



Introduction to Meteorology

02

Vertical structure of the Atmosphere

Introduction



The atmosphere can be divided into homogeneous and inhomogeneous layers depending on the composition of the atmosphere. But besides its composition, various characteristics such as the electrical properties, chemical composition, and temperature can be used to distinguish the vertical layers of the atmosphere.

Contents



1. Air pressure and density
2. Thickness of the atmosphere
3. Atmospheric structure by temperature
4. Atmospheric structure by composition
5. Atmosphere structure by electrical properties

Learning objectives



1. Explain the vertical structure of air pressure and density.
2. Understand and explain the vertical structure of the atmosphere classified by temperature.
3. Describe the vertical structure of the atmosphere classified by composition.
4. Describe the vertical structure of the atmosphere classified by electrical properties.

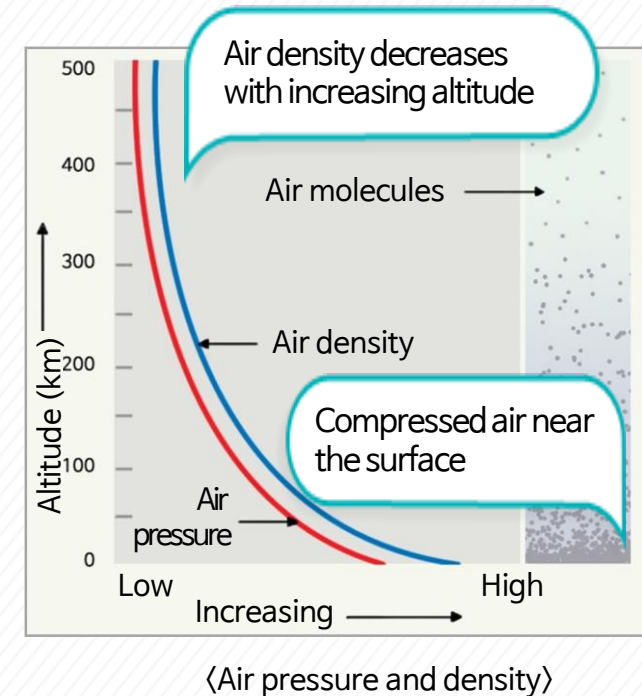
Learning Activities

1. Air pressure and density

Due to Earth's gravitational attraction, air molecules are held near the surface. Air molecules are compressed by strong gravity, which is not visible but pulls the air down, resulting in an increase in the number of air molecules in a given volume. The more air above a level, the greater the compression effect.

The number of air molecules in a given volume, called air density, is highest at the surface and decreases as we move up into the air.

In the following figure, since the air near the surface is compressed, the higher the altitude, the smaller the number of molecules of air and the lower the density of the air.



Learning Activities

1. Air pressure and density

Air molecules have weight which is surprisingly heavy. The weight of all the air around the Earth is about 5,100 trillion tons. The force exerted on an area of surface is called atmospheric pressure or simply, air pressure.

At any level in the atmosphere, air pressure can be measured in terms of the total weight of the air above any level. The higher we go up, the fewer air molecules exist above us. In other words, the atmospheric pressure at a given altitude means the total weight of the atmosphere above that level, so it decreases with altitude.

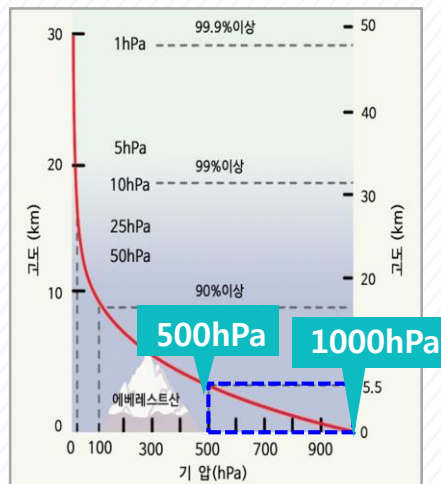
Like air density, air pressure decreases rapidly near the ground and gradually decreases at higher levels. If you measure the weight of the column of air upon an area of one square meter, extending from the sea level to the top of the atmosphere, it would weight nearly 1013.25 N m^{-2} . . On the other hand, when fewer molecules are in the column, the air weighs less, so the surface pressure decreases. Therefore, as the air density changes, the atmospheric pressure changes as well.

