pressure Aloft - *CC BY-SA 4.0*
  - 6.9: Ocean Circulation and Atmospheric Circulation - *CC BY-SA 4.0*
  - 6.10: Future Geographies - Atmospheric Pressure and Winds - *CC BY-SA 4.0*
  - 6.11: Review and Additional Resources - *CC BY-SA 4.0*
- 7: Atmospheric Moisture - *CC BY-SA 4.0*
  - 7.1: Getting Ready for Chapter 7 - *CC BY-SA 4.0*
  - 7.2: Phases of Water - *CC BY-SA 4.0*
    - 7.2.1: Evaporation - *CC BY-SA 4.0*
    - 7.2.2: Transpiration - *CC BY-SA 4.0*
    - 7.2.3: Humidity - *CC BY-SA 4.0*
    - 7.2.4: Condensation - *CC BY-SA 4.0*
  - 7.3: Adiabatic Temperature Change and Stability - *CC BY-SA 4.0*
  - 7.4: Clouds and Precipitation - *CC BY-SA 4.0*
    - 7.4.1: Fog - *CC BY-SA 4.0*
    - 7.4.2: Clouds - *CC BY-SA 4.0*
    - 7.4.3: Precipitation Process - *CC BY-SA 4.0*
  - 7.5: Global Patterns of Precipitation - *CC BY-SA 4.0*
    - 7.5.1: The Equator to the Subtropics - *CC BY-SA 4.0*
    - 7.5.2: Midlatitudes to the Poles - *CC BY-SA 4.0*
  - 7.6: Future Geographies - Global Precipitation Patterns - *CC BY-SA 4.0*
  - 7.7: Looking Ahead - *CC BY-SA 4.0*
  - 7.8: Review and Additional Resources - *CC BY-SA 4.0*
- 8: Weather Systems - *CC BY-SA 4.0*
  - 8.1: Getting Ready for Chapter 8 - *CC BY-SA 4.0*
  - 8.2: Air Masses - *CC BY-SA 4.0*
  - 8.3: Fronts - *CC BY-SA 4.0*
  - 8.4: Wave Cyclones (Cyclogenesis) - *CC BY-SA 4.0*
  - 8.5: Weather and Wave Cyclones - *CC BY-SA 4.0*
  - 8.6: Severe Weather - *CC BY-SA 4.0*
    - 8.6.1: Thunderstorms - *CC BY-SA 4.0*
    - 8.6.2: Lightning - *CC BY-SA 4.0*
    - 8.6.3: Tornadoes - *CC BY-SA 4.0*
    - 8.6.4: Hurricanes - *CC BY-SA 4.0*
  - 8.7: Future Geographies - Severe Weather and Global Warming - *CC BY-SA 4.0*
  - 8.8: Review and Additional Resources - *CC BY-SA 4.0*
- 9: Climate Systems - *CC BY-SA 4.0*
  - 9.1: Getting Ready for Chapter 9 - *CC BY-SA 4.0*
  - 9.2: The Elements of Climate - *CC BY-SA 4.0*
  - 9.3: Climate Classification - *CC BY-SA 4.0*
  - 9.4: Low Latitude Climates - *CC BY-SA 4.0*
    - 9.4.1: Tropical Rain Forest - *CC BY-SA 4.0*
    - 9.4.2: Tropical Monsoon Climate - *CC BY-SA 4.0*
    - 9.4.3: Tropical Wet/Dry (Savanna) Climate - *CC BY-SA 4.0*
    - 9.4.4: Tropical Steppe Climate - *CC BY-SA 4.0*
    - 9.4.5: Tropical Desert Climate - *CC BY-SA 4.0*
  - 9.5: Midlatitude and Subtropical Climates - *CC BY-SA 4.0*
    - 9.5.1: Mediterranean or Dry Summer Subtropical Climate - *CC BY-SA 4.0*
    - 9.5.2: Midlatitude Desert Climate - *CC BY-SA 4.0*
    - 9.5.3: Midlatitude Steppe - *CC BY-SA 4.0*

