ENVIRONMENTAL PHYSICS

Atmospheric Stability

An understanding of why and how air moves in the atmosphere is fundamental to the prediction of weather and climate. What happens to air as it moves up and down is largely governed by fundamental thermodynamics, and governs the types of cloud and precipitation we experience.

1) First Law of Thermodynamics

The atmosphere is a compressible gas, subject to the transfer of energy from radiative processes and changes of state. There are two fundamental processes which result in a change of air temperature:

Diabatic - A process in which heat is added or subtracted from the system, e.g., solar heating, radiation cooling.

Adiabatic - A process in which heat is neither added nor subtracted from the system. In the atmosphere, a process is said to be adiabatic when the expansion or contraction of air happens fast enough for no heat to be exchanged with the surrounding atmosphere. Air has low thermal conductivity, and the bodies of air involved are very large, so transfer of heat by conduction is negligibly small. We will focus on adiabatic processes in this resource.

> Try this at home… Put a thermometer in a 2 litre, empty plastic drinks bottle and close the lid firmly. Leave it for long enough for the thermometer to adjust, then try squeezing the bottle hard. What happens to the temperature? Then release the bottle – what happens now?
> You should see at least a 0.5°C warming when you squeeze the bottle, which then returns to the previous temperature when you release it.

Adiabatic Warming As you squeezed the bottle, the energy you used to compress the air inside is used to increase the kinetic energy of the molecules, raising the temperature.

Adiabatic cooling When you release the bottle, the air inside the bottle does work against the atmosphere outside the bottle. In doing this work, the air inside the bottle uses molecular kinetic energy and the temperature falls. No heat has been added or removed from the system yet the expanding air cools. As you saw, this process is **reversible**.

2. Lapse Rates

The lapse rate is defined as the rate at which temperature decreases as altitude increases. For example, consider a small, isolated parcel of air. When the air is forced to rise (maybe because it has encountered a barrier such as a mountain, or because heat has been added to it from the Earth's surface and it is warmer than the surrounding air) it expands with PV/T = constant according to the Ideal Gas Law, because the pressure is lower at higher altitudes. As the air parcel expands, it pushes on the air around it, doing *work*. Since the parcel does work and gains no heat, it loses *internal energy*, and so its temperature decreases. The reverse occurs for a sinking parcel of air.

There are two types of lapse rate:

i)   **Environmental lapse rate** - **ELR** : which refers to the actual, observed change of temperature with altitude. The ELR at a given place varies from day to day and even during each day. The temperature of the atmosphere does not always fall steadily. For example there can be an *inversion* layer in which the temperature actually rises with increasing height. The internationally accepted average ELR is 6.49 °C/km.

ii)   The **adiabatic lapse rates** - which refer to the theoretical change in temperature of a mass of air as it moves upwards and cools adiabatically. There are two adiabatic lapse rates:

- Dry adiabatic lapse rate- **DALR**. This is the rate at which completely dry air cools as it rises and expands. Alternatively, a rising parcel of moist air can cool at the DALR if it doesn't rise far enough, and cool enough, to become saturated. The DALR is 9.8°C/ km.
- Saturated adiabatic lapse rate – **SALR.** This is the rate at which air cools as it rises and expands when condensation is taking place, releasing *latent heat* into the air. The SALR is very dependent on pressure and temperature, and typically ranges from 3 °C/km to 9.78 °C/km in the atmosphere. The SALR is sometimes called the moist adiabatic lapse rate.

