Introduction to Meteorology

10 Atmospheric stability

Introduction

Clouds form as air rises, expands, and cools. Why does the air rise on some occasions and not on others? Why do the shape and size of clouds vary so much? It is related to atmospheric stability.

Contents

1. Adiabatic process
2. Lapse rate of temperature
3. Atmospheric stability

Learning objectives

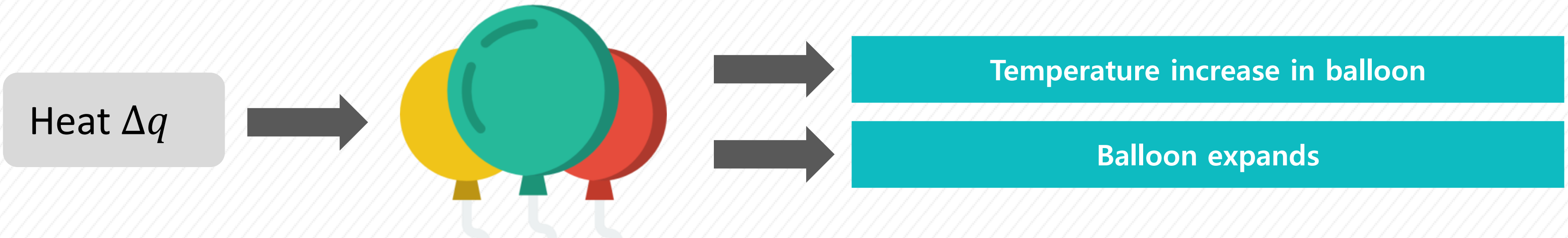
1. Understand the adiabatic process
2. Describe the temperature lapse rate
3. Explain atmospheric stability

Learning Activities

1. Adiabatic process

Heat of the atmosphere transfers to its surroundings through conduction, radiation, friction, etc. A thermodynamic change of state of a system in which the system exchanges energy with its surroundings by virtue of a temperature difference between them is called the diabatic process. Adiabatic process occurs without interchange of heat between the air parcel and its surrounding. The adiabatic process is a very useful concept in explaining cloud formation and development.

Let's take a look at the meaning of the adiabatic process using the first law of thermodynamics



〈Adiabatic process with the first law of thermodynamics〉

Let's consider a balloon with a unit mass of air. When heat is exerted to the balloon, part of energy by raising the temperature is used to increase the internal energy, and the rest is used in the work done by balloon to its surrounding, such as expansion.

Learning Activities

1. Adiabatic process

If the surface area of the balloon is A, the volume increase due to expansion is given by $\Delta V = A \Delta r$ and can be represented as follows:

$$\Delta q = \Delta u + \Delta W$$

Δq is the added heat, Δu is the change in internal energy, and ΔW is work done by the air (balloon expansion). This equation is a mathematical expression of the first law of thermodynamics and represents energy conservation. Internal energy change (Δu) is a product of the specific heat of constant volume (c_v) and the temperature change (ΔT). Work (ΔW) done through expansion is a product the pressure (p) and volume change (ΔV)

If Δq=0, this equation can be expressed as follows.

$$\Delta q = 0, \quad c_v \, \Delta T = -p \, \Delta V$$

When air parcel rises and expands adiabatically, temperature falls. If air sinks and compresses adiabatically, temperature rises. During adiabatic ascending, air molecules in the parcel (or the balloon) have to use their kinetic energy to expand the parcel. Therefore, the molecules lose internal energy and slow down their motions. Therefore, the temperature of the air parcel decreases with elevation. The opposite occurs for adiabatic descending motion.

