Chapter 10 The Atmosphere of Earth

Learning outcomes

1) Understanding the composition of atmosphere

2) How many layers and the properties of each layers and applications

3) Understand Characteristic for each layer

4) Protective role of atmosphere

Related Vocabularies:

Ozone; smog; troposphere; stratosphere; mesosphere; thermosphere and exosphere

10.1 **The evolution of atmosphere:**

Scientists' research shows that in the early days of the formation of Earth about 4.6 billion years ago, the surface temperature of Earth was very high such that there was virtually no atmosphere. As surface temperatures gradually cooled, the atmosphere slowly formed on Earth over time which is called the primitive atmosphere, mainly composed of ammonia, water vapor, carbon dioxide and methane. As the Earth continued to cool, much of the water vapor in original atmosphere began to condense into water. At the same time, the water steam in the upper level of atmosphere was exposed to ultraviolet radiation from the sun at high altitudes and was decomposed into hydrogen and oxygen. Most of the hydrogen escaped from Earth into space, while the heavier oxygen atoms combined to form oxygen components although the portion of oxygen in Earth's early atmosphere was very small. About 2.9 billion years ago, photosynthesis of large amounts of algae gradually increased the oxygen content in the atmosphere in which oxygen molecules were decomposed into oxygen atoms by ultraviolet radiation. Then, a single oxygen atom combined with other oxygen molecules to form Ozone. As ozone increased in the upper atmosphere, the ozone layer gradually formed and then reached the ground through the atmosphere, which reduces UV rays to save life on Earth from the damage of overdose UV radiation. At the beginning, most of life only could live in the ocean and gradually transitioned on land thanks to the protection of Ozone layer. With the increase in plants on land of earth, more photosynthesis produces the large amount of oxygen in the atmosphere, which allowed Earth to be more inhabitable for various of life. Currently, the oxygen on Earth accounts for about 21% of the atmosphere with suitable oxygen concentration for all living things on Earth including humans. The atmosphere is a mixture of gases that surrounds Earth. It helps make life possible by providing us with air to breathe, shielding us from harmful ultraviolet (UV) radiation coming from Sun, trapping heat to warm the planet, and preventing extreme temperature differences between day and night. Without the atmosphere, temperatures would be well below freezing everywhere on Earth's surface. Instead, the heat absorbed and trapped by our atmosphere keeps our planet's average surface temperature at about 15°C (59°F). Some of the atmosphere's gases, like carbon dioxide, are particularly good at absorbing and trapping radiation. Changes in the amounts of these gases directly affect our climate.

Since the Industrial Revolution, global atmospheric carbon dioxide concentrations have risen to 120 ppm (1 ppm is one part per million), due to humanity's overexploitation of fossil fuels. In March 2015, the global average concentration of atmospheric carbon dioxide exceeds 400 ppm, for the first time reaching this record high value. Increased emissions of greenhouse gases such as carbon dioxide are one of the causes of global warming.

10.2 The composition of atmosphere:

The air surrounding Earth is called the atmosphere. The atmosphere is important for life on earth and all activities of human beings. Humans live at the bottom of the atmosphere. The physical state and composition of the atmosphere and changes in ingredients affect the entire human beings all the time. The composition of the atmosphere is the result of the long evolution of the earth. It changes rapidly in a short period of time.

The atmosphere is a mixture of gases as shown in Figure 10.1. The lower atmosphere is mainly composed of three parts: dry clean air, water vapor and impurities. The main components of dry air are nitrogen and oxygen. The volume fractions of nitrogen and oxygen are approximately 78% and 20.9% respectively, and the two together account for about 99%. Nitrogen is an essential component of living organisms on Earth. At the normal conditions, two Nitrogen together forms N_2, a colorless and odorless diatomic gas taking up about 78% of Earth's atmosphere, make it the most abundant component in air. Because of the volatility of nitrogen compounds, nitrogen is relatively rare in the solid parts of the Earth. Relatively speaking, Oxygen is an abundant element after hydrogen and helium, it is the third-most abundant element in the universe. At the normal pressure and temperature, two oxygen atoms bind to form dioxygen O_2 a colorless and odorless diatomic gas, which accounts for 20.9% of Earth's atmosphere. Oxygen is aerobic for humans and other organisms to maintain life activities, also participating in the combustion of burning, putrefaction and decomposition processes.