Currently, the most common unit for air pressure found on the weather charts is the millibar (mb), although the hectopascal (hPa) is gradually replacing the millibar as the preferred unit of pressure. Another traditional unit is mercury height (mmHg), which is commonly used in the fields of aviation, TV or radio weather reports. The standard value for atmospheric pressure at sea level is 1013.25 hPa, equivalent to 760 mmHg. Near the sea level, the pressure decreases steeply, whereas it decreases more smoothly at higher levels.

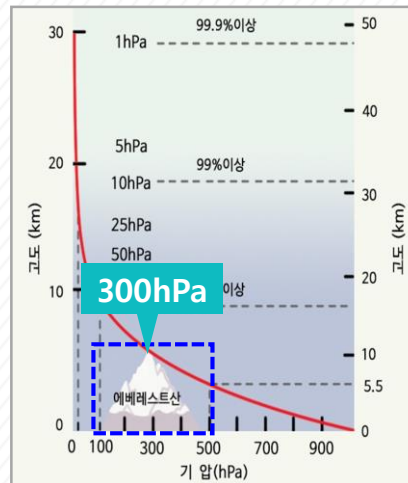
Learning Activities

1. Air pressure and density

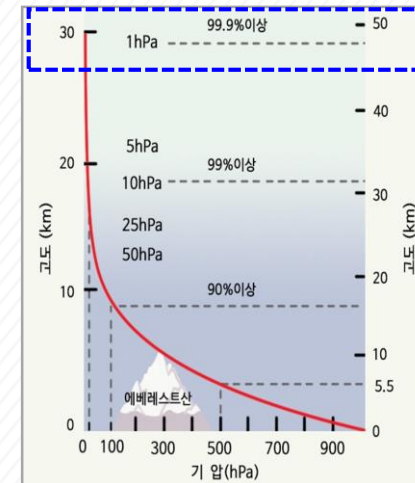
As shown in the figure below, the air pressure changes from 1000 hPa to 500 hPa, half of the sea level pressure, at an altitude of only 5.5 km. It means that half of the air molecules in the atmosphere are below 5.5 km. At an elevation of the summit of Mount Everest (about 9 km), the pressure drops to about 300 hPa, meaning that it is located above nearly 70% of total atmospheric molecules. At an altitude of 50 km, the air pressure is only 1 hPa, which means that 99.9% of all the air molecules are below this level. Yet the atmosphere extends over hundreds of km above the Earth, its density is getting lower and ultimately merges with outer space.



Half of the air molecules in the lower troposphere



Nearly 70% of total atmospheric molecules



99.9% of the air molecules in the lower atmosphere

〈Change in atmospheric pressure by altitude〉

Learning Activities

2. Thickness of the atmosphere

How is the Earth's atmosphere defined? The Earth's atmosphere is the layer of gases that is bound to Earth's gravity, which is within about 1,000 km of the surface. However, even at altitudes above 1,000 km, gases exist although very rare. As shown before, the air density is approximately 10% of the surface air density at 16 km, and about 1% at 50 km.

When you look up into the sky, the atmosphere appears to be very high, although most of the atmosphere exists in a thin layer near the surface. Assuming that the upper bound of the atmosphere is at about 100 km above sea level, the thickness of the atmosphere is less than 2% of the Earth's radius which is about 6,500 km.