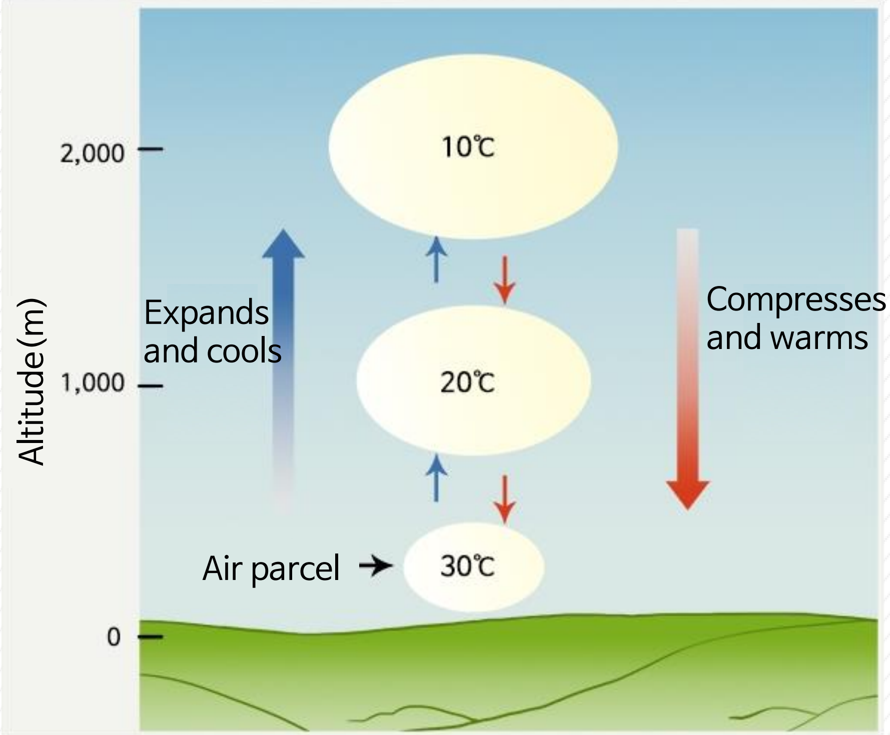
Learning Activities

2. Lapse rate of temperature

1) Dry adiabatic rate

Lapse rate includes dry adiabatic lapse rate, moist adiabatic lapse rate, and environmental lapse rate. First, let's look at the dry adiabatic lapse rate.

As the air parcel rises, it continually passes through altitudes with relatively low pressure. As a result, the ascending air expands and cools adiabatically. The unsaturated rising air cools at the lapse rate of 10 ℃ per 1km in altitude. Conversely, sinking air compresses and warms at 10˚C per 1km. Such cooling and warming rates only apply to unsaturated air moving vertically, which are called dry adiabatic lapse rates.

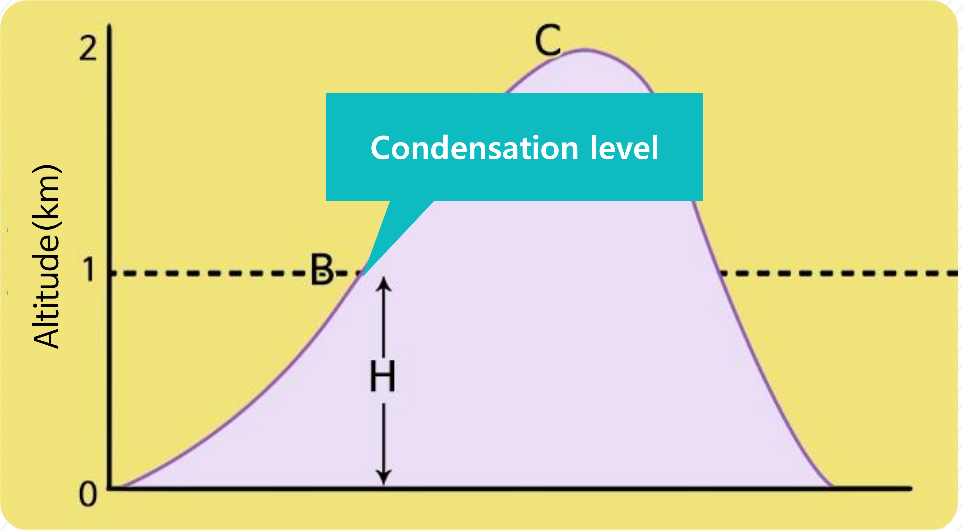


※ Source: Atmospheric environmental science (Min, Kyung-Deok et al., Sigma Press) p96

Learning Activities

2. Lapse rate of temperature

2) Moist adiabatic rate



If the air rises sufficiently high, it will cool to the dew point, and condensation process will start. When condensation occurs, cloud forms, water vapor evaporates, and latent heat gets released, which causes temperature to rise. Because the heat added during condensation offsets some of the cooling due to expansion, the air no longer cools at the dry adiabatic rate but at a lesser rate. This is called moist adiabatic lapse rate which is about 5 ℃ per 1km.

