



Introduction to Meteorology

05

Solar and Earth radiation

Introduction



Sunlight in a clear day feels hotter than in a cloudy day. Paved roads are much hotter than grassy area. The snowy mountain top reminds us that the higher the altitude, the lower the temperature. Severe winter turns into spring again. But do you know that, the blue sky and the red sunset appear for the same reason? Most of meteorological phenomena result from solar radiation as well as the interactions among atmosphere, land, and ocean.

Contents



1. Solar radiation
2. Earth radiation

Learning objectives



1. Explain the effect of solar radiation on Earth's temperature.
2. Describe the phenomena caused by the interaction between solar radiation and atmosphere.
3. Explain the effect of the earth's radiation on the temperature of the Earth's atmosphere.

Learning Activities

1. Solar radiation

The sun supplies the energy needed to sustain life, and it is the cause of the seasonal changes on Earth.



- Center of solar system
- A star in 150 million km from Earth

The sun is a star at the center of the solar system. Its distance from the Earth is 150 million kilometers, defined as one Astronomical Unit (AU).

The size of the sun is 109 times the diameter of the Earth, as the mass is about 330,000 times of the Earth's mass. Solar luminosity is 3.865×10^{26} W. The density of the sun is approximately 1.41 gcm^{-3} and is composed of ionized hydrogen and helium gases.

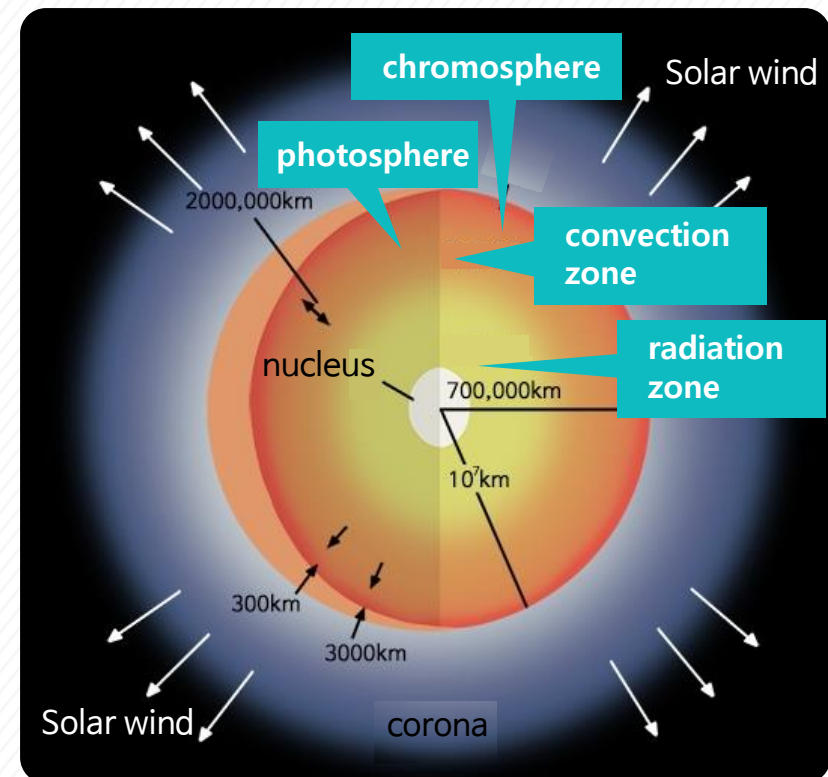
Learning Activities

1. Solar radiation

The sun consists of a convection zone, radiation zone, and core. As the pressure increases toward the center, a thermonuclear explosion in which hydrogen turns into helium occurs and generates energy. The generated energy travels outward to the top of the radiation zone in the form of radiation. Afterwards, the energy reaches the bottom of the photosphere by convection, which is called the convection zone.

In the convection zone, energy is being transferred to a thin surface called photosphere, through convection. The photosphere is considered as the sun's surface where most of the solar energy is released. The effective temperature of the photosphere is 5770K.

While radiation emitted from the sun's photosphere reaches the Earth in about eight minutes, the transfer of radiation within the sun is very slow. It takes about one million years for the energy from the core to be transferred to the bottom of the photosphere.



〈Structure of the Sun〉

Learning Activities

1. Solar radiation

The photosphere, an atmospheric layer of the surface of the sun, has chromosphere and corona. As the temperature and density of the photosphere increase with depth, the edge of the sun is darker than the center. This is known as a limb darkening. The lower photosphere is more dense and hotter than the upper photosphere, therefore larger amount of energy is being radiated.