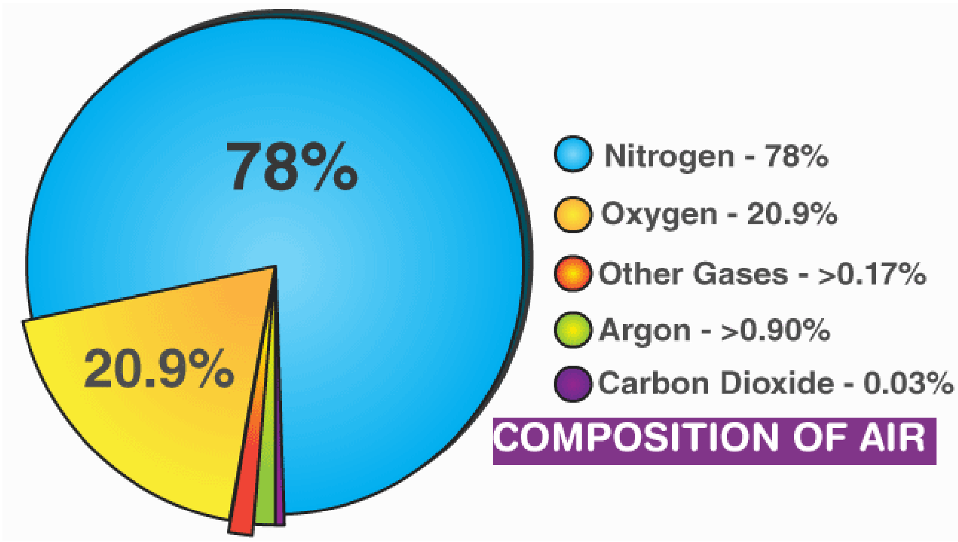

Figure 10.1 Composition of air, adapted from https://byjus.com/physics/air-composition-properties/

Although the amounts of Carbon dioxide and ozone in the atmosphere are small, they play an important role in the natural environment and life activities. Carbon dioxide is the basic raw material for photosynthesis of green plants and plays a role in keeping the ground warm. In Earth's atmosphere, carbon dioxide is an essential constituent forming greenhouse gases, that cause the greenhouse effect (the global warming). At the same time, carbon dioxide plays an important part in carbon cycle, photosynthesis and oceanic carbon cycle. Due to the human activities, the current global average concentration of CO_2 in the atmosphere is 421 ppm as of May 2022 (0.04%), which has increased of 50% since the start of the Industrial Revolution, up from 280 ppm during the 10,000 years prior to the mid-18th century.

Ozone can be powerful in absorbing ultraviolet rays from the sun because the ozone layer protects life on earth from excessive ultraviolet rays. The small number of ultraviolet rays that penetrate the atmosphere and reach the ground also has a sterilizing effect. Dioxygen by the influence of ultraviolet (UV) light and electrical discharges within the Earth's atmosphere forms Ozone, a pale blue gas with a distinctively pungent smell. It is very low in concentrations there, with its highest concentration in the ozone layer of the stratosphere for absorbing most of the Sun's ultraviolet (UV) radiation.

Water vapor is another constituent in Earth's atmosphere, which is the gaseous phase of water produced from the evaporation or boiling of liquid water or from sublimation of ice. Water vapor is transparent, less dense than most of the other constituents of air, which produces convection currents that results in clouds and fog. Horizontally, the water vapor content in the atmosphere is higher over the ocean than over the land. In the vertical direction, the water vapor content is higher above humid areas than over dry areas. Generally, from the ground to the high space, the water vapor content gradually decreases. The impurity content in the atmosphere changes with time, location, and weather conditions. Generally, the near-surface atmosphere has more impure content over land than over sea; more over cities than over rural areas, more in summer than in winter. Although the water vapor and impurities in the atmosphere are very small, they affect weather changes significantly. Within the range of atmospheric temperature, water vapor can transform into three states: gas, liquid, and solid, resulting in a series of weather phenomena such as clouds, fog (as shown in Figure 10.2), rain (as indicated in Figure 10.3), snow (as demonstrated in Figure 10.4), etc. If there is more impurities in atmosphere which can reduce atmospheric visibility, however, impurities also act as condensation nuclei necessary for cloud formation and rain.

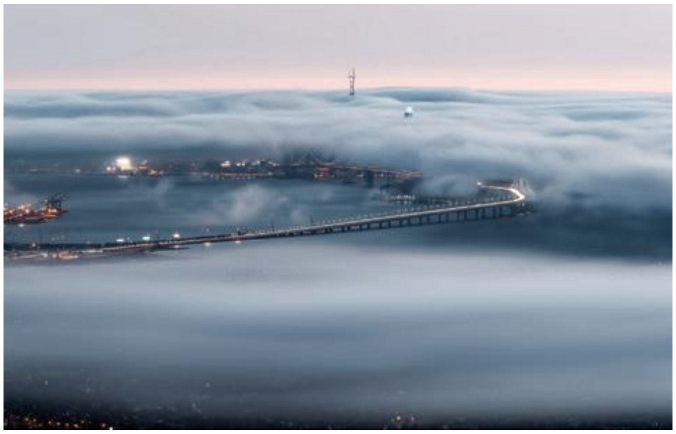

Figure 10.2 Foggy atmosphere hovering above the city of San Francisco, adapted from https://rove.me/to/san-francisco/fogs

