Introduction to Meteorology

04 Heat transfer

Introduction

The solar energy reaching the Earth is the main source of energy that influences not only human activity but also the entire climate system. Because the Earth's rotation axis is tilted 23.5°, incoming solar energy is not evenly distributed: more energy is absorbed in the tropics than in polar regions. Such latitudinal imbalance of the energy drives circulation of the atmosphere and ocean.

Contents

1. Heat transfer
2. Radiation

Learning objectives

1. Describe the heat transfer process.
2. Explain the processes and principal laws of radiation

Learning Activities

1. Heat transfer

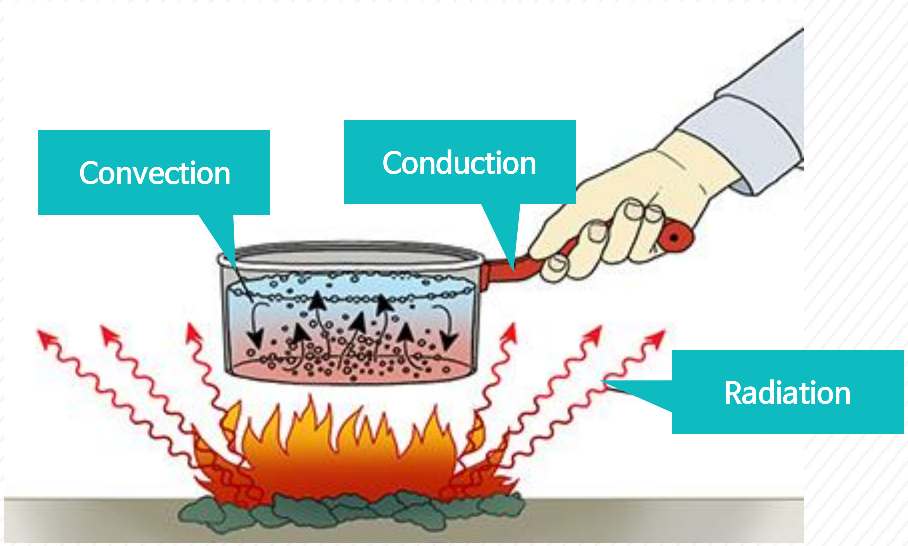
Heat is energy transferred from one object to another because of the temperature difference between them. As we can easily experience, heat moves from higher temperature object to lower temperature object. Heat is transferred by the contact of two objects with different temperatures. As a result, the warm object will cool down and the cool object will warm up.

Heat is energy transferred from one object to another because of the temperature gradient.

Learning Activities

1. Heat transfer

When the temperatures of both objects have reached at the same temperature, heat no longer changes. Such state is called thermal equilibrium state. Heat transfer can happen in three ways: conduction, convection, and radiation. These processes transfer heat between the sun and earth, atmosphere and surface, and among planets.



〈Three ways in which heat is transferred〉

Learning Activities

1. Heat transfer

1) Conduction

Conduction can be experienced easily. When you hold one end of a metal pin with your fingers and place the other end above a flaming candle, you will notice that the heat is transferred along the entire pin. The transfer of heat from molecule to molecule within a substance, without the movement of molecule inside the material, is called conduction.

The molecules in the pin vibrate faster, because of the energy they absorb from the flame. The fast-vibrating molecules pass vibrational energy to their neighboring molecules, until the molecules at the finger-held end of the pin begin to vibrate.
The heat is being transferred from the pin to your finger and you will feel that your hand is getting hot even though you do not contact the flame directly.

The transmission of heat from one end to the other occurs by conduction and it always flows from warmer to colder region.
The greater the temperature gradient, the more rapid the heat transfer.

The conductivity of the heat varies among substances. Materials that easily pass energy from a molecule to another are considered to be good conductors of heat. Heat conduction depends on the molecular bonding structure of the material.
Metal is a good conductor, whereas air is an extremely poor conductor of heat.

An object with poor conductivity, such as air, is called an insulator. Good insulators such as cork, plastic products, and goose down have a lot of air spaces trapped within them. The low conductivity of the trapped air determines the insulation value of these objects. Because the heat transfer by conduction in the atmosphere occurs only in a few centimeters from the surface, it can be ignored when considering most of the weather phenomena.