Mount Everest is 8850m high. If the temperature at sea level at this latitude is 30°C, then, assuming a lapse rate of 6.49 °C/km, the temperature at the top of the mountain would be -27°C!
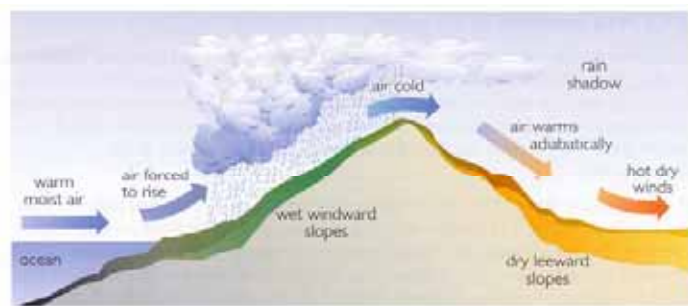

Moisture in the atmosphere

The amount of moisture in the atmosphere is usually given by the relative humidity – the water vapour content of the air as a percentage of the water vapour needed to saturate the air at the same temperature. A useful rule of thumb is that the relative humidity will rise by a factor of 2 for each 11.1 °C decrease in temperature, assuming conservation of absolute moisture. When the relative humidity reaches 100%, the air is saturated and water droplets could form. The temperature at which this occurs is known as the *Dew Point*. The process is complicated by the need for the presence of surfaces (e.g. tiny particles) for the water to condense onto.

Orographic uplift, Mountain Clouds and the Föhn Effect

Cloud formed upstream of the Matterhorn in rising air (photo taken from the CloudBank image library of the Royal Meteorological Society)

- When an air parcel approaches a barrier, like a mountain range, it is forced to rise. As it does so, the pressure falls, the air expands and the temperature falls. As no heat is transferred to or from the air, this process is adiabatic.
- The temperature of the air may fall below the point at which cloud can form, in which case the top of the mountain may be covered in a cap cloud, and latent heat is released as the water vapour condenses. It may rain or snow.
- Downstream of the mountain, gravity pulls the air back down to Earth. As the air falls, it warms adiabatically again. However, if rain fell and removed water from the air, the latent heat taken up as the cloud droplets evaporate will be less than the latent heat released on the other side of the mountain, and so the air can end up warmer - the process is no longer reversible. The classic example is the Föhn wind, which blows south from the Alps. In the right conditions, the air temperature downstream of high mountain ranges can warm 20-30°C in just a few hours. This wind is called the Nor'Wester in New Zealand, the Chinook in North America and the Mistral in France.

Sometimes an air parcel starts off unsaturated, but as it rises and cools at the DALR, it reaches the temperature at which water droplets can form and so as it rises further it cools at the SALR.

Lenticular clouds in the crests of mountain waves. This vertical layering of lenticular clouds can happen if there are alternating layers of relatively dry and relatively moist air.

Copyright Andy Cutcher.

How do we determine the lapse rates?

The DALR is theoretically determined using the First Law of Thermodynamics. The SALR can similarly be determined if the initial moisture content, pressure and temperature of the air is known. However, to establish the ELR, measurements must be made, for example using weather balloons and radiosondes.

3. Stability of the Atmosphere

The stability of the atmosphere is an assessment of what would happen to an isolated parcel of air as it is displaced vertically. The stability of the atmosphere determines the likelihood of convection, and hence cloud type, likelihood of atmospheric turbulence, and the extent of mixing of pollutants etc. To determine stability classification we must examine the tendency of the atmosphere to resist or enhance an initial

displacement. The stability of the atmosphere is basically determined by comparing the lapse rate of a parcel of air to the lapse rate of the surrounding air. If we know the temperature and humidity of the air parcel before it begins to rise, then we can accurately determine the temperature change as it rises.

A few simplifying assumptions have been made:
   i)   The pressure of the parcel of air and the surrounding atmosphere are the same.
   ii)   As a parcel of air rises or sinks, there is no compensating motion in the displaced environmental air. The environment around the parcel is static.
   iii)   The rising or sinking parcel is isolated from the environment such that the rising and sinking air and the environmental air do not mix.

There are three basic categories in which the atmosphere can be classified in terms of stability - stable, neutral, and unstable. We will also consider two special cases – conditional and convective instability.