A solar flare has the highest temperature of the sun. It occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. The temperature of flare is about 108K. The flare only exists for a few minutes, but it emits a tremendous amount of energy in the form of X-rays and ultraviolet rays.

The chromosphere is usually invisible, but can be seen during the eclipse. The corona can be seen when the moon blocks out both the photosphere and chromosphere. The chromosphere radiates electromagnetic energy, and the corona releases protons, electrons and particles. Together, it is called solar wind. These particles are captured by the Earth's magnetic field and interact with gases in the ionosphere giving rise to aurora. The solar wind can interfere with radio and television waves.

Learning Activities

1. Solar radiation

1) Conduction

Solar energy penetrates space without changing its physical properties since it does not receive any interference until it reaches the atmosphere. Consequently, the solar energy that travels through space has constant wavelength and amount of energy. However, as it moves farther away from the sun, the radiation is distributed over large area, reducing the intensity of radiation.

Imagine a sphere with radius equal to the Earth's radius and the distance of 1.5×10^{11} m from the sun. As the distance from the sun increases, the radiation intensity decreases proportionally to the square of the distance.

Solar constant is the flux of solar energy at the Earth. Solar constant is the total radiation energy received from the Sun per unit time per unit area on a theoretical surface perpendicular to the Sun's rays at Earth's mean distance from the Sun.

$$S = \frac{3.865 \times 10^{26} \text{ W}}{4\pi(1.5 \times 10^{11} \text{ m})^2} = 1.367 \text{ Wm}^{-2}$$

Learning Activities

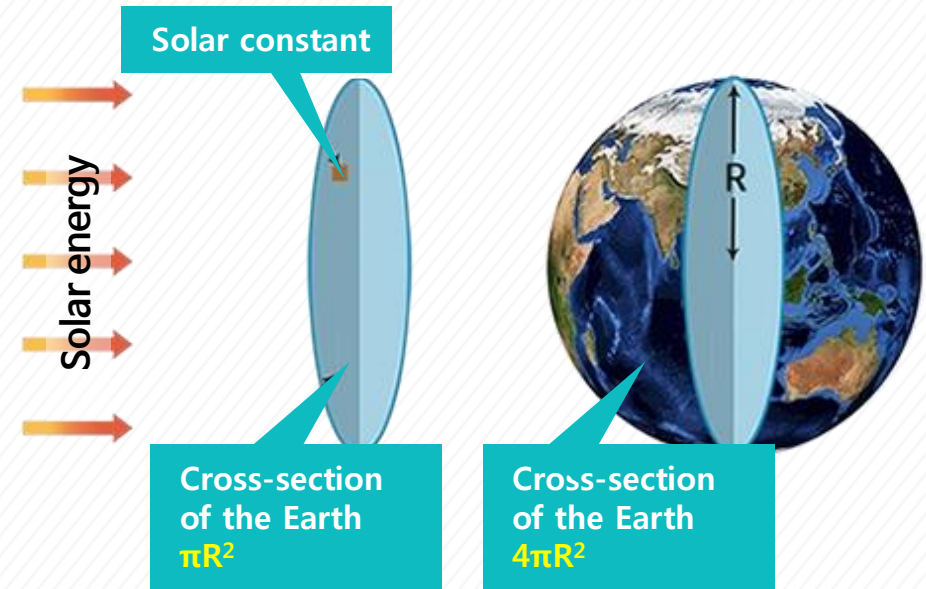
1. Solar radiation

Let's think about the solar flux density reaching the Earth.

About half of the Earth faces the sun during daytime, but because not all of the area is perpendicular to the sun's light, only the area corresponding to the cross-sectional area of the Earth receives the solar radiation. Therefore, if the radius of the Earth is R , the cross-sectional area that receives the solar constant (S) is πR^2 , then the energy over the entire Earth's surface area ($4\pi R^2$) can be calculated as:

$$\pi R^2 : S = 4\pi R^2 : \dot{I}_E$$

The average energy intensity is a quarter of the solar constant which is $0.5 \text{ cal cm}^{-2} \text{ min}^{-1}$. This is about 7,000 times the intensity of the energy that the Earth emits, and it is the primary source for large-scale circulations.