Learning Activities

1. Heat transfer

2) Convection

The transfer of heat by the mass movement of a fluid, such as water and air, is referred to convection. Convection is important for heat transfer between atmosphere and ocean. On a warm and sunny day, certain areas of Earth’s surface absorb more heat from the sun than others.

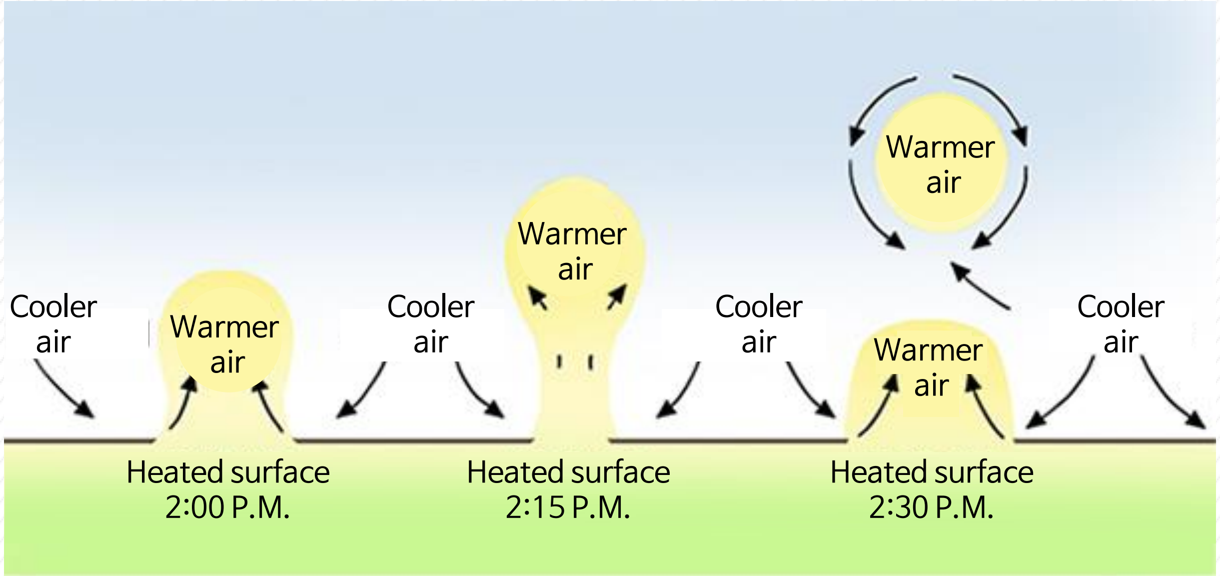
The global large-scale circulation is induced by uneven heating of the Earth's surface. For example, the air above the asphalt is heated more than that above grass. Due to such uneven surface heating, in the relatively strongly heated area, air molecules acquire additional heat through collisions and conduction.

The heated air expands and becomes less dense than the surrounding cooler air. The expanded warm air is buoyed upward and transfers heat energy upward. Cooler and heavier air flows downward. Repeatedly, this descending air rises as it gets warmer.

Learning Activities

1. Heat transfer

The heated material transfers heat directly through circulation. The rising air bubbles are known as thermals. Such circulations are responsible for redistribution of heat between warm tropical regions and cold polar regions.



〈The development of a thermal through uneven surface heating〉

Learning Activities

1. Heat transfer

Although the atmospheric circulation includes both the vertical and horizontal components, meteorologists usually restrict the term convection to the process of rising and sinking motion. The horizontal components of the circulation carry properties of the air. The transfer of these properties by horizontal wind is called advection.

The horizontal advection transports characteristic of the air in the area to which it originally belonged. People in the mid-latitudes often experience heat transfer effects by advection. For example, in January, cold air from Canada hits the Midwest and drives extremely cold winter in the Midwest. On the other hand, the air from the Gulf of Mexico to the north drives warmer weather.