The Stable Atmosphere

A stable atmosphere is one that is strongly resistant to change. If some external force such as *lifting* or *convergence* pushes the air parcel upward, the temperature of the rising air relative to the environment suggests that the air would prefer to go back to its original position. If pushed down, the air parcel tends to rise.
Imagine a cork floating on a lake. If you push the cork under water then release it, the cork would float back to the surface. Likewise, if you were to lift it out of the water then let it go, it would fall back to the surface. The cork is denser than the air and less dense than the water, so it falls or sinks to the surface where it is in equilibrium with its environment. This is very much like a stable atmosphere.

In a stable atmosphere, if you lift a parcel of air and it cools at the DALR or SALR, the temperature of the rising air will decrease fast enough that its temperature will always be colder than the temperature of the surrounding atmosphere, and it will be denser. If the force pushing the air up suddenly disappeared, the parcel would sink back down to its original position where its temperature and pressure would be in equilibrium with the environment. Another way of stating that the atmosphere is stable, remembering that a positive lapse rate indicates a decrease in temperature with height, is to say that the lapse rate of the rising air is greater than the lapse rate of the environment.
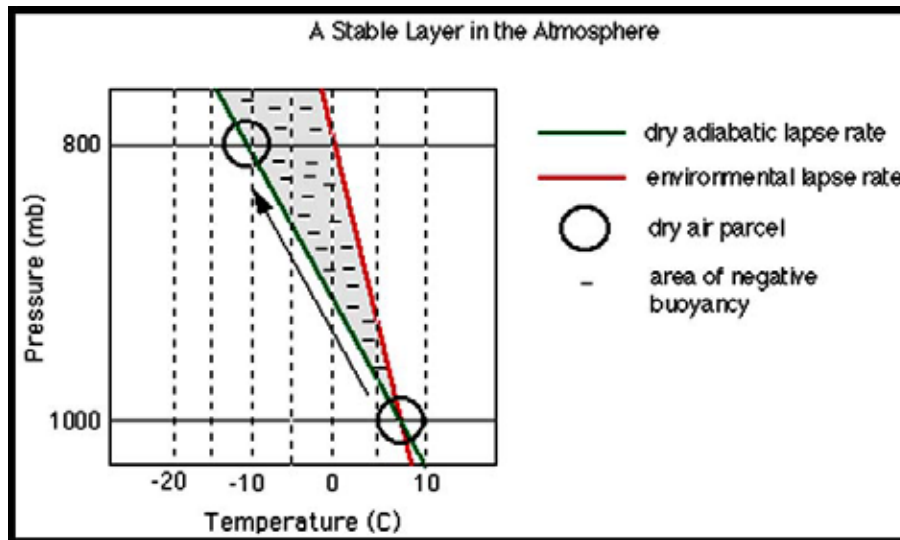**Inversions**
A region of the atmosphere with a negative lapse rate, is considered extremely stable and is called a temperature inversion. These inversions near the surface often occur in the early morning hours before sunrise. Pollution episodes are commonly associated with inversions, as pollutants are trapped in the lowest layers of the atmosphere.