Learning Activities

2. Lapse rate of temperature

Unlike dry adiabatic rate, moist adiabatic rate is not constant and changes greatly depending on temperature and humidity. Warm saturated air contains more water than cold saturated air. Therefore, warm saturated air releases more latent heat by condensation. If the temperature of the rising air is very high, the moist adiabatic rate is much lower than the dry adiabatic rate. If the rising air temperature is very low, the moist adiabatic rate and the dry adiabatic rate are almost the same.

Warm rising air	Cold rising air
moist adiabatic lapse rate < dry adiabatic lapse rate	moist adiabatic lapse rate ≒ dry adiabatic lapse rate

Learning Activities

2. Lapse rate of temperature

3) Environmental lapse rate

The environmental lapse rate is the rate of air temperature change with altitude. Figure below shows the comparison between the environmental lapse rate and adiabatic lapse rate.

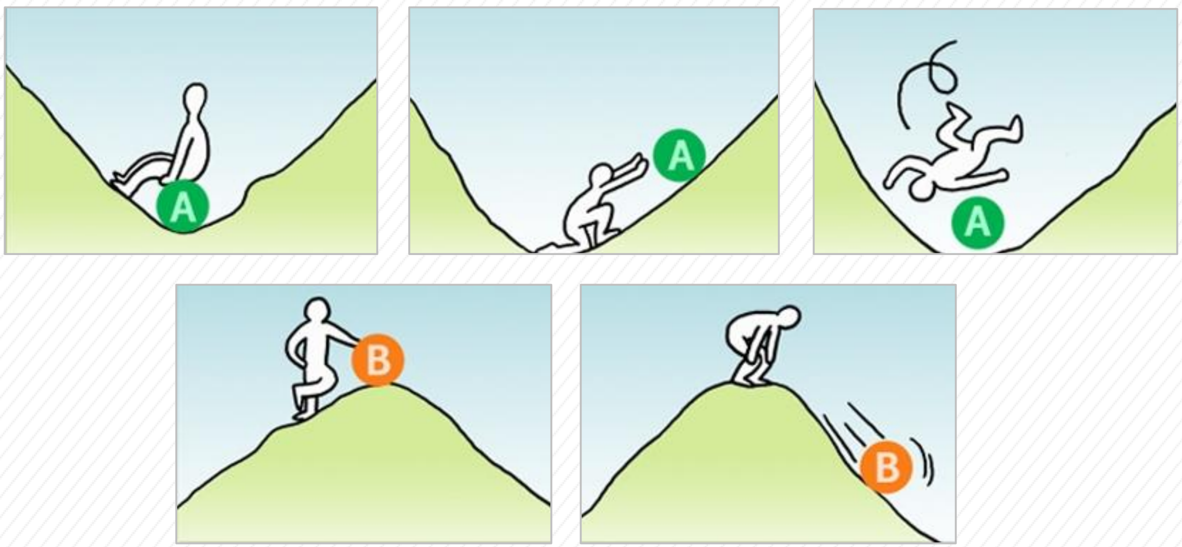
Environmental lapse rate		adiabatic lapse rate
The actual air temperature measured by the radiosonde or aircraft	VS	The temperature of a vertically moving air parcel.

Learning Activities

3. Atmospheric Stability

1) Stability

Atmospheric stability refers to equilibrium conditions. For example, the rock A placed in the depression is in a stable equilibrium. If the rock is pushed up, it quickly returns to its original position. Conversely, rock B on the top of the hill is in unstable equilibrium. So, even if you push a little, it will move away from its original position. Applying this concept to the atmosphere, the stable equilibrium state of the atmosphere refers to the tendency to return to its original position after being lifted or lowered. On the other hand, the atmosphere in unstable equilibrium refers to being away from its original position even with a little force.