Learning Activities

1. Heat transfer

3) Radiation

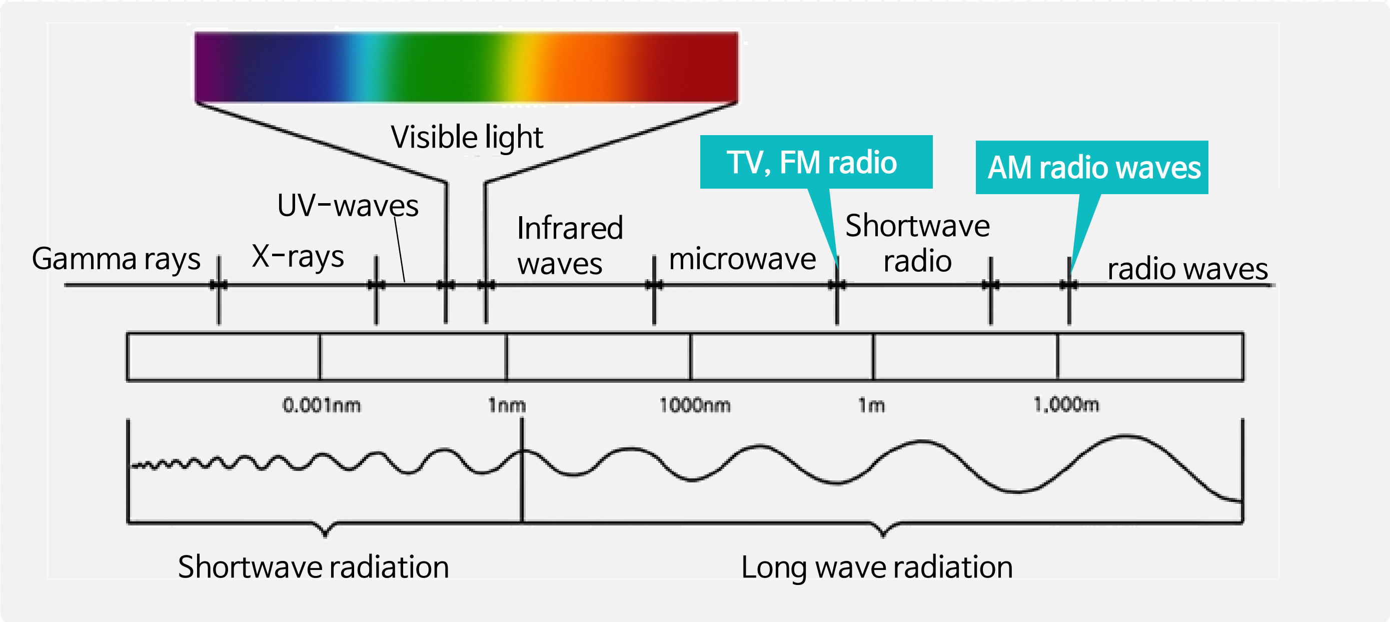
Unlike conduction and convection, the process of transferring heat in the form of electromagnetic waves, without a medium, is called radiation. Radiant energy (or radiation) is easily transmitted in a vacuum. Radiation is the heat transfer mechanism that allows solar energy to reach the Earth.

Every object emits radiant energy depending on its the temperature. On a summer day, you may have noticed how warm your face feels as you stand facing the sun. If you go under the shade of a tree, you feel cool.

Learning Activities

1. Heat transfer

Sunlight travels through the air with little effect on the air itself. However, your face absorbs that energy and turns it into thermal energy. Sunlight warms your face without warming the air. The energy transferred from the sun to your face is called radiant energy or radiation. Radiation energy moves in the form of waves, which are called electromagnetic waves because these waves have magnetic and electrical properties. Electromagnetic waves do not need molecules to propagate themselves. In vacuum, electromagnetic waves travel at a speed of about 300,000 km per second, the speed of light.



⟨Electromagnetic spectrum with various types of radiation according to wavelength⟩

Learning Activities

1. Heat transfer

Nearly all the energy used on Earth is originated from the solar radiation. Solar radiation is the most important energy source for ocean and atmospheric circulation. While radiation and convection are both important in the troposphere, the atmosphere above the stratosphere is less convective, making radiation more essential. In addition to solar energy, there is a small amount of cosmic radiation and energy emitted from the Earth, although very small compared to the solar energy.