Figure 10.3 A rainy day in the city of Seattle, adapted from https://www.seattletimes.com/seattle-news/weather/extreme-rainstorms-becoming-more-common-in-seattle-says-city-meteorologist/

Figure 10.4 Heavy snow in the city of Detroit, adapted from https://www.metrotimes.com/arts/sick-of-winter-in-detroit-good-thing-you-didnt-live-here-137-years-ago-8941464

Smog is a combination of fog and haze. In many areas around the world, particularly in those developing countries, smog as a disastrous weather phenomenon results from fog, which is merged into haze. In fact, fog and haze are two completely different weather phenomena although they are Indistinguishable to the naked eye and both of them can appear at any time of the day. When the content of water vapor in the air is more than the saturated amount under certain temperature conditions, along with the presence of nuclei, excess water vapor condenses out and turns into small water droplets or ice crystals. Condensation of suspended water vapor in the atmosphere is called fog in meteorology. Fog could reduce horizontal visibility to less than 1 km. Haze, also known as "haze", is a collection of large amounts of tiny dust particles, soot particles or salt particles suspended in the atmosphere. The particles that make up haze are extremely small. Haze is one of consequences of air pollution. A haze phenomenon that makes the air turbid reduces horizontal visibility to less than 10 kilometers as shown in Figure 10.5. A Haze can be caused by various suspended particulates in the atmosphere, among which PM2.5 (particles with a diameter less than or equal to 2.5 microns) is considered to be the primary "culprit" of haze.

Figure 10.5 A haze day in India, adapted from https://www.gulftoday.ae/lifestyle/2020/11/15/northern-india-chokes-on-toxic-air-day-after-diwali-festival

10.3 Vertical stratification of the atmosphere:

From the ground upward, as the height increases, the atmosphere becomes thinner and thinner, and the air pressure gets lower and lower. The upper boundary of the atmosphere can extend to 2,000 to 3,000 kilometers high above the ground. According to the physical properties and movement conditions of the atmosphere in the vertical direction, the atmosphere can be divided into troposphere, stratosphere, mesosphere, thermosphere and exosphere. The last three layers together are also called as the upper atmosphere.

Troposphere

The troposphere is the lowest layer of Earth’s atmosphere as shown in Figure 10.6. It is the layer with the highest pressure and density in the atmosphere. The height of the top of the troposphere varies among different latitudes. Even in the same area, during different seasons, the height also varies slightly. Generally, the height of the top of the troposphere in the equatorial region is 17 to 18 kilometers, 10 to 12 kilometers in mid-latitude areas, and 8 to 9 kilometers in high latitudes areas. In the same region, the height of the top of the troposphere is slightly higher in summer than that in winter. About 3/4 of total amount of air is concentrated in the troposphere with almost all water vapor. The tropospheric atmosphere mainly absorbs heat from the ground and transfers it to the upper layer atmosphere, so the air temperature in the troposphere decreases while altitude increases, which explains the upper part of the troposphere is cold and the lower part is warmer. The heat is transferred through convection. The convection is the rising movement of large group of warmer water molecules along with the sinking movement of a large group of cold-water molecules transferring heat. During the hear transferring movement, clouds, rain, snow and other weather phenomena easily occur.

10.6 Troposphere adapted from https://spaceplace.nasa.gov/troposphere/en/

In the troposphere, air temperature generally decreases with altitude increasing, but sometimes there is a phenomenon where the temperature increases with altitude increasing, which is called an inversion. The atmosphere where temperature inversion occurs is called an inversion layer. Usually on a clear, windless or breezy night, the ground cools due to radiation. The temperature of the atmosphere close to the ground cools relatively quickly, while the air in the upper layers cools relatively slowly, then the inversion phenomenon of "hot at the top and cold at the bottom" occurs, forming an inversion layer. As the temperature near the ground increases after sunrise, the temperature inversion phenomenon gradually disappears. In the inversion layer, the atmosphere tends to be stable and convective movements are less likely to occur. Water vapor, suspended particles and various harmful substances in the air near the ground, tend to accumulate in the atmosphere below the inversion layer, often causing atmospheric pollution, which reduces air quality.