※ Source: Atmospheric environmental science
(Min, Kyung-Deok et al., Sigma Press) p95

Learning Activities

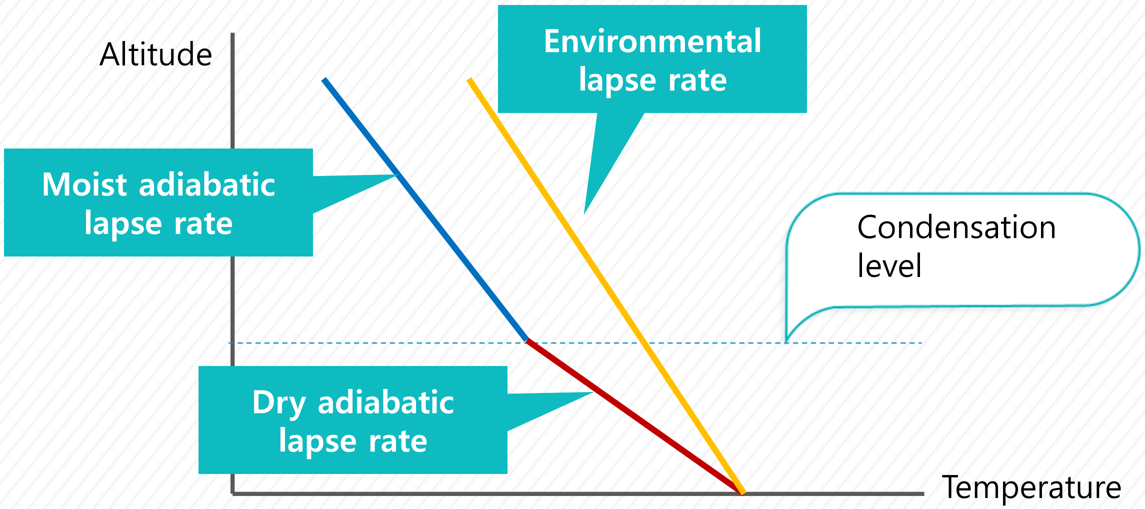
3. Atmospheric Stability

How can we easily explore the atmospheric stability? The stability of the atmosphere can be determined by comparing the temperature of the rising air to the ambient temperature. If the temperature of the rising air is lower than the surrounding air, the density of the rising air is higher, so the air parcel will sink back to its original position. In this case, the air is stable. Conversely, if the ascending air temperature is higher than its surrounding, therefore less dense, it will continue to rise until it becomes equal to the environment. This is an example of unstable air. In order to determine the stability of the air, it is necessary to measure the temperature of the rising air and the environment air at various levels.

