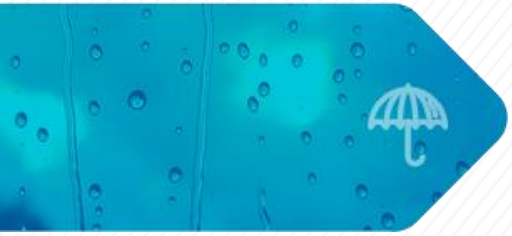
# Introduction to Meteorology

## 07 Water in the atmosphere
(evaporation, condensation, saturation)

## Introduction

The atmosphere is mainly made up of nitrogen and oxygen. The mass of water vapor in the atmosphere is less than 4% of the total air mass. Unlike nitrogen or oxygen, water vapor is influenced by the temperature and pressure, and it changes to various states. It can exist in solid, liquid, and vapor state and can change from one state to another. Although water vapor, or water, accounts for a very small fraction of the total air, it plays an important role in forming precipitation through clouds and ice crystals.

## Contents



1. Characteristics of water
2. Water cycle in the atmosphere
3. Change in the state of water

## Learning objectives

1. explain unique properties of water by understanding its molecular structure
2. Describe water cycle in the atmosphere.
3. Understand changes in the state of water and explain the energy involved.

# Learning Activities

## 1. Characteristics of water

Most of the liquid on the surface is in the form of water. Water has the following exceptional characteristics when compared to other liquids. First, water in solid, liquid, and vapor state can easily change to other states. Second, solid state of water (ice) is less dense than liquid water. Third, water has higher heat capacity than other liquids.

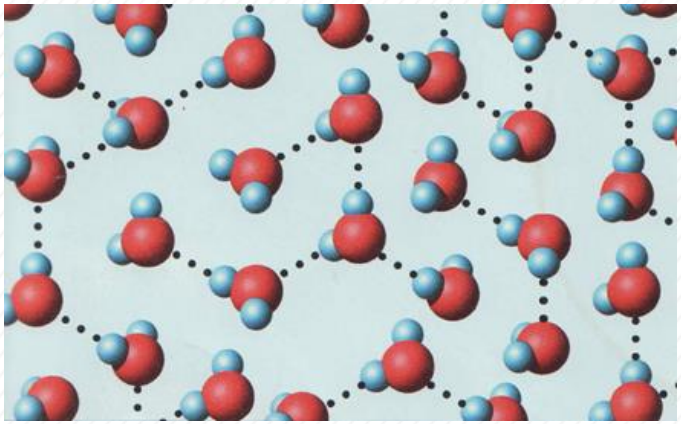
Such characteristics have great impact on Earth's weather and climate and provides an environment important to life on Earth. These characteristics of water occur because water molecule is constituted by hydrogen bonding. Let's take a closer look at the structure of water.

# Learning Activities

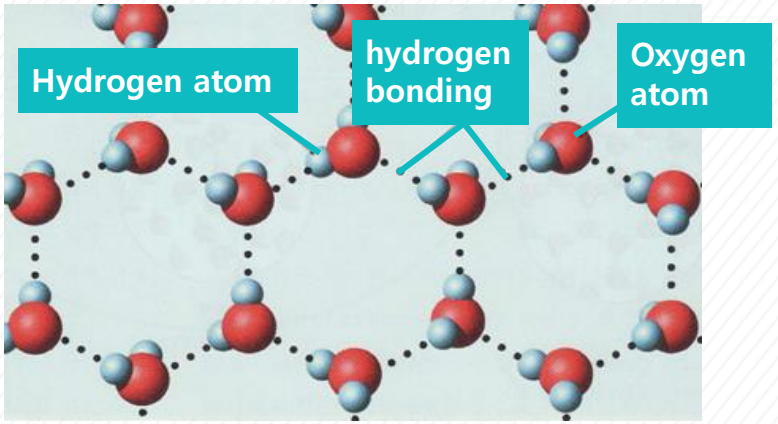
## 1. Characteristics of water

### 1) Hydrogen bonding

In the case of water, hydrogen bonds form between neighboring hydrogen and oxygen atoms of adjacent water molecules. The attraction between individual water molecules creates a bond known as a hydrogen bond. A water molecule ($H_2O$) consists of two hydrogen atoms bonded to an oxygen atom. Due to the high electronegativity of the oxygen atom, the oxygen end of the water molecule becomes partly negative, while the hydrogen end becomes partly positive. Consequently, this polarity of water molecule makes water molecules attract each other. The hydrogen of one water molecule is attracted to the oxygen of another water molecule, which is the hydrogen bonding of water.