Stratosphere

10.7 stratosphere adapted from https://en.wikipedia.org/wiki/Stratosphere

The stratosphere is the second layer of the atmosphere right above the troposphere, spreading up from the top of the troposphere to about 50 kilometers above the ground. It is an ideal layer for flying aircraft as shown in Figure 10.7. Unlike the troposphere which is very turbulent due to the presence of convection currents, the stratosphere is very stable and calm because of a lack of any vertical air currents flowing from the warmer (lower) layer to the colder (upper) layer, attributed to temperature inversion which leads to no or little flow of vertical air current upwards. The atmospheric pressure at the top is only about 1/1000 of that at sea level. There is an ozone layer in the stratosphere, which is composed of high concentrations of about 90% ozone (Chemically written as O_3), formed by the effect of the sun's rays on oxygen in the stratosphere. Ozone is important as it absorbs harmful ultraviolet rays of the sun. Ultraviolet rays destroy human cells and are harmful to life on earth. Thus, stratosphere supports life on the earth. The ozone layer is very important because it absorbs most of harmful ultraviolet rays that enter the atmosphere as the ultraviolet rays could damage human cells and very detrimental to life on Earth. Therefore, the stratosphere supports life on Earth as well. Due to absorption of ultraviolet rays by the ozone layer, temperature inversion is caused in the stratosphere that explains the temperature increases with increasing altitude in this stratosphere. Therefore, in the stratosphere the atmosphere is hot at the top and cold at the bottom, in which advection dominates the heat transfer. At the same time, stratospheric water vapor and the dust content is relatively low and the air is relatively stable, making it suitable for aircraft to fly in this layer with high altitudes. In all, the stratosphere is very critical to the survival of humans and very important for the jet aircrafts.

Mesosphere

The next layer, the mesosphere, is located in the region of the upper atmosphere directly above the stratosphere and below the thermosphere extending from about 50 and 80 km (30 and 50 miles) above our planet. It is the coldest layer because there are almost no air molecules to absorb heat energy. Because temperature drops with increasing altitudes in the mesosphere, the coldest temperatures about -90° C (-130° F), are near the top of this layer. There are so few molecules for light to refract off such that the sky also changes from blue to black in this layer. The composition of oxygen, nitrogen, and carbon dioxide in the air in the mesosphere is technically identical to that in the troposphere. The only difference is that there is much less air and very little water vapor in the mesosphere, and higher percentages of ozone than the lower levels. In spite of thinner air, there is certain vertical movement in the mesosphere as a result of absorbing heat from Sun. There is very little radiation and the temperature is very low, very scarce water vapor can rise in this layer.

Sometimes, stratosphere and mesosphere together are called the middle atmosphere. Air comprising of different types of atoms and molecules is a mixture by turbulence at the top of the mesosphere (called mesopause) and below. Above the mesosphere in the thermosphere, air particles collide so violently that they have different chemical elements than they are close to Earth. There are numerous air movements influencing the mesosphere, which carry energy from the troposphere and the stratosphere upward into the mesosphere, leading to the global circulation.

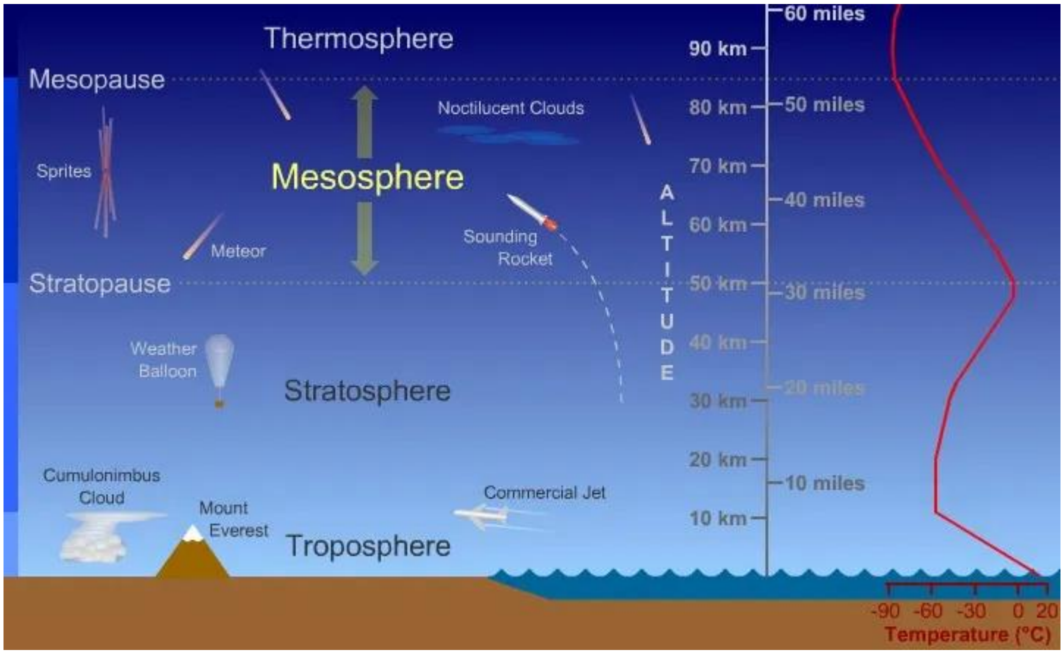

Figure 10.8 Mesosphere adapted from https://scied.ucar.edu/learning-zone/atmosphere/mesosphere