Learning Activities

3. Atmospheric Stability

2) Absolute stability

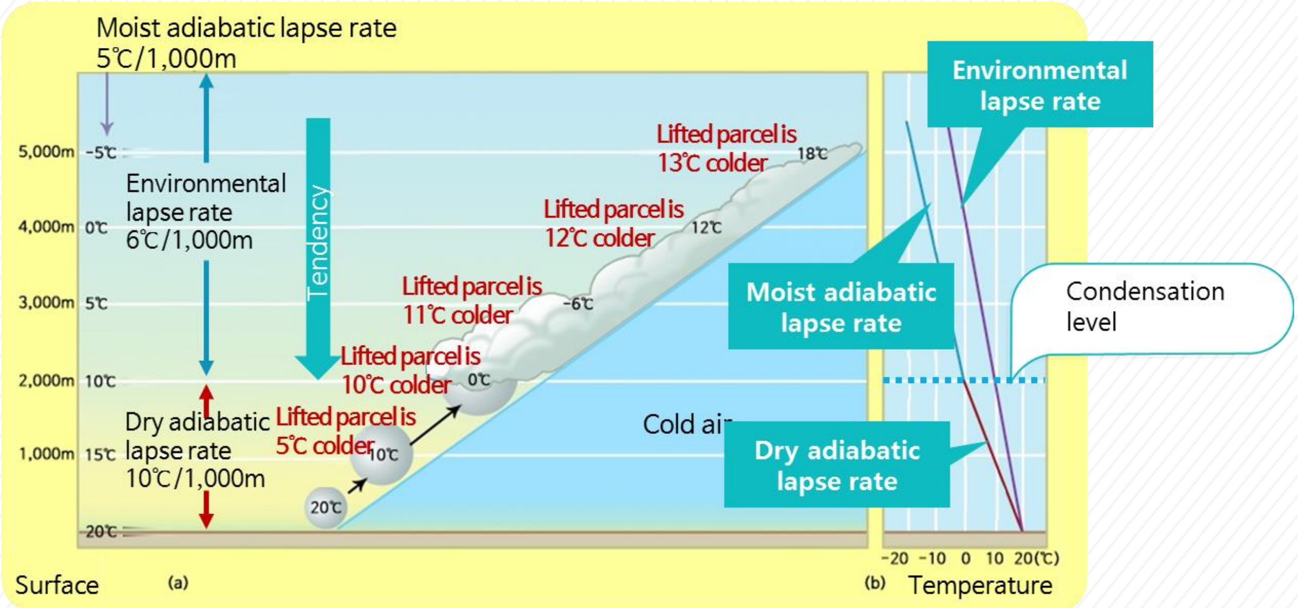


If a stable air is forced to rise above the lifting condensation level (LCL), this stable air will still be colder and denser than its surroundings and tend to return to the surface. Such stable condition of the atmosphere is called absolute stability. Absolute stability usually occurs when the environmental lapse rate is smaller than the moist adiabatic lapse rate.

Learning Activities

3. Atmospheric Stability

In the figure, the temperature of the unsaturated air on the surface is 20˚C. When this air rises, it expands and cools to 10˚C. The environmental temperature at that level is 15˚C. Therefore, the lifted air becomes colder and heavier than its surrounding, so that the air tends to return to its original level.



〈The composition of the volcanic gas〉

※ Source: Atmospheric science (Ahn, Joong-Bae, et al., Sigma Press) p143

Learning Activities

3. Atmospheric Stability

Since stable air strongly resists upward vertical motion, when it is forced to rise, it will spread out horizontally. If clouds form in this ascending air, they will also spread out horizontally, forming a relatively thin layer with flat bases and tops. In such a stable atmosphere, we might expect to see cirrostratus, altostratus, nimbostratus, or stratus.

An inversion represents an atmospheric condition where the air becomes warmer with height. The inversion occurs frequently on sunny nights or early morning before and after sunrise as a result of radiative cooling of the surface. Under such condition, air close to the ground will cool faster than the air above, causing an inversion. When an inversion exists near the ground, pollutants are kept close to the surface.

There are many other factors that increase atmospheric stability. First, it is the radiative cooling of the surface after sunset. After sunset, cold air near the surface stabilizes the atmosphere. Second, atmosphere can be stabilized through cooling of the surface air by cold air advection.

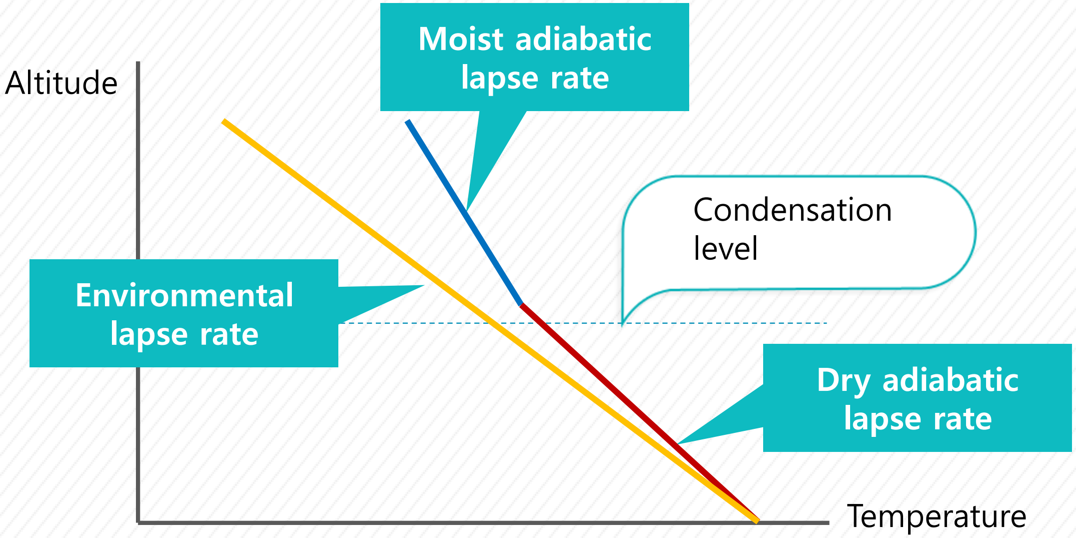
Finally, when the air sinks within its air column, the air is warmed over the large area as the air gradually falls and adiabatically compresses. The upper part of the air is heated more by compression than the lower part. In general, the air near the surface cannot subside, hence the temperature of the air near the surface does not change. Therefore, the air near the surface will warm up and stabilize the air.