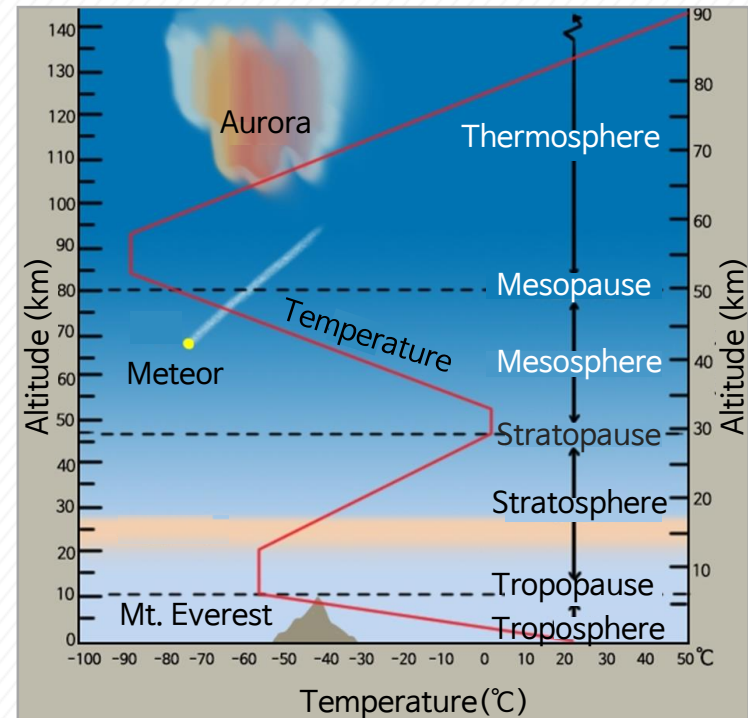
Although a well-developed thunderstorm cloud can reach up to about 12 km altitude, these clouds seem to be attached to the Earth's surface when looked from space. The atmosphere is a relatively thin layer, but contains considerable mass which is equivalent to 5.14×10^{15} ton.

Since the atmosphere is thin, large-scale atmospheric motions occur in the horizontal direction rather than in vertical. Horizontal wind speeds are more than 1,000 times larger than vertical wind speeds. Although the vertical motion is relatively small and difficult to observe and predict, it plays an important role in determining the characteristics of the atmosphere.

Learning Activities

3. Atmospheric structure by temperature

We've looked at how air pressure and density decreases with height - rapidly in the lower level and then more slowly in the upper level. However, the atmospheric temperature has a more complicated vertical profile. The atmosphere can be divided into four layers according to the atmospheric temperature vertical profile. Let's learn more about each layer.



〈Thermal structure of the atmosphere〉

Learning Activities

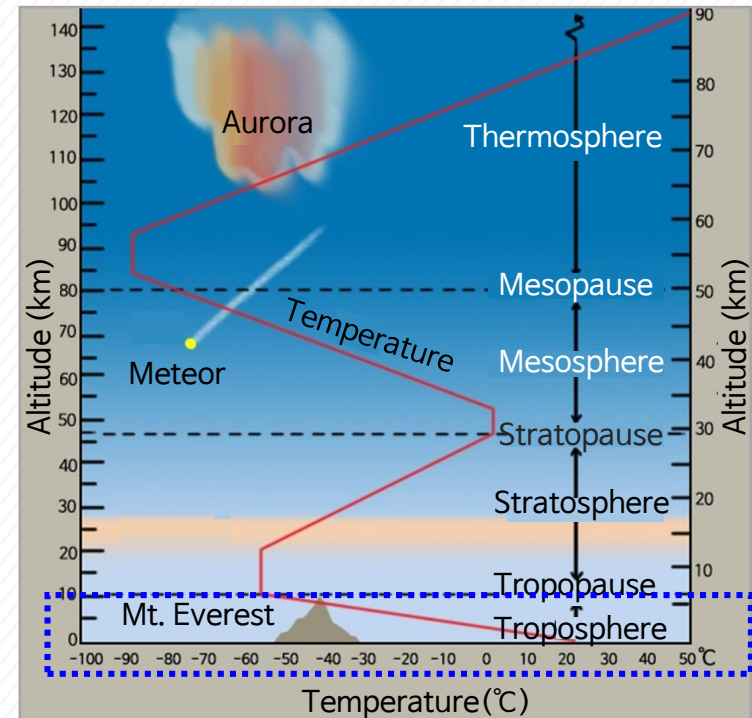
3. Atmospheric structure by temperature

1) Troposphere

The very bottom layer is the troposphere, where almost all weather phenomena occur. The temperature decreases as the altitude increases. It is the thinnest layer among the four layers, but contains about 80% of the mass of the atmosphere. The thickness of the troposphere varies with location ranging from 8 to 16 km.