〈Crystal structure diagram of liquid state water〉




〈Crystal structure of solid state water〉

※ Source: Atmospheric Science 10th Edition (Ahn, Joong Bae, et al., Sigma Press) p119

# Learning Activities

## 1. Characteristics of water

### 2) Density change

Now let's look at the change in water density. Ice is the solid state of water formed by hydrogen bonding. In an ice crystal, the water molecules are arranged in layers of hexagonal rings and are highly hydrogen bonded with the oxygen atoms of other neighboring water molecules. Because of the increased empty spaces between water molecules within the ice structure, ice becomes less dense than liquid water.

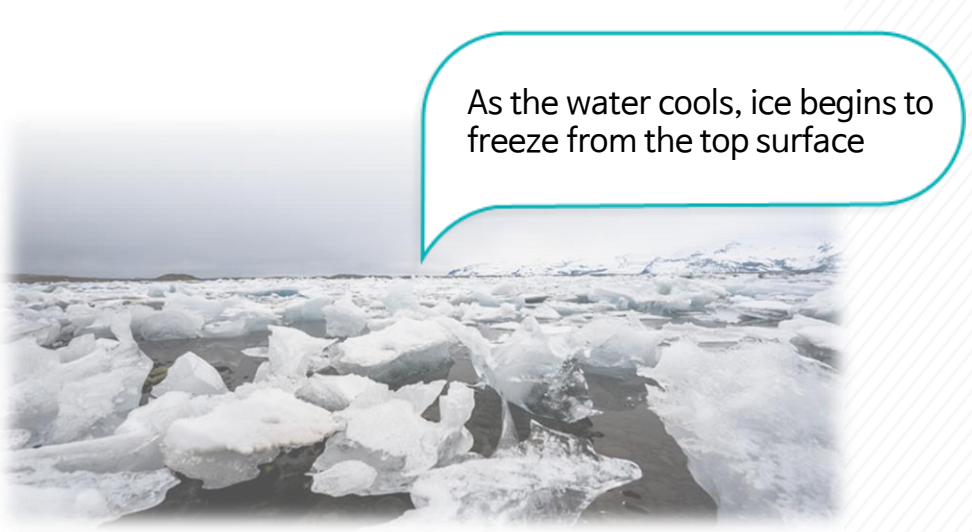
The strength of hydrogen bonds between water molecules forming ice is weaker than that of the chemical bond between oxygen and hydrogen forming water molecules. Therefore, warming ice above freezing does not separate water molecules into oxygen and hydrogen but break the hydrogen bonds between water molecules eventually leading ice to melt. Even if the ice melts, not all of the hydrogen bonds that make up the ice are cut off, but only some of the hydrogen bonds will be broken. Accordingly, liquid water molecules are arranged more narrowly than ice, resulting in higher density.

Reaching the maximum at 4˚C, the density of the water in the liquid state gradually increases as the temperature increases. As the temperature exceeds 4˚C, the energy of the water molecules increases, causing the molecules to distribute less densely as they move faster and faster, and their density gradually decreases. Since ice is less dense than water, the ice begins to freeze from the top surface. These characteristics of water have a profound effect on the atmospheric and oceanic circulation and the marine life.

# Learning Activities

## 1. Characteristics of water

If the density of ice were higher than that of liquid water, as the water freezes from the lake or ocean, marine life on the bottom would no longer survive. Likewise, Ice and glaciers would no longer function as insulation.



# Learning Activities

## 1. Characteristics of water

### 3) Heat capacity

Owing to the hydrogen bonds, water has a higher heat capacity than other liquid. When the water is heated, part of the energy is used to increase the movement of water molecules, and other energies are used to break hydrogen bonds. Therefore, water gets warmed up or cooled down more slowly than most other liquids, which means that the heat capacity of water is high. This is why the ocean is relatively warmer than the land in winter and cooler in summer.

# Learning Activities

## 1. Characteristics of water

### 4) Latent heat of evaporation

When water evaporates, the hydrogen bond is broken. For water molecule to move enough to break the attraction between the water molecules and for liquid water to evaporate, it needs energy.

The energy absorbed when liquid water evaporates to become vapor is called latent heat. Latent heat refers to the energy absorbed or released by a substance or thermodynamic system during the process without changing the temperature. Latent heat impacts weather and climate, significantly. When water vapor condenses in the atmosphere, it releases latent heat. This is called latent heat of condensation. The emitted energy increases the temperature of the surrounding atmosphere and makes it buoyant. Therefore, latent heat can lead to the growth of thunderstorms or contribute to the formation and development of typhoons.