Learning Activities

1. Solar radiation

However, this does not take into account the Earth albedo, which is about 0.3. The Albedo (A) is the percentage of the radiation energy that is reflected back to the space by the planet. The term $1 - A$ is added to manifest the energy that returns to space. Therefore, the computed average energy intensity considering the albedo is reduced to $0.35 \text{ cal cm}^{-2} \text{ min}^{-1}$

$$\pi R^2 : S = 4\pi R^2 : \dot{I}_E$$



$$0.5 \text{ cal cm}^{-2} \text{ min}^{-1}$$

$$\pi R^2 \times S(1 - A) = 4\pi R^2 \times I_E$$



$$0.35 \text{ cal cm}^{-2} \text{ min}^{-1}$$

The results are obtained by ignoring other factors. In accordance with Kirchoff's law by which the absorption and emission rates are the same at a given wavelength, the Earth will emit energy with the calculated intensity.

Learning Activities

1. Solar radiation

By assuming that the Earth is a blackbody and applying the Stefan-Boltzmann law, the intensity of the radiation emitted by the Earth is:

$$I_E = \sigma T^4$$

The temperature is called the radiative equilibrium temperature. The Earth's radiative equilibrium temperature is about 255K, which is much lower than the observed surface temperature. This is because the Earth's atmosphere absorbs and emits infrared radiation. Unlike Earth, the atmosphere is not a blackbody, therefore it absorbs radiation at certain wavelength or is transparent to others. Objects that selectively absorb and emit radiation are known as selective absorbers.

Once radiation reaches an object, three phenomena occur. First, the particles that receive the radiation energy absorb part of the energy. When energy is absorbed, the particles that receive the energy vibrate the molecules more quickly, resulting in temperature increase. Some of the unabsorbed energy bounces out of the object and the direction of the solar radiation changes via reflection or scattering. The rest transmit the radiation of a specific wavelength by objects such as water or air. The transmitted energy does not provide energy to the object. In short, radiation energy can be absorbed, transmitted, or reflected.