The thickness of the troposphere depends on the column mean air temperature - thick in high temperature area and thin in low temperature area. Therefore, the troposphere is thicker in the tropics than pole, and thicker in summer than winter.

What about the temperature change within the troposphere?
 Temperature varies across the troposphere, with having the global mean temperature of about 15°C near the surface and -57 °C in the upper troposphere. On average, the temperature is decreasing by 6.5 °C per km, which is called the temperature lapse rate. The boundary separating the troposphere from the stratosphere is called the “tropopause” where temperature is consistent. The layer where the temperature no longer changes is called the isothermal layer.



〈Thermal structure of the atmosphere〉

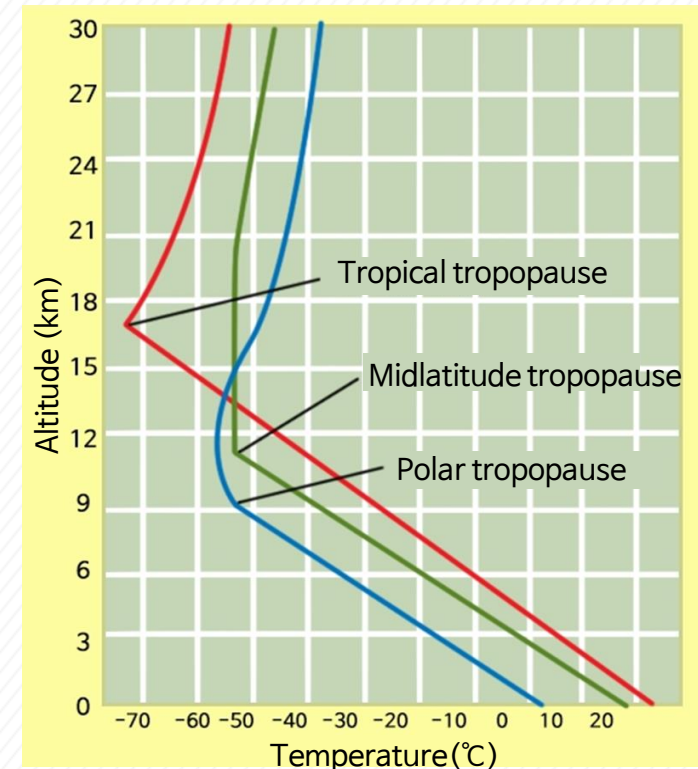
Learning Activities

3. Atmospheric structure by temperature

The height of the tropopause varies. It is normally higher over equatorial regions and lower in the pole due to the temperature.

In some regions, the tropopause is difficult to locate where the tropospheric air mixes with stratospheric air or vice versa. The disappearance of tropopause is due to the strong Jet streams of over 50m/s. You may think that 'the closer you are to the sun, the higher the temperature should be'. However, temperature decreases as you move away from the ground because the Earth is affected by the Earth's radiation. Moreover, the atmosphere selectively transmits the radiative energy from the sun. This will be discussed later.

Even though the temperature is expected to be reduced as altitude increases, sometimes the temperature inversion occurs where the temperature increases with height



〈Tropopause height by regions〉

Learning Activities

3. Atmospheric structure by temperature

2) Stratosphere

The layer above the troposphere is called the stratosphere. The stratosphere rarely experiences meteorological phenomena with exception of strong thunderstorms penetrating from the lower troposphere. Temperature from the lowest stratosphere to about 20 km is constant at about -59°C and can increase up to -2°C above 50 km.