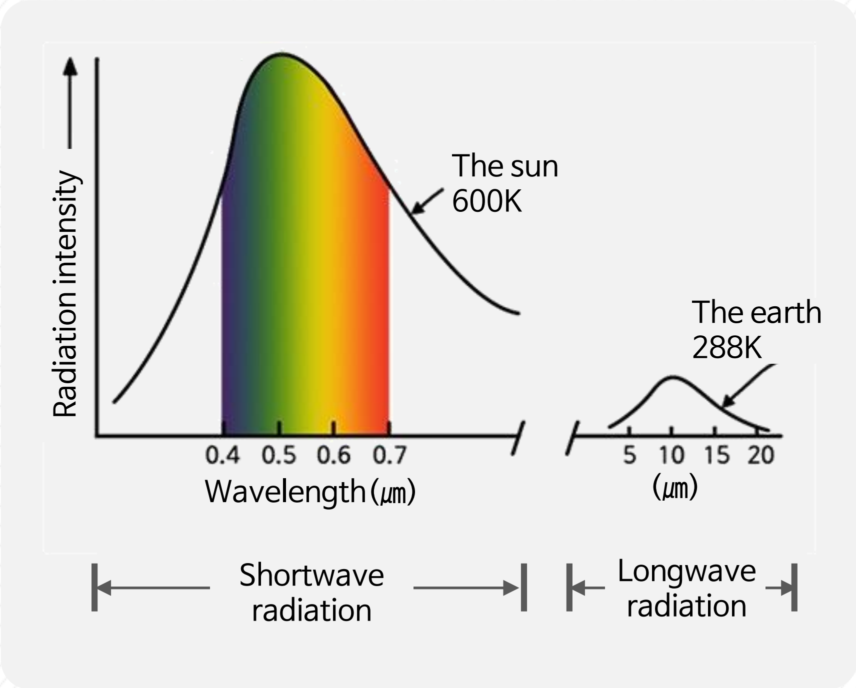
All objects with temperatures above 0K release radiation. The higher the object's temperature, the shorter is the wavelength of emitted radiation. Sun emits radiation at almost all wavelengths. Because its surface is extremely hot, it radiates the majority of energy at short wavelength.

Learning Activities

1. Heat transfer

Electromagnetic radiation appears as a continuum of wavelengths called electromagnetic spectrum or radiation spectrum. The distance between two crests of in a wave is called wavelength.

The figure shows the intensity of solar radiation and earth radiation. While the shape of the Sun's spectrum curve looks similar to that of Earth's spectrum curve, the total amount of energy released by Earth is much lower than that of the Sun. In addition, Sun's radiation peaks at shorter wavelengths. The sun emits a maximum amount of radiation at wavelength near 0.5 ㎛. The human eye is only sensitive to radiation between 0.4 and 0.7 ㎛, and these waves stimulate the sensation of color. Therefore, this part of the solar spectrum is referred to as the visible region, and the radiant energy that reaches our eye is called visible light. While the sun emits only a part of its energy in the infrared spectrum, the Earth emits almost all of its energy at infrared band. The Earth with an average surface temperature of 288 K (15˚C) radiates almost all of its energy at a wavelength of 5 to 25 ㎛ and emits the maximum radiation at approximately 10 ㎛.



〈Electromagnetic spectrum of the sun and earth with the names of each region〉

The wavelength that emits the maximum radiation depends on the temperature of the surface and the atmosphere. Since the sun radiates most of its energy at much shorter wavelengths than the Earth, solar radiation is often called shortwave radiation, whereas Earth's radiation is called longwave radiation.

Learning Activities

2. The law of radiation

1) Planck's law

Planck's law describes the spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature T and can be expressed by the formula below. E_λ is the spectral density of electromagnetic radiation emitted per unit wavelength (unit: $Wm^{-2}s^{-1}\mu m^{-1}$), h is the Planck constant ($h=6.626 \times 10^{-34} Js$), c is the speed of light ($c=2.998 \times 10^{8} ms^{-1}$), and k is Boltzmann constant ($k=1.3806 \times 10^{-23} JK^{-1}$).

Learning Activities

2. The law of radiation

2) Wien's law

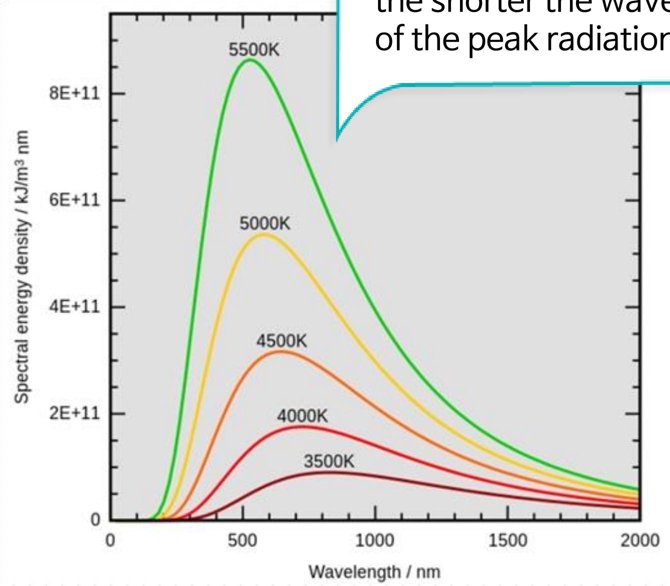
Wien's law, after the physicist Wilhelm Wien, relates an objective's maximum emitted wavelength of radiation to the objective's temperature. It can be expressed as:

$$\lambda_{max} = W/T$$

where λ_{max} is the wavelength at which maximum radiation emission occurs, T is temperature in degree kelvins (K), and W is constant (2897 μm K). In the figure, it can be seen that an object with higher temperature (5500 K) emits the maximum radiation at much shorter wavelength than the lower temperature object (3500 K). Hotter objects radiate more energy in the form of short-wavelength radiation than cooler objects.

The wavelength of maximum radiation of the sun is 0.㎛, while the Earth with lower temperature has its maximum at around 10 ㎛. It indicates that the wavelength of the maximum radiation emitted by an object is inversely proportional to the objective's absolute temperature.

The hotter the objective, the shorter the wavelength of the peak radiation



⟨Black body radiation emitted from all wavelengths per unit time and area by various temperature⟩

Learning Activities

2. The law of radiation

3) Stefan-Boltzmann law

As the temperature of an object increases, more total radiation over a given area is emitted each second. This relationship between temperature and emitted radiation is known as the Stefan-Bpltzmann law after Josef Stefan and Ludwig Boltzmann. It can be expressed as:

$$I = \sigma T^4$$

Where I is the maximum rate of radiation emitted by unit area of surface, σ is Stefan-Boltzmann constant (σ=5.67 X 10^{-8} Wm^{-2} K^{-4}) and T is temperature.

A blackbody is a theoretical object that absorbs 100% of the radiation that hits it. The sun is close to 6000K, so it absorbs and emits nearly 100%. Most liquids and solids are a gray body that emits only a certain percentage of the maximum possible radiation at a given temperature.

Emissivity is defined as the ratio of the energy radiated from a material's surface to that radiated from a blackbody (a perfect emitter). Emissivity ranges from 0 to 1 and often symbolized by ε (epsilon). Most objects have emissivity larger than 0.9.

Learning Activities

2. The law of radiation

4) Kirchoff's law

Kirchhoff's law is that if an object is in a thermodynamic equilibrium, the absorption and emission rates are the same at a given wavelength. Good absorbers are good emitters. Kirchhoff's law is given by:

$$\alpha_\lambda = \varepsilon_\lambda$$

where α_λ is the absorption rate at a given wavelength, ε_λ is the emission rate. For blackbody, both alpha and epsilon are equal to one.

Summary

1. Heat transfer

Heat is energy transferred from one object to another because of the temperature difference between them. Heat transfer can happen in three ways: conduction, convection, and radiation.

- Conduction
  - Refers to the transfer of heat from molecule to molecule without the movement of molecules.
  - The heat transfer by conduction in the atmosphere occurs only in a few centimeters from the surface
  - Conduction is not critical in terms of heat transfer in the atmosphere thus can be ignored for most of the meteorological phenomena.
- Convection
  - Refers to the transfer of heat by the mass movement of a fluid.
  - Meteorologists usually restrict the term to the process of rising and sinking motion.
  - The horizontal transfer of any atmospheric property by the wind is called advection.
- Radiation
  - Refers to the process of transferring heat in the form of electromagnetic waves, without a medium.
  - Solar radiation is the most important energy source for ocean and atmospheric circulation.
  - While radiation and convection are both important in the troposphere, the atmosphere above the stratosphere is less convective, making radiation more important.
  - Since the sun radiates most of its energy at much shorter wavelengths than the Earth, solar radiation is often called shortwave radiation, whereas Earth’s radiation is called longwave radiation.

Summary

2. The law of radiation

- Planck's law: the spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium at a given temperature T.
- Wien's law: Wien's law relates an object's maximum emitted wavelength of radiation to the object's temperature.
- Stefan-Boltzmann law: total radiative energy emitted from a surface is proportional to the fourth power of its absolute temperature.
- Kirchoff's law: the absorption and emission rates are the same at a given wavelength under thermodynamic equilibrium.