The warming effect by subsidence of several hundred meters is enough to evaporate clouds. Therefore, clear sky can be seen under such condition. The inversion caused by subsidence is called subsidence inversion.

Learning Activities

3. Atmospheric Stability

3) Absolute instability

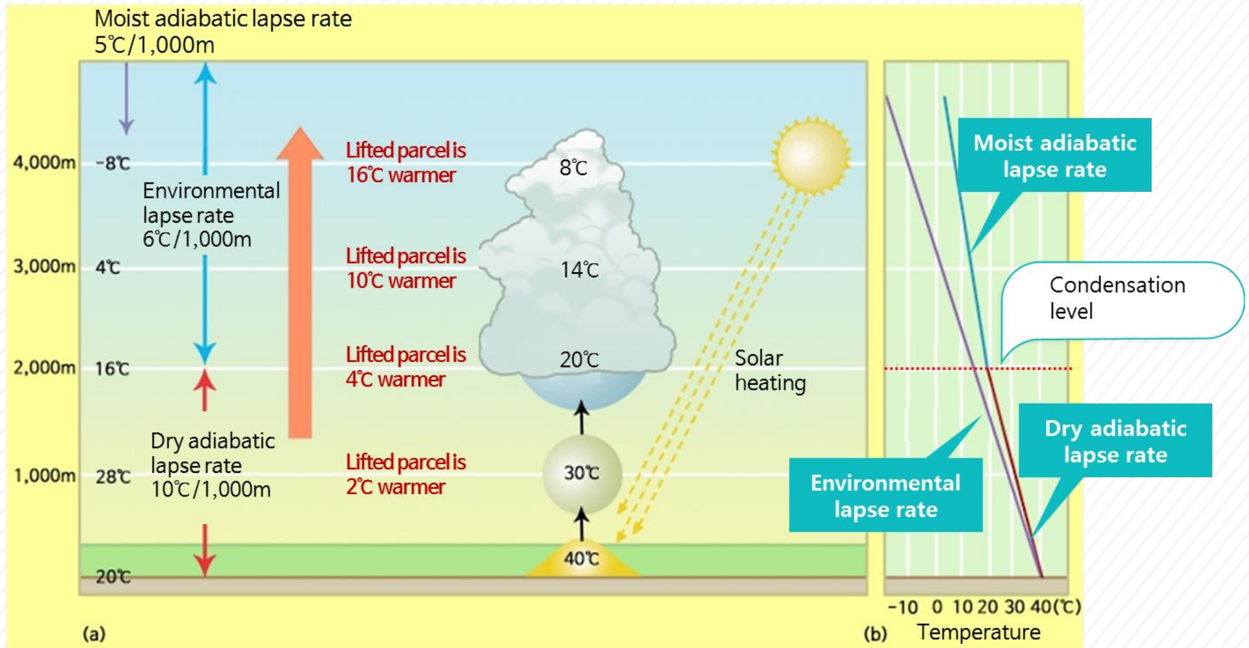


Absolute instability occurs when environmental lapse rate is greater than dry adiabatic lapse rate. If the ascending air parcel is always warmer than its surrounding, it continues to rise because of the buoyancy of the air. Such absolute instability occurs mostly on sunny and warm days when solar heating is intense. Under this condition, the surface becomes warmer than the air above, resulting in a very unstable atmosphere.

Learning Activities

3. Atmospheric Stability

Atmosphere becomes unstable when the temperature drops sharply towards the upper level. In the figure, as the altitude increases by 1 km, the temperature drops by 10˚C, which indicates that the environment lapse rate is 10˚C per 1km. Unsaturated dry air up to 2 km and saturated moist air up to 4 km have higher temperature than its surrounding at all altitudes. As the rising air is warmer and lighter, once the air starts to rise, it will continue to rise and move away from the surface.