Fog, or ground level cloud, forms where there is a ground level temperature inversion and the atmosphere is therefore extremely stable, forming a lid to the fog layer. The air near the ground cools (through losing infra-red radiation to space) until it becomes saturated and cloud forms. The inversion clears when sunlight warms the Earth's surface.
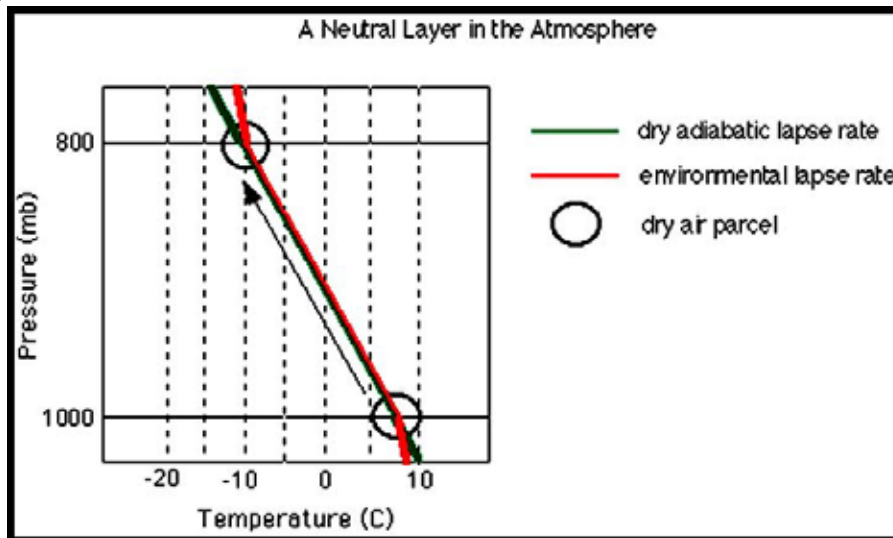
(photo taken from the CloudBank image library of the Royal Meteorological Society)

Consider a parcel of dry air which is lifted from a pressure of 1000mb (ground level) at 7 °C to a pressure of 800mb (80kPa) [meteorologists prefer to work in pressure rather than height coordinates, as they are independent of the local height of the surface of the Earth]. At 800mb the temperature of the parcel is -10°C while the temperature of the surrounding air is about 1°C. As the diagram below shows, the DALR is greater than the average ELR and so at every pressure level the rising parcel is colder than the environment. If at any time during the expansion the lifting force disappeared, the parcel would sink back to the 1000mb pressure level.
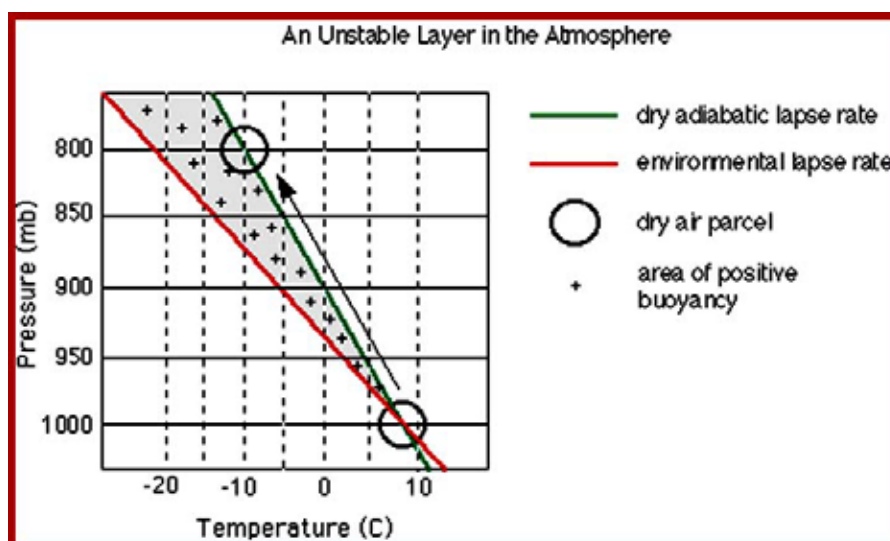

The Neutral Atmosphere

In a neutral atmosphere, the lapse rate of the parcel (dry or saturated) is identical to the environmental lapse rate. If a parcel of air is lifted, the temperature and pressure of the parcel will be identical to the temperature and pressure of the surrounding air at every height and is always in equilibrium with the environment. If the force producing the motion ceases, the parcel will neither continue to rise nor begin to sink, but stay where it is. Neutral conditions are rare in the real world!