Thermosphere

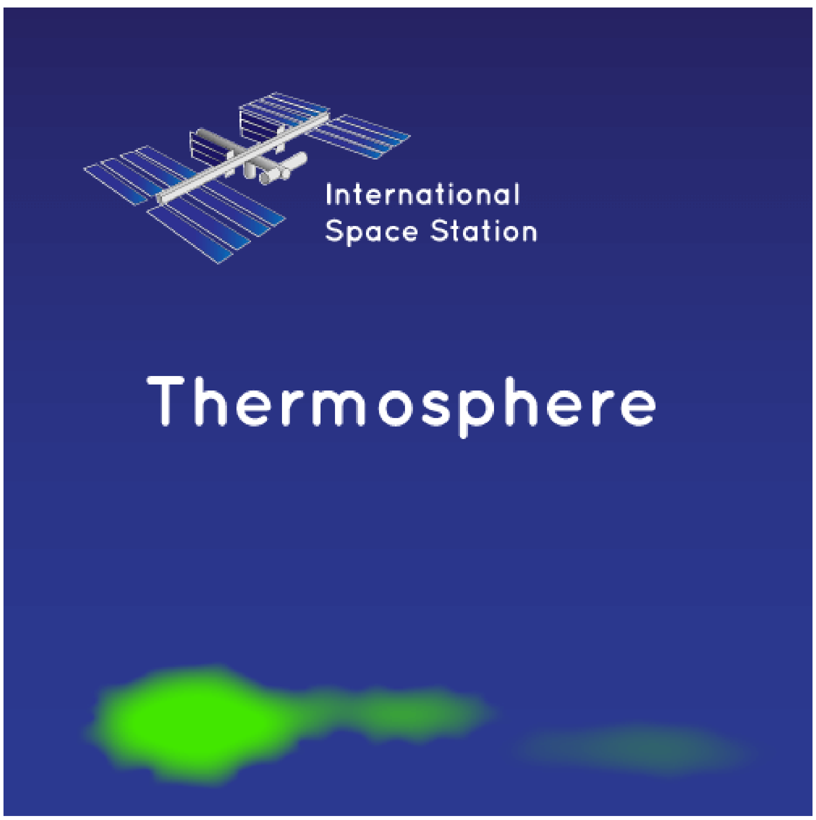

Figure 10.9 Thermosphere adapted from https://spaceplace.nasa.gov/thermosphere/en/.

Between the exosphere and the mesosphere lie the thermosphere, also called ionosphere. “Thermo” means heat. The temperature increases with altitude. This layer of air absorbs large amounts of solar ultraviolet rays. According to satellite data, the thermosphere begins from 80 to 160 kilometers, and the air heats up dramatically. The temperature increases by 970°C within 80 kilometers. The temperature reaches as high as 1027°C at 250 kilometers and as high as 1201°C at 500 kilometers. But from above 500 kilometers, the temperature does not change much. The sharp increase in temperature is due to the absorption of solar ultraviolet radiation with a wavelength less than 0.175 microns by the warm layer. The thickness of the thermosphere is about 319 miles (513 kilometers) which is much thicker than the inner layers of the atmosphere, but not nearly as thick as the exosphere. The air in the thermosphere above 80 kilometers is very thin. Ultraviolet rays and X-rays in sunlight can ionize air molecules. Free electrons can move freely for a short time before merging with positively charged ions. In this way, at this altitude plasma can be created. As one of 4 states of matter, gas, liquid, solid and plasma, Plasma is electrically charged gas, composed of the number of electrically charged particles, which are affected by electrical and magnetic fields. In turn, those charges impact the propagation of radio waves.

In the ionosphere, sunlight ionizing atmospheric molecules is balanced by the process by which ions recapture free electrons. Generally speaking, the higher the altitude and the thinner the atmosphere, the more dominant the ionization process will be. However, the properties of the ionosphere are also affected by many other factors. The main force in the ionization process is solar activity. The degree of ionization in the ionosphere is mainly affected by the solar radiation received. The ionosphere therefore changes with the day of the week and the season (in winter the sunlight is at a lower angle, so less radiation is received). Solar activity varies primarily with the sunspot cycle. Generally speaking, the more sunspots on the surface of the sun, the more intense the solar activity. In addition, the intensity of solar radiation received by the local area varies with the latitude of the earth's surface. Charged particles in flares and solar winds can interact with Earth's magnetic field, causing disturbances in the ionosphere.