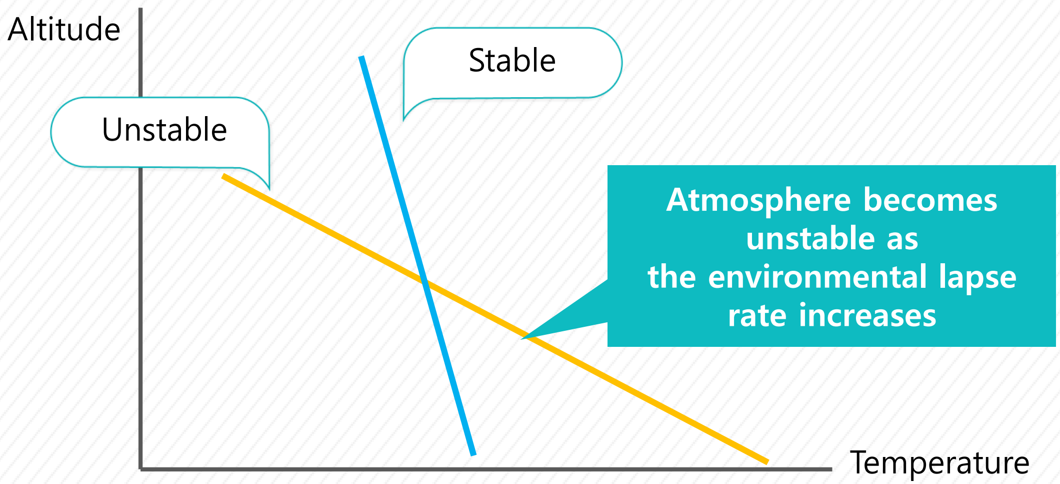


〈Absolutely unstable atmosphere〉

※ Source: Atmospheric science (Ahn, Joong-Bae, et al., Sigma Press) p144

Learning Activities

3. Atmospheric Stability



Atmosphere becomes unstable as the environmental lapse rate steepens. The increase in environmental lapse rate means faster decrease in temperature with increasing height. This can be caused by colder upper air or warmer surface air. Therefore, the factors that increase the instability are: the heating of the surface by the sun during the day, the warm air inflow, the radiative cooling at the top of the cloud, and the forced uplift by orography, frontal system, and convergence.

Learning Activities

3. Atmospheric Stability

In general, as the surface temperature increases during the day, the atmosphere becomes more unstable. The upper atmosphere can be cooled by cold air advection or radiative cooling. If the upper layer is dry and the moist lower layer moves up, it forms an unstable atmosphere. The air becomes more unstable as it rises and stretches vertically in the less-dense air aloft. Such stretching effect steepens the environmental lapse rate as the top of the layer cools more than the bottom. Instability by the lifting is often associated with the development of severe weather, such as thunderstorms and tornados. Absolute instability is usually limited to a very shallow layer near the surface on hot and sunny days. In such case, the environmental lapse rate can exceed the dry adiabatic rate, and the lapse rate is called super-adiabatic.