Consider a dry parcel of air lifted again from 1000mb to 800mb through an atmosphere where DALR=ELR. At 1000mb the parcel and the environment have a temperature of about 7 °C. If the parcel is lifted to 800mb, the temperature of the parcel and the environment is -10 °C. As the parcel rises and cools, it remains at the same temperature and pressure as the surrounding air. At every height, the parcel is in equilibrium with the environment.
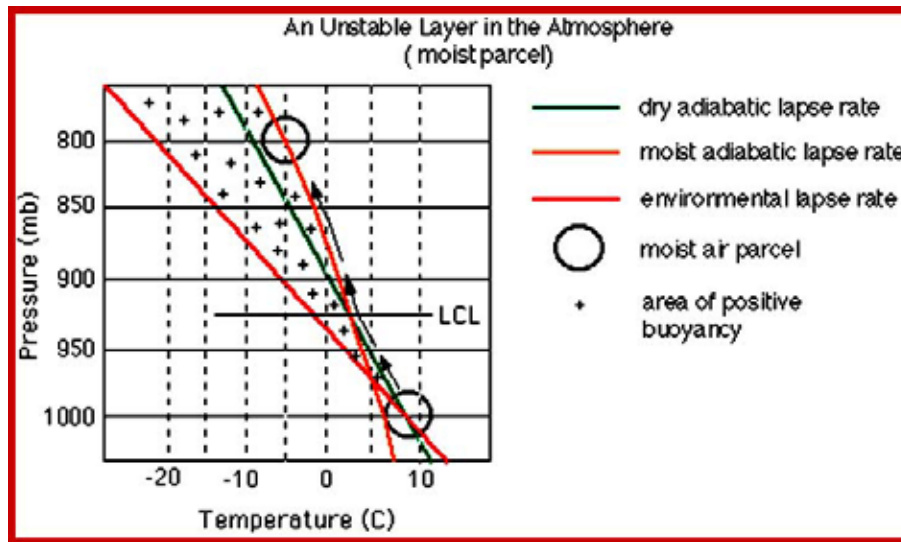
The Unstable Atmosphere

If the lapse rate of a rising parcel is less than the lapse rate of the surrounding atmosphere, is it said to be unstable. Though the parcel cools as it rises, its temperature remains warmer than the surrounding air. Because the parcel is warmer than the environment, it is less dense, and therefore continues to rise after the lifting force disappears.

Consider the case of a parcel of dry air that is lifted through an atmosphere where the DALR is less than the ELR. Just as before, at 1000mb the parcel and the surrounding air are at 7 °C. At 950mb the parcel has cooled to about 5 °C but is 2°C warmer than the surrounding air, and will therefore continue to rise once the lifting force is removed. In fact, the parcel will be warmer than the surrounding air at all levels, and therefore only a tiny lift could start it rising to high levels, as long as it remains warmer than the surrounding air.

So far, we have limited our examples to lifting a dry parcel. What if, more realistically, there is some moisture in the air parcel?