What causes the temperature increase with height in the upper stratosphere? The reason for the inversion in the stratosphere is that the gas ozone plays a major part in heating the air. As discussed in previous chapters, ozone absorbs ultraviolet (UV) solar energy. As solar energy passes through the stratosphere, it becomes smaller and smaller, so the temperature decreases due to less UV absorption. The area where the temperature is almost constant is the location where absorption of both UV and earth radiation occurs.

The stratosphere accounts for approximately 19.9% of total air mass. The troposphere and stratosphere together account for 99.9% of the total air mass. Because the atmosphere is a compressible, most of the atmospheric mass exists in the lowest two layers (troposphere and stratosphere). Although the thickness of the stratosphere is more than three times of that of the troposphere, it is only a quarter of the mass of the troposphere.

The stratospheric ozone layer exists from 20 km to 30 km above sea level. Ozone density near 25 km above sea level is the maximum at about 10 ppm. Although the stratospheric ozone concentration is low, it absorbs solar energy to increase the temperatures and protects the earth's life from harmful UV radiation.

In the stratosphere, the water vapor is rare. Also, the increase of temperature with height in the stratosphere results in strong atmospheric stability, inhibiting vertical motion that can form clouds. Therefore, precipitation cannot be observed, and particles injected by volcanic eruptions can stay in the stratosphere for months. Moreover, strong wind in the stratosphere spreads aerosols over the globe, forming a cover that blocks solar radiation.

Learning Activities

3. Atmospheric structure by temperature

3) Mesosphere

About 0.1% of the atmosphere is in the mesosphere which extends to roughly 80km above sea level. The air is extremely thin and the pressure is low. The ratio of nitrogen and oxygen in the mesosphere is about the same as that in the Earth's surface, but the number of molecules is much smaller than in the troposphere. The average temperature at the top of the mesosphere reaches -90°C which represents the coldest part of Earth's atmosphere.

Like the situation in the troposphere, temperature decreases with height. The solar radiation absorption at the bottom of the mesosphere supplying the heat into the mesosphere is dissipated by vertical motion.

4) Thermosphere

The “hot layer” above the mesosphere is called the thermosphere. This is because oxygen molecules absorb energetic solar rays and warm the air in this layer. As the altitude increases, the temperature may exceed $1,500^{\circ}\text{C}$.

Learning Activities

4. Atmospheric structure by composition

1) Heterosphere

The layer above 80km is called the heterosphere where the atmosphere is rare and its compositions are not uniformly distributed. In the heterosphere, atmosphere does not mix well and collisions between atoms and molecules are infrequent, so that the air is unable to keep itself stirred. Therefore, diffusion takes over as heavier atoms and molecules (such as oxygen and nitrogen) tend to settle to the bottom and lighter gases (such as hydrogen and helium) float to the top.

Thus, the heterogeneous layer can be divided into four layers according to the characteristic composition. Each layer is dominated successively by nitrogen molecules, oxygen atoms (O), helium atoms (He), and hydrogen atoms (H) in order of increasing height.

Gas	Symbol	Percent (by Volume)	Molecular weight
Nitrogen	N ₂	78.08	28.01
Oxygen	O ₂	20.95	32.00
Argon	Ar	0.93	39.95
Neon	Ne	0.002	20.18
Helium	He	0.0005	4.00
Krypton	Kr	0.0001	83.8
Xenon	Xe	0.00009	131.3
Hydrogen	H ₂	0.00005	2.02

〈Permanent Gases in the Atmosphere of the Earth〉

※ Source: Environmental atmospheric science (Kim, Kyung-Eak et al., Donghwa Technology) p13

Learning Activities

5. Atmosphere structure by electrical properties – Ionosphere

The ionosphere is not really a layer, but an electrified region with large concentrations of ions and free electrons in the upper atmosphere. The atoms or molecules that make up the atmosphere take short wavelengths of solar radiation for ionization, that is, photoionization. This creates an area rich in free electrons and positive ions at the top of the atmosphere.