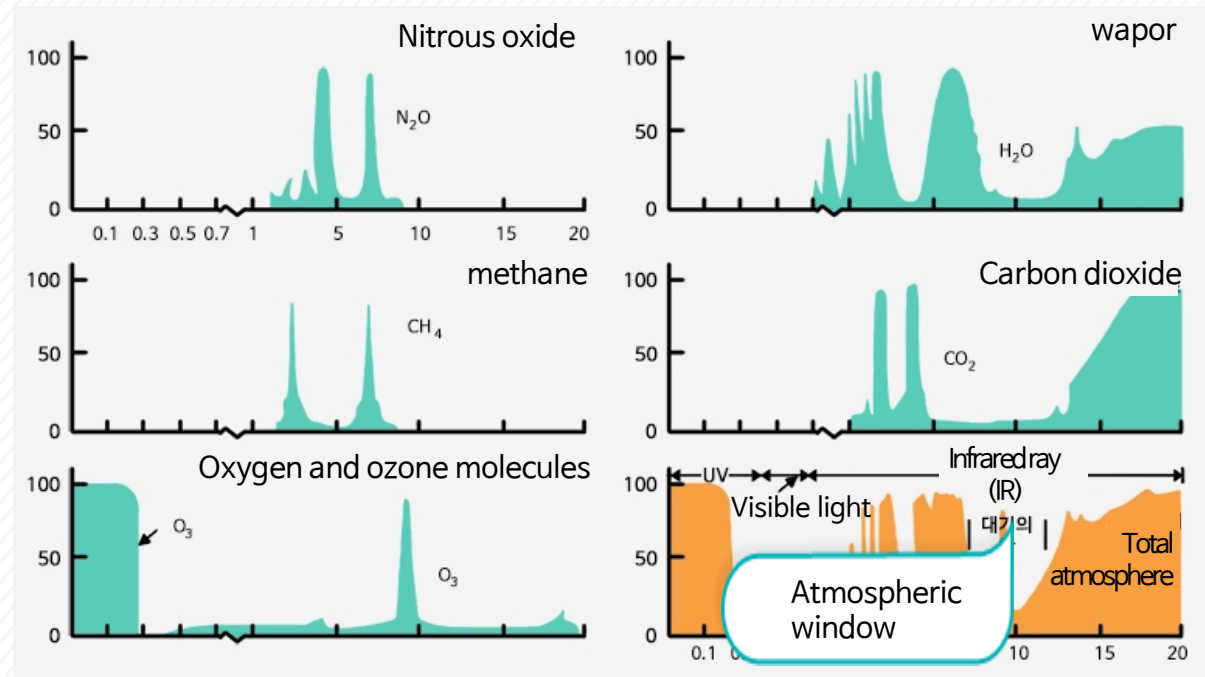
Learning Activities

1. Solar radiation

2) Absorption

When radiation energy is absorbed by gases or aerosols in the atmosphere, the absorber gains energy and heats up, while the amount of radiation reaching the surface is reduced. Absorption rate is the rate at which the incident ray is absorbed. The solar radiation absorbed by the atmosphere depends on the wavelength. This selective absorption is very important to our lives.

The figure above shows that there is no gas in the total atmosphere that absorbs radiation at the wavelength ranging from 0.3 to 0.7 μm . It corresponds to a visible light band that accounts for 43% of the solar radiation. Most of the visible light can reach the Earth surface because there are no atmospheric gases that absorb visible light well. Longwave radiation ranging from 8 to 12 μm is not well absorbed except 9.6 μm absorbed by ozone.



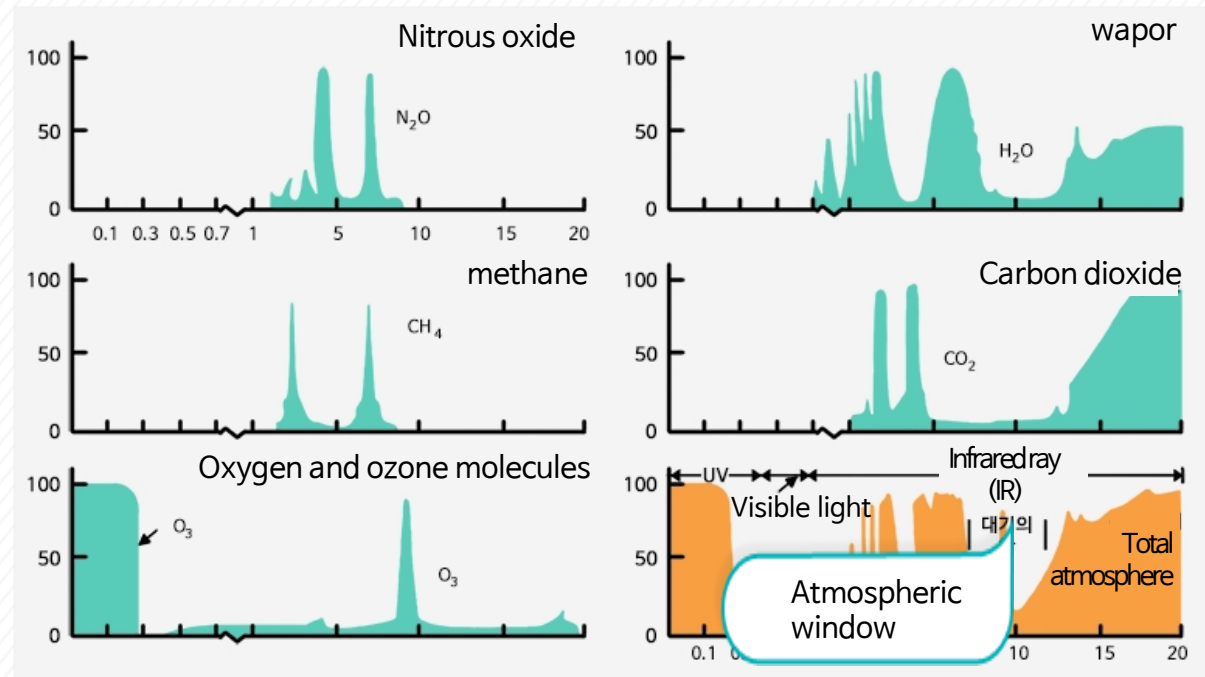
〈Absorption of radiation by atmospheric gases〉

Learning Activities

1. Solar radiation

Just as visible light is transmitted through a window, the radiation of this wavelength is transmitted through the atmosphere, so this wavelength band is called the atmospheric window. Because these wavelengths of emitted energy pass upward through the atmosphere and out into space, the wavelength range is known as the atmospheric window.

This wavelength range (between 8 and 12 μm) is most meaningful because the earth infrared radiation is the strongest.