As before, consider a parcel or air lifted from 1000mb and at an initial temperature of 7°C. It is initially unsaturated and cools according to the DALR. The DALR is less than the ELR and so the parcel is unstable. At 925mb, the parcel has cooled enough for it to become saturated (this depends on the initial moisture content of the parcel). This level is known as the Lifting Condensation Level (LCL). Above the LCL, the parcel cools according to the SALR, which is even less than the DALR, so the parcel continues to be unstable.
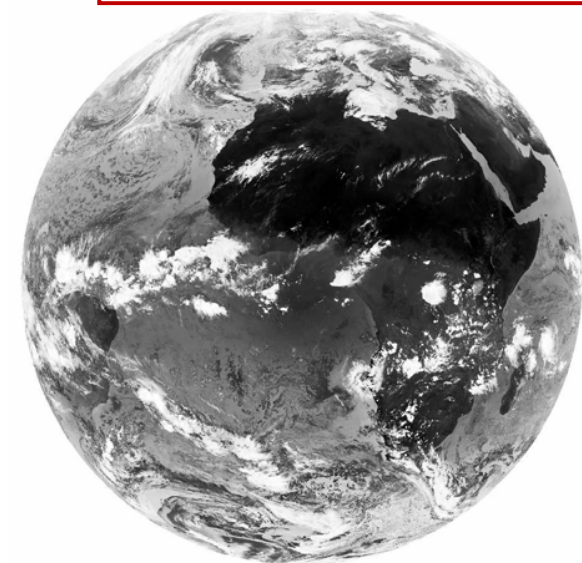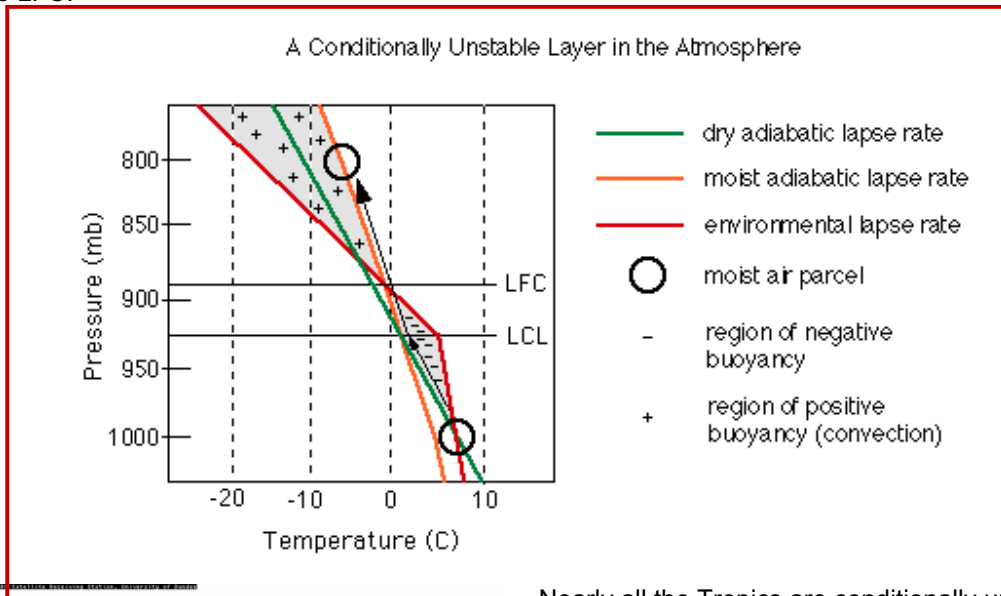

Unstable environments are common in the afternoons during the summer and are often responsible for producing late afternoon thunderstorms. The initial lifting force is provided by heat transferred from the ground to the air, which then continues to rise far into the atmosphere, producing fast updrafts and stunning cumulus and cumulonimbus clouds.

(photo taken from the CloudBank image library of the Royal Meteorological Society)

Conditional Instability

The atmosphere is described as conditionally unstable if the environmental lapse rate is less than the dry adiabatic lapse rate beneath the LCL and greater than the saturated adiabatic lapse above the LCL. Conditional instability can easily be determined by comparing all three lapse rates.

As before, consider a parcel or air lifted from 1000mb and at an initial temperature of 7°C. It is initially unsaturated and cools according to the DALR. The DALR is now greater than the ELR and so the parcel is stable. At the LCL, the parcel has cooled enough for it to become saturated. Above the LCL, the parcel cools according to the SALR, which is less than the DALR, so, as shown in the diagram, at some level the parcel becomes warmer than the surrounding atmosphere and becomes unstable. The point between the stable and unstable regions, where the parcel temperature and the environmental temperature are equal, is called the Level of Free Convection (LFC). The atmosphere is only unstable to parcels which are lifted past the LFC.