The bottom of the ionosphere is usually about 60km above the Earth's surface. From here, the ionosphere extends upward to the top of the atmosphere. Therefore, the bulk of the ionosphere is in the thermosphere.

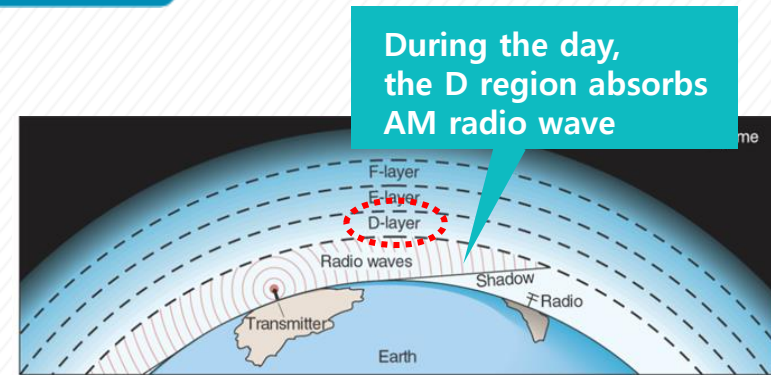
The ionosphere can be classified into D, E and F layers according to the density distribution of electrons. The F layer is divided into the F1 and F2 layers. The E layer gained its name because the electric field vector E of the wave is reflected in this region. Why is the electron density of the ionosphere different for different altitudes? It is because the solar radiation is selectively absorbed, and because the composition and density of the atmosphere change with altitude. Therefore, the fact that the ionosphere is divided into four layers does not merely reflect altitude differences, but by different physical processes.

Learning Activities

5. Atmosphere structure by electrical properties – Ionosphere

The ionosphere plays a critical role in the transmission and reception of radio waves. The ionosphere is important since it reflects AM radio signals back to the earth and allows one to broadcast to a large area. As shown in the figure, the lowest layer (D layer) is present only during the daytime and absorbs AM radio waves. At night, the D region gradually disappears and E layer weakens by free electron recombination giving rise to positive ions. Radio waves bounce repeatedly from the ionosphere (F layer) to the Earth's surface and back to the ionosphere, so the AM radio waves are able to travel for hundreds of kilometers during the night.

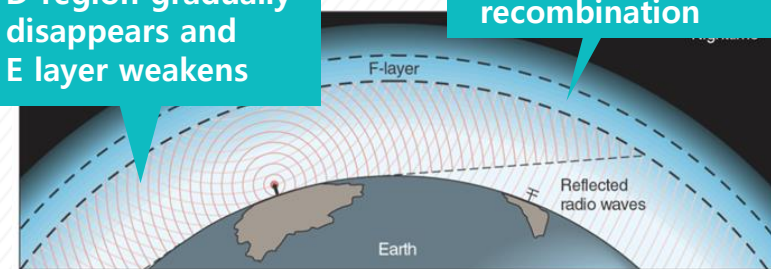
When you listen to AM radio at night, have you ever experienced a situation where you can hear a broadcast from a radio station but cannot hear it the next day? This phenomenon is related to the collapse of the D and E layers.



(a)

D region gradually disappears and E layer weakens

Producing positive ions by free electron recombination



(b)

(Role of the Ionosphere)

Learning Activities

5. Atmosphere structure by electrical properties – Ionosphere

Aurora is formed in the ionosphere as well, especially in the Arctic and Antarctic which is called Southern Lights and Northern Lights, respectively.

The ionosphere does not have much effect on the daily weather. However, you can see the polar lights, one of the most interesting phenomena. The Northern Lights and the Southern Lights are very diverse. Sometimes they appear to have vertical glints and movements, and sometimes they appear as continuous expansion of light or as fog.

The occurrence of polar light is related to the solar flare activity and magnetic field. The solar flare is a huge magnetic storm of the sun. A solar flare occurs when magnetic energy that has built up in the solar atmosphere is suddenly released. This magnetic storm emits enormous amounts of energy and fast moving atomic particles.