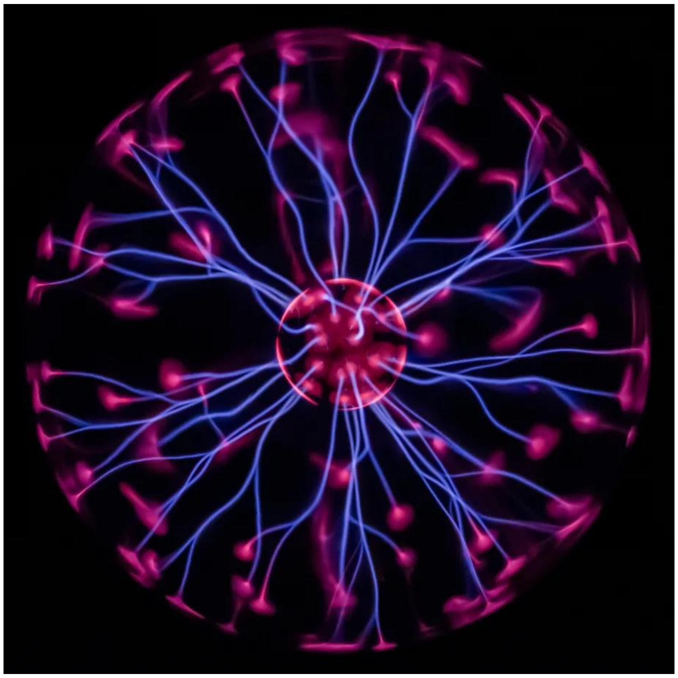

Figure 10.10 plasma, adapted from https://scied.ucar.edu/learning-zone/sun-space-weather/plasma

Since the air density is very small, under the action of solar ultraviolet rays and cosmic rays, oxygen molecules and nitrogen molecules are decomposed into atoms and are in an ionized state. Therefore, there are a large number of charged particles in the thermosphere (warm layer) - charged Ions and electrons have the ability to reflect radio waves. The stronger the degree of ionization, the stronger the ability to reflect radio waves. Without this layer, radio waves cannot be transmitted over long distances.

Some studies have shown that the temporary contraction of the thermosphere is related to the dramatic decline in solar ultraviolet radiation. Major changes in solar energy output will cause drastic changes in the Earth's outer atmosphere. The discovery is important for orbiting satellites as well as space stations. The reduced thickness and density of the thermosphere means that it is easier for satellites to stay in their orbit, but at the same time, the damage to satellites could be caused by debris and other objects in space. In addition, the ionosphere has the ability to reflect radio waves, and humans can use it to spread radio signals communications, broadcasting and global navigation systems.

Exosphere

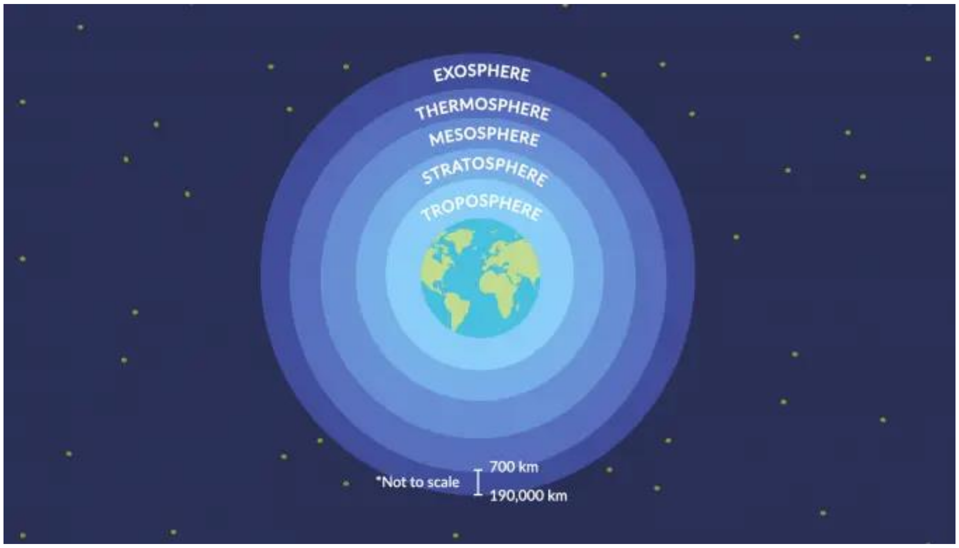

Figure 10.10 Exosphere, adapted from https://earthhow.com/exosphere/.

The exosphere is the outermost layer of the Earth's atmosphere, and its temperature increases slightly with height rising. Compared with the troposphere where we live, the air in the exosphere is extremely thin. Gas molecules can "travel" hundreds of kilometers without colliding with each other.