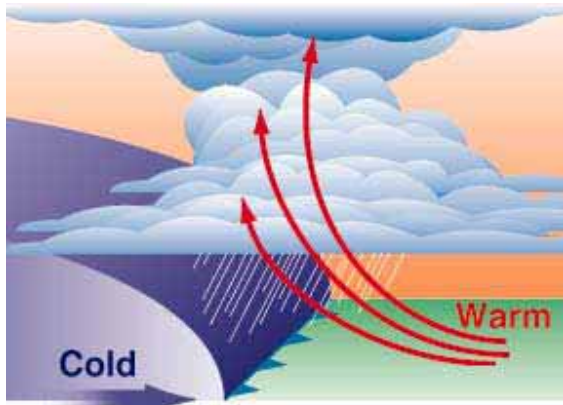A Conditionally Unstable Layer in the Atmosphere

Nearly all the Tropics are conditionally unstable up to a height of about 15 km, but there is only sufficient lifting to cause deep convection in a few tropical locations, as shown in this satellite image by the presence of clouds.

Geostationary infra-red satellite image 1200UTC, 4/3/2008 Copyright Dundee Satellite receiving station.

Convective or Potential Instability

Until now, we have only considered lifting a single isolated parcel to determine the stability of the atmosphere. While this might be appropriate for some of the convective clouds we observe, the atmosphere is not always so simplistic. Often, rather than a parcel of air, an entire layer is lifted.

For example, a layer of warmer air is lifted over a colder layer as an atmospheric front passes. When a layer of air is lifted its stability can be altered. A layer which initially appears stable can become unstable very suddenly when the entire layer is lifted. A layer in the atmosphere which has this potential is called convectively unstable and often produces violent storms which result in large hail, damaging winds, and even tornadoes.

Summary:

- When air rises, it expands and its temperature decreases.
- When air subsides, its temperature increases.
- When the temperature of a parcel of air decreases, its relative humidity increases.
- When the temperature of a parcel of air increases, its relative humidity decreases.
- The average environmental lapse rate is 6.49 °C/km.
- The dry adiabatic lapse rate applies to rising air, when the relative humidity is below 100%.
- The dry adiabatic lapse rate also applies to air that is subsiding, if there is no liquid water present, and no evaporation is taking place.
- The saturated adiabatic lapse rate applies to rising air, when the relative humidity has reached 100%, and condensation is taking place, releasing latent heat.
- The lapse rates may be used to determine whether or not the atmosphere is stable at a given place and time.
- The stability of the atmosphere can determine what cloud and precipitation can be expected.

Stability Problems

1. An air parcel at the surface has a temperature of 30 °C and becomes saturated at 25 °C. Assuming it moves adiabatically and the SALR = -8.5 °C/km what will be the air temperature at 3000 m?

Solution:

Air is initially dry so we need to find when the air has cooled down enough to become saturated.
DALR =10 °C /km

T_0=30 °C z0= 0 m

T_1= 25 °C z_1=? m

$$DALR = \frac{T_0 - T_1}{z_1 - z_0}$$

$$\frac{10}{1000} = \frac{30 - 25}{z_1 - 0}$$

500 m = z_1

So at this height the air is saturated - now can calculate what the temperature will be at 3000 m.

SALR =8.5°C /km

T_1=25 °C z_1= 0 m

T_2= ? °C z_2=3000 m

$$SALR = \frac{T_1 - T_2}{z_2 - z_1}$$

$$\frac{8.5}{1000} = \frac{25 - T_1}{3000 - 500}$$

3.75 °C = T_2

Temperature at 3000 m is 3.75 °C

---

2. What would be the temperature at 3000 m be if the air were completely dry?

Solution:

DALR =10 °C /km

T_0=30 °C z0= 0 m

T_1= ? °C z_1=3000 m

$$DALR = \frac{T_0 - T_1}{z_1 - z_0}$$

$$\frac{10}{1000} = \frac{30 - T_1}{3000 - 0}$$

0°C = T_1

The temperature at 3000 m is 0°C

---

3. Why is it so much colder?

Solution:
The release of Latent Heat when water condenses in saturated adiabatic expansion warms the air.

Kingsley Kodom AMInsP.
Kwame Nkrumah University of Science & Technology, Ghana.

Dr Sylvia Knight FRMetS
Royal Meteorological Society