# Learning Activities

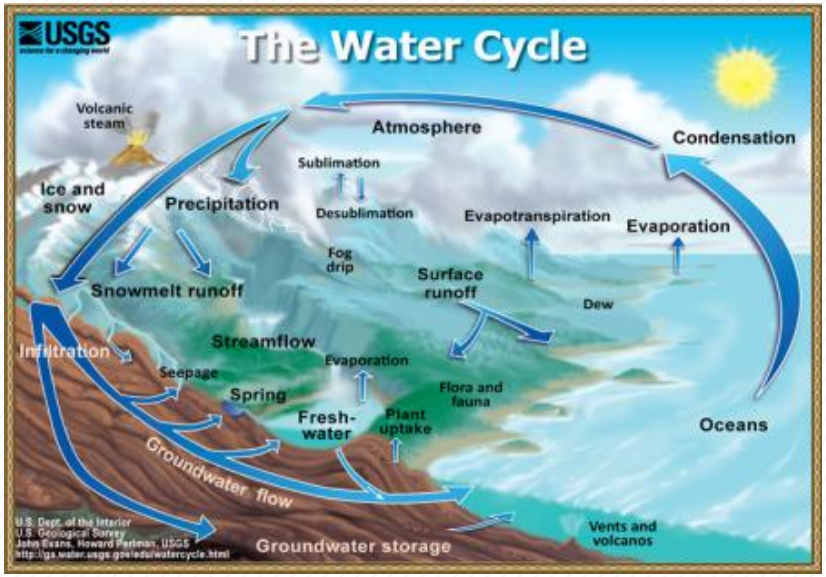
## 2. Water cycle in the atmosphere

### 1) The water cycle

The hydrosphere consists of ocean, glaciers, lakes, and river, and the ocean which occupies more than 70% of water. A process by which liquid water evaporates, and water vapor water vapor transforms back to liquid water is called the hydrologic (water) cycle.

Solar energy evaporates huge amount of water into the atmosphere. Through the process of condensation, water vapor becomes liquid or solid state, cloud particles. These cloud particles grow under certain conditions and fall to the ground. This is called precipitation and includes rain, snow and hail. The precipitation in the ocean evaporates into the atmosphere.

On the other hand, most of the precipitation on land will return to the ocean through the following complex pathways. Part of the precipitation on the land is permeated into the ground, and the rest runs off into low level areas, where it flows into lakes, rivers, etc., or ocean. The water flowing into the ground, lake, river, or ocean, is evaporated into the atmosphere. Some of the water may be intercepted by vegetation, and water taken up by plants moves upward and provides moisture into the atmosphere by a process called transpiration.




〈The water cycle〉

※ Source: Wikipedia

# Learning Activities

## 2. Water cycle in the atmosphere

### 2) Water balance

What is water balance? Water equilibrium refers to quantitative interpretation of water circulation. Since the total amount of water vapor distributed throughout the Earth's atmosphere remains almost constant, the average annual average precipitation and evaporation rate stays constant. However, precipitation is greater than evaporation over the land, while evaporation is greater than precipitation in the oceans. Therefore, to maintain the sea level, the deficit of water in the ocean should be supplemented by the water from the land. The total amount of water evaporated from the oceans is about 320,000 $km^{3,}$ per year and the total amount of evaporation from land is approximately 60,000 $km^{3,}$ per year. From the total evaporation (380,000 $km^3$), about 284,000 $km^{3,}$ and 96,000 $km^{3.}$ precipitate into the ocean and land, respectively. Approximately 36,000 $km^3$ of water from land flows into the ocean. The water cycle refers to the continuous circulation of water from the ocean to the atmosphere, from the atmosphere to the land, and from land to ocean.