<Absorption of radiation by atmospheric gases>

Learning Activities

1. Solar radiation

3) Reflections

We recognize an object through the reflection of visible light. Reflection occurs at various wavelengths, as well as a way of scattering by gas molecules in the atmosphere, as well as reflection from the Earth's surface and clouds into space. Albedo is defined as the ratio of radiation reflected back into space to the radiation incident on a surface. In meteorology, albedo due to surface and cloud is important. It has a large impact on the Earth's radiation balance.

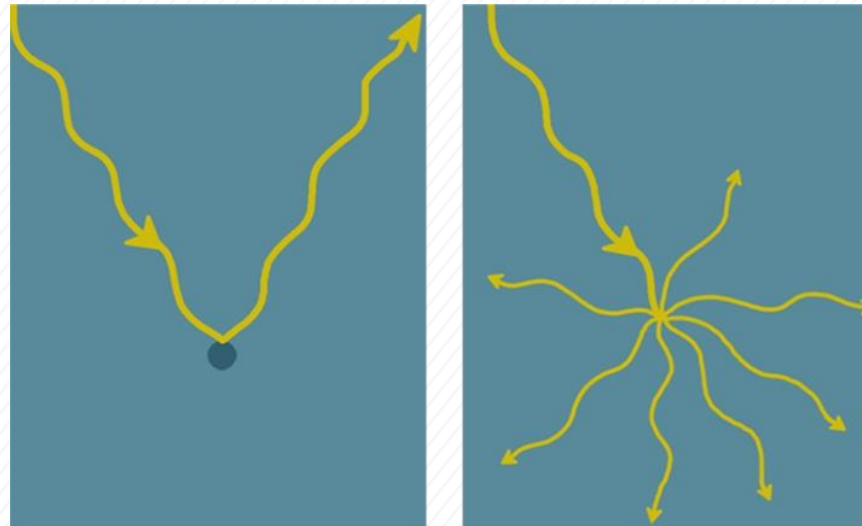
Albedo differs greatly depending on cloudiness, aerosol in the atmosphere, the incidence angle of the sun depending on the season, properties of earth's surface, space and time. The average global albedo is 30 to 35%, which includes the amount of radiation sent back to the space by backscattering. The reflected radiation does not warm the atmosphere. The albedo of the earth is mostly influenced by cloud and the earth's surface. The reflection of the earth's surface is much smaller than the reflection of clouds. Also, the fresh snow and the thick clouds have a high reflectivity and high albedo, while the dark soil does not reflect much and absorbs most of the received radiation. In a lake or ocean, the angle of sunlight entering the water surface determines albedo.

Learning Activities

1. Solar radiation

4) Scattering

Light scattering can be thought of as the deflection of a solar ray from a straight path by irregularities in the propagation medium. For example, part of the solar energy is absorbed by gases such as ozone in the upper atmosphere, hit by small objects such as air molecules or dust, and scattered in various direction, resulting in weakened rays. Scattering is the process in which the radiation is forced to travel in a direction different from the incident direction after a collision with a gas or particle. Scattering includes reflection, refraction, and diffraction. Scattering can disperse light forward or backward, but more energy is dispersed forward.