The lower boundary of the exosphere is more than 800km from the surface, while the top boundary is about 2000-3000km in altitude. This can also be regarded as the upper boundary of the earth's atmosphere. Due to the high temperature and high velocity of air particles, and being too far away from the center of the earth leading to the extremely small gravity of the earth in this layer, the main feature of atmospheric particles is that they often escape into interstellar space. As there no gravity holding them, gases and particles keep on escape into space. Therefore, the density of the atmosphere is very close to that of the interstellar atmosphere, and the mass of this layer of atmosphere is only 10-11 of the total mass of the atmosphere. The earth's atmosphere gradually transitions to interstellar space in this layer, and the geocorona also exists in this layer.

The temperature in the exosphere is extremely high, and the temperature is distributed vertically from low to high, and increases with altitude. The principle of high temperature in the exosphere is the same as that in the thermosphere. Atmospheric molecules are heated by absorbing short-wave radiation from the sun. But because the density of the atmosphere in the exosphere is so low that people don't feel any warmth, which is beyond an ordinary thermometer which only could measure below zero degrees Celsius.

Spacecrafts such as satellites and rockets could be operated in the exosphere. Atmospheric resistance is basically negligible due to extremely low air density.

10.4 **The atmospheric heating process**

The colorful light or clouds appears in the sky before and after sunrise or sunset, caused by the sunlight near the horizon passing through the atmosphere. Sun light get scattered by dust, water vapor and air molecules to form colorful light. At sunrise and sunset, the sun's rays pass through the longer distance in the air than that at noon, more blue and purple light are scattered than red light and orange light from the sun as shown in the figure 10.11.

Figure 10.12 sunrise image, adapted from https://www.noaa.gov/jetstream/clouds/color-of-clouds

Weakening solar radiation by the atmosphere

Solar radiation has to pass through the thick atmosphere to reach the earth's surface. Due to the atmosphere's impact on the sun light reflection, scattering and absorption of radiation, the solar radiation projected to the upper boundary of the atmosphere cannot completely reach the surface of Earth. Clouds and larger particles of dust in the atmosphere can deflect the solar radiation as well. Part of the radiation is reflected back into space. For instance, the reflection of clouds is the most significant. When the lower and thicker the clouds are, the stronger the reflection is. When the sky is cloudy in summer, the daytime temperature is relatively not be too high because the reflection of clouds reduces the solar radiation reaching the ground. The atmosphere's reflection of solar radiation is not selective, so the reflected light appears white. When solar radiation encounters air molecules or tiny dust particles in the atmosphere, solar radiation are centered on these particles and get dispersed in all directions. This phenomenon is called the atmosphere scattering. Scattering changes, the direction of solar radiation so that part of the solar radiation cannot reach the ground. Among the visible lights of solar radiation, blue light and violet light have shorter wavelengths and are easily scattered by air molecules, causing a clear sky to appear blue as shown in Figure 10.13.

The atmosphere's absorption of solar radiation is selective. Ozone in the stratospheric atmosphere mainly absorbs the shorter wavelength light like ultraviolet rays in solar radiation. Water vapor, oxygen, and carbon dioxide etc. in the tropospheric atmosphere primarily absorb the longer wavelength infrared rays in solar radiation. In the atmospheric solar radiation, visible light with the strongest energy is absorbed very little, and most of the visible light can be emitted through the atmosphere, not reach the ground. In other words, only a small part of the solar radiation is directly absorbed by the atmosphere. Therefore, solar radiation is not the main direct heat source for the ground, which especially is the case in the tropospheric atmosphere.

The reflection, scattering and absorption of solar radiation by the atmosphere weakens the ability of solar radiation to reach the ground. Once the solar radiation reaches the ground, the amount of solar radiation is not uniformly distributed, decreasing from low latitudes to the two poles. The higher of the sun in low latitudes is, and the shorter distance that solar radiation travels through the atmosphere, such that the solar radiation is not weakened by the atmosphere and more solar radiation reaches the ground; While the situation in the polar regions is the opposite.

10.13 image of blue sky adapted from https://www.worldatlas.com/articles/why-is-the-sky-blue.html

The thermal insulation effect of the atmosphere

The ground absorbs solar radiation that passes through the atmosphere, which in turn heats up the ground. At the same time the ground releases radiant energy into the atmosphere to form ground radiation. As confirmed by experiments, the higher the temperature of an object, the shorter the wavelength of the strongest part of the radiation will radiate; conversely, the lower the temperature of an object, the longer wavelength it emits. Due to the fact that the temperature of the ground is much lower than that of the sun, so the wavelength of ground radiation is much longer than that of solar radiation, and the amount its energy is mainly concentrated in the infrared part. Usually, solar radiation is called shortwave radiation, while ground radiation is called longwave radiation as shown in Figure 10.14.