- 9.5.4: Humid Subtropical Climate - *CC BY-SA 4.0*
- 9.5.5: Humid Continental Climate - *CC BY-SA 4.0*
- 9.5.6: Marine (Humid) West Coast Climate - *CC BY-SA 4.0*
- 9.6: High Latitude Climates - *CC BY-SA 4.0*
  - 9.6.1: Subarctic Climate - *CC BY-SA 4.0*
  - 9.6.2: Tundra Climate - *CC BY-SA 4.0*
  - 9.6.3: Ice Cap Climate - *CC BY-SA 4.0*
- 9.7: Urban Climate - *CC BY-SA 4.0*
- 9.8: Future Geographies - The Evidence for Climate Change - *CC BY-SA 4.0*
- 9.9: Review and Additional Resources - *CC BY-SA 4.0*
- 10: The Hydrosphere - *CC BY-SA 4.0*
  - 10.1: The Hydrosphere - *CC BY-SA 4.0*
  - 10.2: The Hydrologic Cycle - *CC BY-SA 4.0*
  - 10.3: The Water Balance - *CC BY-SA 4.0*
    - 10.3.1: Computing a Soil - Moisture Budget - *CC BY-SA 4.0*
    - 10.3.2: Soil Moisture Seasons - *CC BY-SA 4.0*
  - 10.4: Future Geographies - Water Resources and Climate Change - *CC BY-SA 4.0*
  - 10.5: Review and Additional Resources - *CC BY-SA 4.0*
- 11: Soil Systems - *CC BY-SA 4.0*
  - 11.1: Soil Development - *CC BY-SA 4.0*
  - 11.2: Horizon Development Processes - *CC BY-SA 4.0*
  - 11.3: Soil Properties - *CC BY-SA 4.0*
  - 11.4: Soil Profiles - *CC BY-SA 4.0*
  - 11.5: Factors Affecting Soil Development - *CC BY-SA 4.0*
  - 11.6: Soil Forming (Pedogenic) Processes - *CC BY-SA 4.0*
  - 11.7: Soil Orders - *CC BY-SA 4.0*
  - 11.8: Review and Additional Resources - *CC BY-SA 4.0*
- 12: Biogeography of the Earth - *CC BY-SA 4.0*
  - 12.1: Fundamentals of Biogeography and Ecology - *CC BY-SA 4.0*
    - 12.1.1: Biogeography and ecological systems - *CC BY-SA 4.0*
    - 12.1.2: Habitat Occupation - *CC BY-SA 4.0*
    - 12.1.3: Principle of Limiting Factors - *CC BY-SA 4.0*
  - 12.2: Ecology of Vegetation and Plant Succession - *CC BY-SA 4.0*
  - 12.3: Energy Flow Through Ecosystems - *CC BY-SA 4.0*
  - 12.4: Review and Additional Resources - *CC BY-SA 4.0*
- 13: Earth Biomes - *CC BY-SA 4.0*
  - 13.1: Patterns of the Biosphere - *CC BY-SA 4.0*
  - 13.2: The Forest Biome - *CC BY-SA 4.0*
    - 13.2.1: Tropical Forests - *CC BY-SA 4.0*
    - 13.2.2: Midlatitude Forests - *CC BY-SA 4.0*
    - 13.2.3: Northern Forests - *CC BY-SA 4.0*
  - 13.3: Savanna Biome - *CC BY-SA 4.0*
  - 13.4: Grassland Biome - *CC BY-SA 4.0*
  - 13.5: The Desert Biome - *CC BY-SA 4.0*
  - 13.6: Tundra Biome - *CC BY-SA 4.0*
  - 13.7: Review and Additional Resources - *CC BY-SA 4.0*
- 14: Earth Materials and Structure - *CC BY-SA 4.0*
  - 14.1: The Earth's Interior - *CC BY-SA 4.0*
  - 14.2: Forces that Shape the Surface of the Earth - *CC BY-SA 4.0*
  - 14.3: Orders of Relief - *CC BY-SA 4.0*
  - 14.4: Minerals - *CC BY-SA 4.0*
  - 14.5: Rocks - *CC BY-SA 4.0*
    - 14.5.1: Rocks and the Rock Cycle - *CC BY-SA 4.0*
    - 14.5.2: Igneous Rocks - *CC BY-SA 4.0*
    - 14.5.3: Sedimentary Rocks - *CC BY-SA 4.0*
    - 14.5.4: Metamorphic Rocks - *CC BY-SA 4.0*
  - 14.6: Review and Additional Resources - *CC BY-SA 4.0*
- 15: Tectonics and Landforms - *CC BY-SA 4.0*
  - 15.1: Plate Tectonics and Continental Drift - *CC BY-SA 4.0*
  - 15.2: Plate Boundaries - *CC BY-SA 4.0*
  - 15.3: Crustal Deformation - *CC BY-SA 4.0*
    - 15.3.1: Folding and Faulting - *CC BY-SA 4.0*
    - 15.3.2: Types and Geographic Patterns of Faults - *CC BY-SA 4.0*
    - 15.3.3: Tsunamis - *CC BY-SA 4.0*
  - 15.4: Review and Additional Resources - *CC BY-SA 4.0*
- 16: Volcanic Processes and Landforms - *CC BY-SA 4.0*
  - 16.1: Features of Volcanoes - *CC BY-SA 4.0*
  - 16.2: Distribution of Volcanoes - *CC BY-SA 4.0*
  - 16.3: Types of Volcanoes and Landscapes - *CC BY-SA 4.0*
  - 16.4: Volcanic Hazards - *CC BY-SA 4.0*
  - 16.5: Review and Additional Resources - *CC BY-SA 4.0*
- 17: Weathering, Erosion, and Mass Movement - *CC BY-SA 4.0*
  - 17.1: Weathering - *CC BY-SA 4.0*

- 17.2: Mass Movement - *CC BY-SA 4.0*
- 17.3: Water Erosion - *CC BY-SA 4.0*
- 17.4: Review and Additional Resources - *CC BY-SA 4.0*

- 18: Fluvial Systems - *CC BY-SA 4.0*
  - 18.1: The Stream System - *CC BY-SA 4.0*
  - 18.2: Channel Geometry and Flow Characteristics - *CC BY-SA 4.0*
  - 18.3: Geologic Work of Streams - *CC BY-SA 4.0*
  - 18.4: Stream Gradation - *CC BY-SA 4.0*
  - 18.5: Landforms of Alluvial Rivers - *CC BY-SA 4.0*
  - 18.6: Fluvial Processes in Dry Regions - *CC BY-SA 4.0*
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- 19: Glacial Systems - *CC BY-SA 4.0*
  - 19.1: Glaciation - *CC BY-SA 4.0*
  - 19.2: Geologic Work of Glaciers - *CC BY-SA 4.0*
  - 19.3: Landforms of Continental Glaciation - *CC BY-SA 4.0*
  - 19.4: Landforms of Alpine Glaciation - *CC BY-SA 4.0*
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- 20: Eolian Systems - *CC BY-SA 4.0*
  - 20.1: Eolian Processes - *CC BY-SA 4.0*
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  - 20.3: Review and Additional Resources - *CC BY-SA 4.0*
- 21: Ocean and Coastal Systems - *CC BY-SA 4.0*
  - 21.1: Water in Motion - *CC BY-SA 4.0*
  - 21.2: Coastal Landforms and Processes - *CC BY-SA 4.0*
  - 21.3: Types of Coasts - *CC BY-SA 4.0*
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