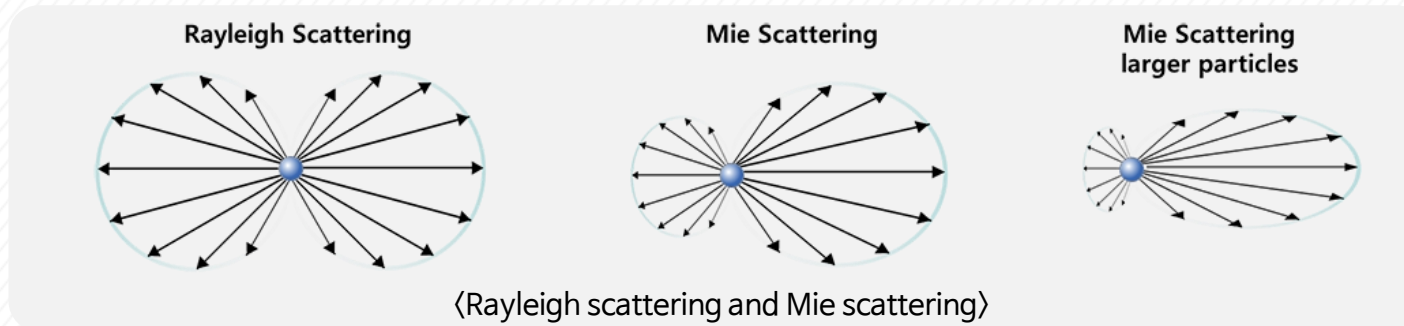


⟨Reflection and scattering⟩

Learning Activities

1. Solar radiation

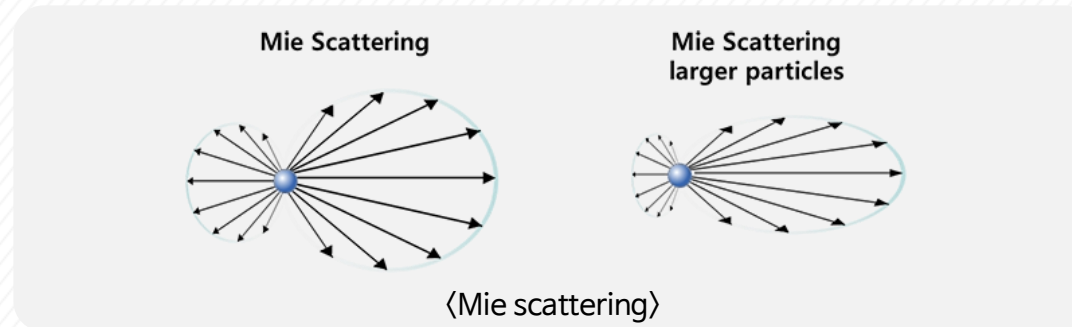
There are two types of scattering—Rayleigh and Mie scattering.



Rayleigh scattering occurs when the ratio of the particle radius to the wavelength of radiation is less than 0.1, i.e., the wavelength is larger than the particle. The percentage of light that will be scattered is inversely proportional to the fourth power of the wavelength. Small particles will scatter a higher percentage of short wavelength light than long wavelength light. Because the air molecules are much smaller than the wavelength of visible light, they act as effective scatterers for blue light with a shorter wavelength than red with longer wavelength. Rayleigh scattering scatters radiation both forward and backward. When the Sun is high overhead on a clear day, some of the blue light bounces off in all direction. Much of it is scattered more than once before eventually hitting our eyes, so we see blue light coming not directly from the sun but from all over the sky. However, at sunrise and sunset, the layer of the atmosphere through which the sunlight passes becomes thicker. As the sunlight enters the atmosphere, shorter wavelength light is scattered more than longer wavelength of the visible light spectrum (red, yellow, orange).

Learning Activities

1. Solar radiation



Mie scattering occurs when the wavelength of the incident light is smaller than that of the particles, that is, the ratio of the particle radius to the wavelength is about 0.1 to 50. Unlike the Rayleigh scattering, the Mie scattering intensity is not related to the wavelength. Large energy is scattered forward and relatively small energy is scattered backward. Different from Rayleigh scattering, shorter wavelength tends not to scatter. The reason why the sky is gray on a foggy day or on a day with air pollution is because the light in the visible spectrum is fully scattered in the direction of the earth's surface.

Learning Activities

1. Solar radiation

5) Transmission

While the solar radiation travels through space, there is no factor that changes the intensity and direction or wavelength of solar radiation. However, when it reaches the atmosphere, only part of the radiation will pass through the atmosphere and eventually reach the surface. The amount of radiation blocked by the atmosphere depends on the state of the atmosphere. A clear and dry atmosphere transmits more than 80% of insolation in the form of direct radiation without scattering or absorbing. On cloudy or foggy days, only a small amount of solar radiation arrives at the surface in the form of a direct solar radiation and the rest travels in the form of diffusion and scattering.

Learning Activities

2. Earth radiation

1) Warming the Earth surface and atmosphere

Earth emits significantly less radiation than the sun, and it emits radiation as longwave radiation. Solar radiation is emitted at wavelengths shorter than $2.5\mu\text{m}$, while more than 95% of earth radiation is in infrared radiation band.

The atmosphere absorbs not only solar radiation but also Earth's emitted infrared longwave radiation and emits longwave radiation again. Because the gas particles in the infrared spectrum are close to blackbody, it reemits as much as it absorbs. The radiation emitted by the gas molecules such as methane, carbon dioxide, water vapor, and clouds is called atmospheric radiation. Atmospheric radiation absorbs the radiation of the earth surface and controls the temperature of the atmosphere by restricting heat lost to the space. Gases with selective absorption wavelength absorb a small amount of the Earth's radiation, but they hardly absorb solar radiation.