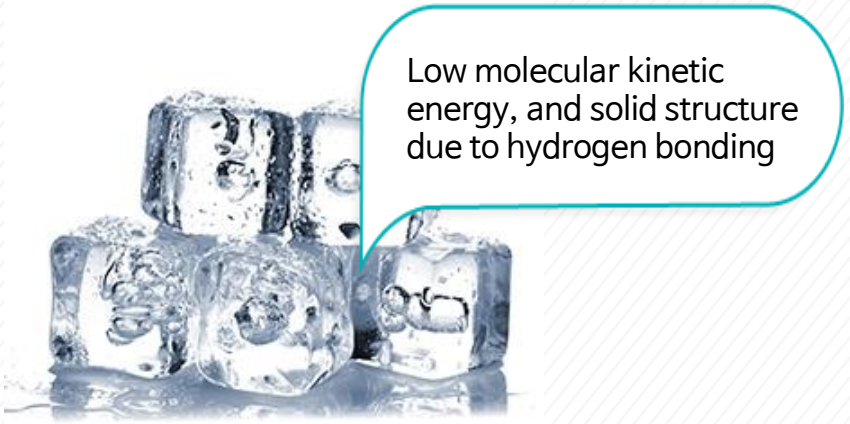
# Learning Activities

## 3. Change in the state of water

### 1) State of water

Solid state water (ice) has low molecular kinetic energy and solid structure due to the hydrogen bonding. Therefore, solid water molecules, compared to liquid or vapor molecules, the movement and vibration is inactive. If the ice is heated, the vibration and motion of molecules get faster and the solid structure is broken, and thus melted.

Although melted liquid water has also relatively strong bonding, the movement is relatively free. Therefore the liquid water has fluidity. If the water molecules in the liquid state are heated enough to break the surface tension of the water, it becomes vapor. These vapor molecules are very active and irregular. When the state of water changes, it can change the state of bonding between molecules or the distance between molecules.




〈Water molecule in solid state〉


〈Water molecules in liquid state〉

# Learning Activities

## 3. Change in the state of water

### 2) Evaporation, condensation, and saturation

Let's look at evaporation, condensation and saturation. Suppose you have a sealed container filled with pure water. A transparent film which cannot pass water vapor is covered inside assuming that there is no vapor in the empty space above the surface of the water in the container. If the film covering the water surface is removed, part of the water molecules will be evaporated in the form of water vapor. The process in which water molecules in a liquid state are separated and become water vapor is referred to as evaporation. The process of converting water vapor molecules into liquid water is called condensation.

In the early stages of evaporation, the amount of water vapor is less than the amount of condensed water. As time goes on, the amount of water vapor in a given space will increase until the rates of evaporation and condensation reaches to equal, which is called saturation.

For a liquid water to evaporate, it must absorb energy, which is called the latent heat of vaporization. On the contrary, the energy for water vapor to condense into liquid water is called the latent heat of condensation.

How much energy should be absorbed ~~in order~~ for liquid water to evaporate? The latent heat of vaporization required for water to evaporate is about 600 cal/g at 0℃ and about 540 cal/g at 100 ℃, respectively. In order for water vapor to condense into liquid water, it releases the equal amount.

# Learning Activities

## 3. Change in the state of water

### 3) Vapor pressure

The pressure due to water vapor in the atmosphere is called vapor pressure *(e).* Based on the ideal gas law, *e* equals $\rho_v R_v T$, *where* $\rho_v$ denotes a water vapor density ($kgm^{-3}$), $R_v$ is the specific gas constant (461 $J K^{-1} kg^{-1}$) of water vapor, and *T* is the water vapor temperature (K).

A saturation vapor pressure ($e_s$) is the vapor pressure when the water vapor is saturated at a given temperature. The unit of vapor pressure is usually hPa (hecto-pascal) or mb (millibar). 1 Pa is the pressure exerted by a force of magnitude 1N (newton) perpendicularly upon ~~an~~ unit area of one square meter ($m^2$). Units of Pa (Pascal) is equal to $Nm^{-2}$.

Saturated water vapor pressure changes with temperature. As shown in the figure, it gradually increases at temperatures below 0˚C and steeply increases as temperature increases. The saturated water vapor pressure as a function of temperature can be expressed as $e_s(T)$, as an exponential function. $e_{so}$ refers to a saturated water vapor pressure (= 6.11 hPa) at $T_0$ (= 273.15 K) and *L* represents the latent heat of condensation.