Water vapor and carbon dioxide in the tropospheric atmosphere can strongly absorb ground radiation except for a very small part of the energy released by ground radiation returning to space through the atmosphere. Most of ground radiation (75% to 95%) is trapped in the tropospheric atmosphere, warming the atmosphere. So, it is believed that the ground radiation is the main direct heat source of the tropospheric atmosphere.

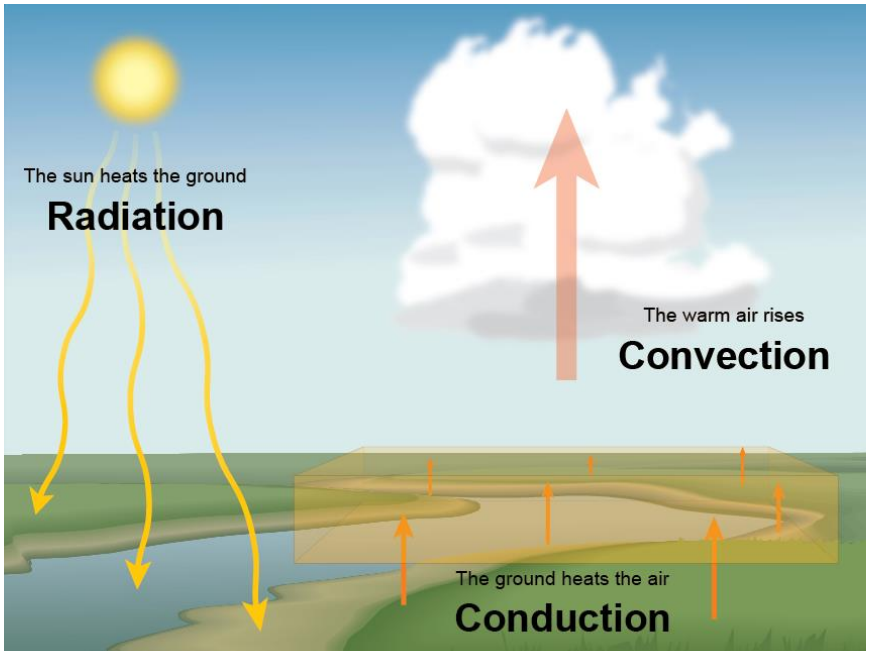

Figure 10.14 the heating process of atmosphere, adapted from
https://www.noaa.gov/jetstream/atmosphere/transfer-of-heat-energy

While the atmosphere absorbs ground radiation to increase atmospheric temperature, it also radiates energy outward. However, it is much lower than the ground, so atmospheric radiation is also long-wave radiation. Part of the atmosphere radiation shoots upward into space and most of it shoots down to the ground. Atmospheric radiation directed toward the ground is in the opposite direction to the ground radiation, so it is called atmospheric inverse radiation. Atmospheric reverse radiation returns heat to the ground, compensating to a certain extent for the heat lost by radiation from the ground, which has a negative impact on the ground for more heat trapping.

Clouds in the sky, especially dense low clouds, or humidity in the air have the insulating effect as well. When they are relatively large, the atmospheric reverse radiation will be enhanced, however, they could weaken the solar radiation. The effect of weakening solar radiation and the insulation effect on the ground not only reduce the maximum air temperature during the day time, which also increase the minimum temperature at night, thereby reducing the diurnal temperature range caused by the ground due to the alternation of day and night. Then temperature fluctuations tend to be moderate. Without the insulation effect of the atmosphere, the average temperature on the earth's surface would drop by -18°C, most ecosystems on Earth would cease to exist. It is the thermal insulation effect of the atmosphere that increase the average temperature on the earth's surface to around 15°C, forming a temperature environment suitable for human survival.

Summary:

The earth's ever-changing atmospheric composition, atmospheric layers with different properties, and constantly changing atmospheric conditions profoundly affect human activities. The atmosphere movement maintains energy circulation and transformation which are closely associated with the composition, vertical stratification and heating process of the atmosphere. Deep understanding about thermodynamic circulation and the formation of wind, will allow humans to develop, utilize and protect climate resources, to effectively preventing and mitigating the adverse influence of meteorological disasters and realizing the harmony between humans and nature.

Problems:

1. how many components are there in the air?

2.what role does the ozone layer play?

3. how many layers are there in the atmosphere vertically?

4.what properties does each layer has and what applications of each layer in the atmosphere?

5. how do the human activities affect the atmosphere?

6. what is smog?

7. why is the sky blue in a clear day?

8. how many roles of an atmosphere play to protect the life on the ground?

9.what percentage does Nitrogen account for in the air?

10. what is the plasma? The plasma is actually another type of gases as far as the properties are concerned?

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