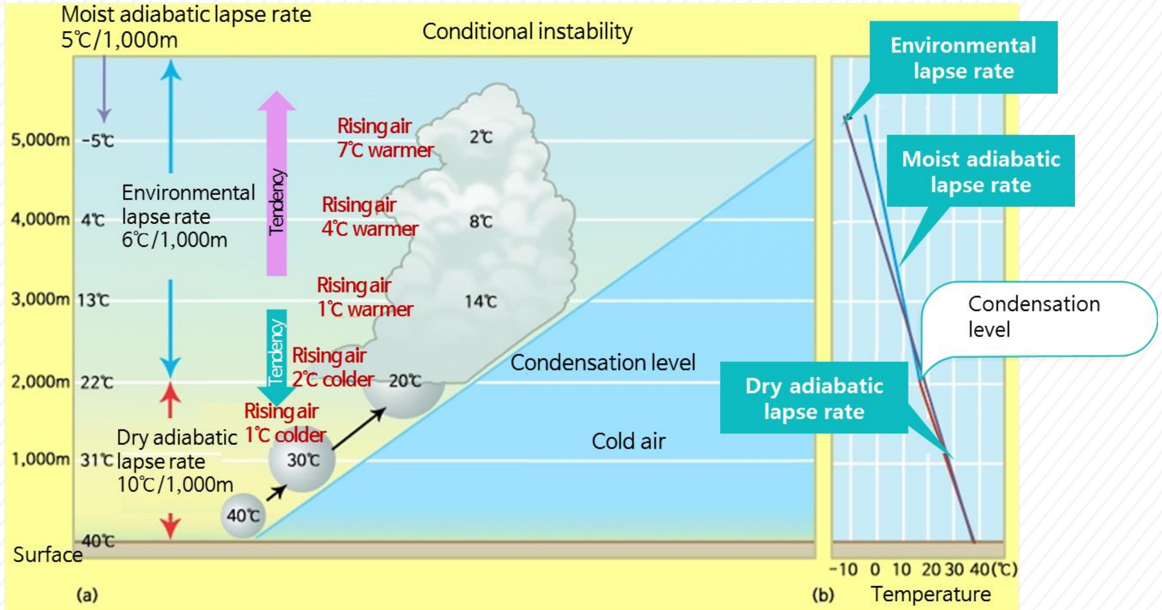
Learning Activities

3. Atmospheric Stability

4) Conditional instability

The atmosphere is conditionally unstable when the atmosphere is stable with respect to the unsaturated air and unstable with respect to the saturated air. This occurs when the moist air has an environmental lapse rate between the moist and dry adiabatic lapse rate.

In the figure, you can see that the rising air parcel is colder than its surrounding within 2 km. In other words, the atmosphere up to this altitude is stable. The parcel will expand as it ascends and its temperature will cool with a dry adiabatic lapse rate until it reaches the dew point temperature. The rising air saturates and the relative humidity becomes 100%, and as it continues to rise, condensation takes place and clouds form. Lifting condensation level (LCL) is the altitude at which clouds are first formed. Above the LCL, the latent heat release causes the air parcel to become warmer than the surroundings. From this altitude, the air continues to rise due to buoyancy, without external force, and is cooled with a moist adiabatic lapse rate.



〈Conditionally unstable atmosphere〉

※ Source: Atmospheric science (Ahn, Joong-Bae, et al., Sigma Press) p145

Learning Activities

3. Atmospheric Stability

The level where the parcel, after being lifted, becomes warmer than the air surrounding, is called the level of free convection. Atmospheres up to 5km in altitude show that the rising air has changed from stable to unstable because it contains enough moisture for saturation, cloud formation, and latent heat release to heat the air. If clouds were not formed, the temperature of the rising air would have been lower than the ambient air at all altitudes.

The atmospheric layer from the surface to an altitude of 5 km is called a conditionally unstable atmosphere, because its stability depends on whether the rising air saturates or not.

In the figure, the environmental rate is 9 ˚ C per kilometer, which is between the dry and moist adiabatic lapse rate. Such situation causes conditional instability. The role of stability that determines the daily weather very important. Depending on the stability of the atmosphere, clouds will develop and produce heavy precipitation or thunderstorm

Summary

1. Adiabatic process

- Adiabatic expansion
  - As the air rises, air expands and cools without interchange of heat with its surroundings.
- Adiabatic compression
  - As the air sinks, air compresses and warms without interchange of heat with its surroundings.

Summary

2. The temperature lapse rate

- Dry adiabatic lapse rate
  - The rate of the decreasing air temperature when the unsaturated air rises.
- Moist adiabatic lapse rate
  - The rate of the decreasing air temperature when the saturated air rises.
- Environmental adiabatic lapse rate
  - The rate of air temperature change with altitude.

Summary

3. Atmospheric stability

- Absolute stability
  - When the air rises or sinks, it does not rise or fall anymore, so that the air tends to return to its original level. $(\gamma < \gamma_{\delta})$
- Absolute instability
  - When ascending (descending) air continues to rise. (fall) $(\gamma > \gamma_{d})$
- Conditional instability
  - When the atmosphere is stable with respect to the unsaturated air and unstable with respect to the saturated air. $(\gamma_{\delta} < \gamma < \gamma_{d})$