Learning Activities

2. Earth radiation

2) Atmospheric heating

The atmosphere is a selective absorber which selectively absorbs and emits radiation. The most effective absorber for radiation plays an important role in controlling the temperature of the atmosphere. Clouds composed of small droplets are good absorbers of infrared radiation and can enhance the atmospheric greenhouse effect. This is why the temperature at night is high on cloudy days rather than sunny days. The clouds absorb the outgoing infrared radiation and re-emit much of this energy back to the surface. Thus, cloud closes the atmospheric window. This will slow down the rate at which the surface is cooled. The atmosphere transmits shortwave solar radiation and absorbs longwave radiation emitted from Earth. Therefore, lower atmosphere is heated by the earth radiation, and the temperature drops in the troposphere with increase of latitude.

Learning Activities

2. Earth radiation

3) Greenhouse effect

The greenhouse effect refers to circumstances where the short wavelengths of visible light from the sun pass through the atmosphere, but part of longwave radiation from Earth is trapped in the atmosphere and leads to more heating. The energy re-emitted to the surface further heats the surface. Therefore, the surface average temperature reaches 33°C higher than the radiative equilibrium temperature.

Carbon dioxide and methane emitted by human activities are considered to be the main cause of global warming. Global warming and greenhouse effect are not the same. Without the greenhouse effect, the Earth would be inadequate for life. However, there is evidence that human activity causes global warming through enhancing the greenhouse effect, although still controversy.

Summary

1. Solar radiation

- Solar constant
 - Solar constant is the total radiation energy received from the Sun per unit time per unit area. Solar radiation can be absorbed, transmitted, or reflected/scattered.
- Absorption
 - When radiation energy is absorbed by gases or aerosols in the atmosphere, the absorber gains energy and heats up, while the amount of radiation reaching the surface is reduced.
 - The atmosphere selectively absorbs radiant energy
 - Water vapor and carbon dioxide strongly absorb infrared radiation energy.
 - Most of the visible light can reach the earth surface because there are no gases in the atmosphere that absorb visible light well.
 - Wavelength of emitted energy pass upward through the atmosphere and out into space in the wavelength between 8 to 12 μm .
- Reflection
 - Reflection occurs through scattering by gas molecules in the atmosphere as well as reflection from the Earth's surface and clouds into space.
 - Albedo is defined as the ratio of radiation reflected to the radiation incident on a surface. Albedo differs greatly depending on cloudiness, aerosol in the atmosphere, seasonal change of sun's incidence angle, properties of earth's surface, space and time.

Summary

1. Solar radiation

- Scattering
 - When the radiation strikes a gas or particle and travels in a direction different from the incident direction, it is called scattering.
 - Types of scattering: Rayleigh and Mie scattering.
 - Rayleigh scattering
 - Rayleigh scattering occurs when the wavelength is larger than the particle. The scattering intensity is inversely proportional to the fourth power of the wavelength.
 - Blue sky, and red sunset and sunrise are due to Rayleigh scattering
 - Mie scattering
 - The intensity of Mie scattering is not related to wavelength.
 - Gray sky on a foggy day or polluted day is due to Mie scattering
- Transmission
 - While the solar radiation travels through space, there is no factor that changes the intensity and direction or wavelength of solar radiation. However, when it reaches the atmosphere, only part of the radiation will pass through the atmosphere and reach the surface

Summary

2. Earth radiation

- More than 95% of the radiation emitted from the surface and atmosphere has a wavelength at the infrared band.
- Most solar radiation emits at a wavelength shorter than $2.5 \mu\text{m}$ (shortwave radiation)
- Atmospheric heating
 - Earth's atmosphere is a selective absorber that absorbs a specific wavelength band.
 - Although it is small, it can absorb the earth's radiation but hardly absorbs the sun's radiation.
 - As the atmosphere transmits shortwave solar radiation but absorbs longwave radiation emitted from Earth, the atmosphere is heated by the surface as the altitude increases the temperature drops in the troposphere.
- Greenhouse effect
 - The greenhouse effect refers to circumstances where the short wavelengths of visible light from the sun pass through the atmosphere, but part of longwave radiation from earth is trapped in the atmosphere and leads to more heating.
 - Carbon dioxide and methane emitted by human activities are considered to be the main cause of global warming, but global warming and greenhouse effect are not the same.