These changes generate currents of charged particles, which then flow along lines of magnetic force into the Polar Regions. These particles are boosted in energy in Earth's upper atmosphere, and when they collide with oxygen and nitrogen atoms, they produce dazzling auroral light. Since the occurrence of solar flares is closely related to the activity of the sunspot, there is a noticeable amount of aurora when the sunspot is at its maximum.

Summary

1. Air pressure and density

- Air density decreases with increasing altitude.
- Air pressure refers to the total mass of the atmosphere above a certain given level, consequently, the air pressure decreases as the altitude increases.
- Like air density, air pressure decreases rapidly at first, then decreases gradually at higher levels.

Summary

2. Thickness of the atmosphere

- Earth's atmosphere: the layer of gas that is bound to Earth's gravity, which is at about 1,000 km altitude.
- Due to the thin atmosphere, atmospheric motion typically occurs in the horizontal direction, which is more than 1,000 times larger than the vertical motion.
- The vertical motion, although small, significantly affects the state of the atmosphere.

Summary

3. Atmospheric structure by temperature

It can be classified into four layers according to the vertical temperature profile.

- Troposphere
 - Almost all meteorological phenomena occur in the troposphere.
 - As the altitude increases, the temperature decreases because the atmosphere selectively transmits the solar energy.
 - It is the thinnest layer, but contains 80% of the total mass.
- Stratosphere
 - Meteorological phenomena rarely occur, except the strong thunderstorm clouds which penetrate from the lower troposphere.
 - Temperatures from the lowest stratosphere to about 20 km are constant at about -59°C .
 - Near the top of the stratosphere of about 50 km, the temperature increases with altitude. (up to -2°C)
 - The main reason for high temperatures in the upper stratosphere: ozone absorbs UV solar energy.
 - The stratosphere accounts for about 19.9% of the total air mass.

Summary

3. Atmospheric structure by temperature

It can be classified into four layers according to the vertical temperature profile

- Mesosphere
 - 99.9% of the 0.1% of the atmosphere which is not included in the troposphere and stratosphere is in the mesosphere, stretching to about 80 km above sea level.
 - As the solar radiation absorption occurs in the lower mesosphere, the temperature decreases as the altitude increases, such as the troposphere.
- Thermosphere
 - As the altitude increases, the temperature increases and can exceed 1,500 °C
 - The temperature of the thermosphere is estimated by the kinetic energy of gas molecules.

Summary

4. Atmospheric structure by composition

- The atmosphere within 80km is chemically homogeneous, so it is called homosphere.
- The layer above 80km is called heterosphere where the atmosphere is rare and its compositions are not uniformly distributed.
- In heterosphere, atmosphere does not mix well and collisions between atoms and molecules are infrequent.
- As a result, heavier atoms and molecules (such as oxygen and nitrogen) tend to settle to the bottom and lighter gases (such as hydrogen and helium) float to the top of the layer.

Summary

5. Atmosphere structure by electrical properties

- The ionosphere is not really a layer, but an electrified region with large concentrations of ions and free electrons in the upper atmosphere.
- The bottom of the ionosphere is usually situated about 60km above the Earth's surface. Therefore, the bulk of the ionosphere is in the thermosphere.
- The reason why electron density of the ionosphere differs by altitudes is because the solar radiation is selectively absorbed, and the composition and density of the atmosphere change with altitude.
- The ionosphere is important since it reflects AM radio waves back to the earth and allows one to broadcast to a large area.
- Auroras are formed in the ionosphere, which are called the Northern Lights in the Arctic region and the Southern Lights in the Antarctic region.
- In the ionosphere, subatomic particles from the Sun are captured by the Earth's magnetic field region.
- The trapped energy makes the atmospheric gas excited.
- When the electrons return to the normal state, radiation gets released.
- The aurora does not reflect radiation like a cloud but rather absorbs light like a neon lamp.