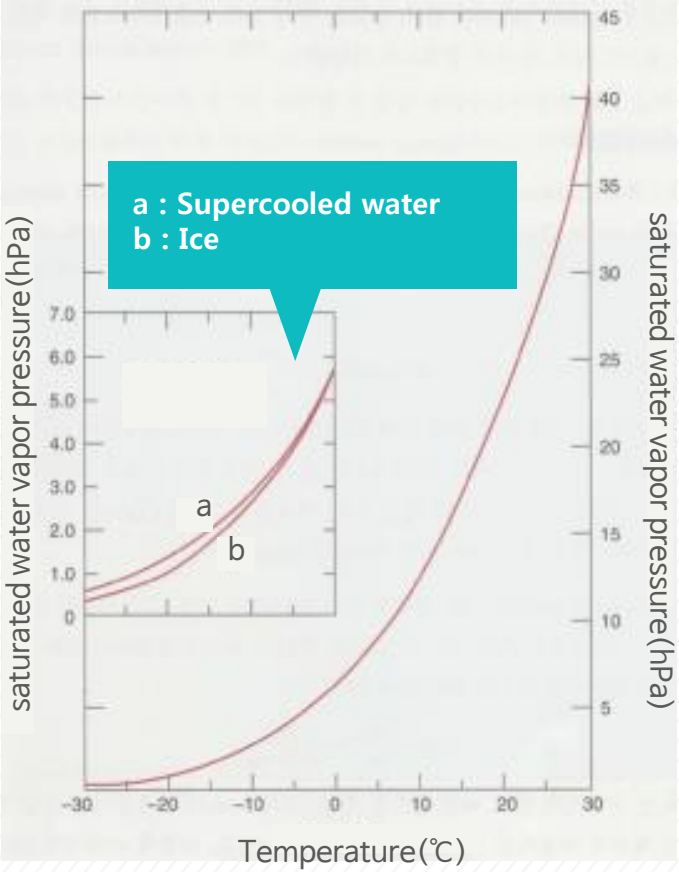
$$e_s(T) = e_{so} \exp\left[\frac{L}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

# Learning Activities

## 3. Change in the state of water

At the same temperature, the saturated water vapor pressure of the supercooled liquid water is higher than that of ice.

This is because the bonding force of the water that constitutes the supercooling liquid water is weaker than that of the ice water molecules. Therefore, the separation of water molecules from water is more likely to occur, consequently the saturation water vapor pressure becomes larger.




〈Change of saturated water vapor pressure as a function of temperature〉

※ Source: Environmental atmospheric science
(Kim, Kyung-Eak et al., Donghwa Technology) 73 page

# Learning Activities

## 3. Change in the state of water

### 4) Sublimation, deposition

〈Sublimation〉

Sublimation refers to the process in which a solid material does not go through the intermediate liquid state but turns into a gaseous state. Decrease in volume of ice in the freezer or white smoke in dry ice can be examples

# Learning Activities

## 3. Change in the state of water

〈 Deposition 〉

Deposition is a phase transition in which gases transforms into solid without passing through the liquid phase (opposite to sublimation).

For example, when a leaf cools down enough, water vapor in the air surrounding the leaf loses enough thermal energy to change into a solid and forms frost on the leaf. For sublimation, energy is absorbed from the surroundings, and when deposits occur, energy is released to the surroundings. In the case of water, up to 680 cal/g can be absorbed and released.

# Summary

## 1. Characteristics of water

Most of the liquid on the surface is water. Water has the following exceptional characteristics when compared to other liquids

- Water in solid, liquid, and vapor state can easily change to other states
- Solid phase of water (ice) is less dense than liquid phase of water.
- Water has higher heat capacity than other liquids.
  - These characteristics of water attributed from hydrogen boding of water molecules

# Summary

## 2. Water cycle in the atmosphere

- A process by which liquid water evaporates, and water vapor water vapor transforms back to liquid water is called the hydrologic (water) cycle.
- Water equilibrium refers to quantitative interpretation of water cycle. Since the total amount of water vapor distributed throughout the Earth's atmosphere remains almost constant, the average annual average precipitation and evaporation rate stays constant.
- Precipitation is greater than evaporation in land, and evaporation is greater than precipitation in ocean.
- To maintain the sea level constant, the deficit of water in the ocean should be supplemented by the water from the land.

# Summary

## 3. Change in the state of water

- When the state of water changes, it can change the state of bonding between molecules or the distance between molecules.
- The process in which water molecules in a liquid state are separated and become water vapor is referred to as evaporation. The process of converting water vapor molecules into liquid water is called condensation.
- The state when the evaporation and condensation is in equilibrium is called saturation.
- For a liquid water to evaporate, it must absorb energy, which is called the latent heat of vaporization.
- The energy for water vapor to condense into liquid water is called the latent heat of condensation.
- A saturation vapor pressure is the vapor pressure when the water vapor is saturated at a given temperature
- At the same temperature, the saturated water vapor pressure of the supercooled liquid water is higher than that of ice.
- Sublimation refers to a process in which a solid material does not go through an intermediate liquid state but turns into a gaseous state.
- Deposition is a phase transition in which gas transforms into solid without passing through the liquid phase (opposite to sublimation).