LECTURE 3: Dynamics and Thermodynamics of the Atmosphere

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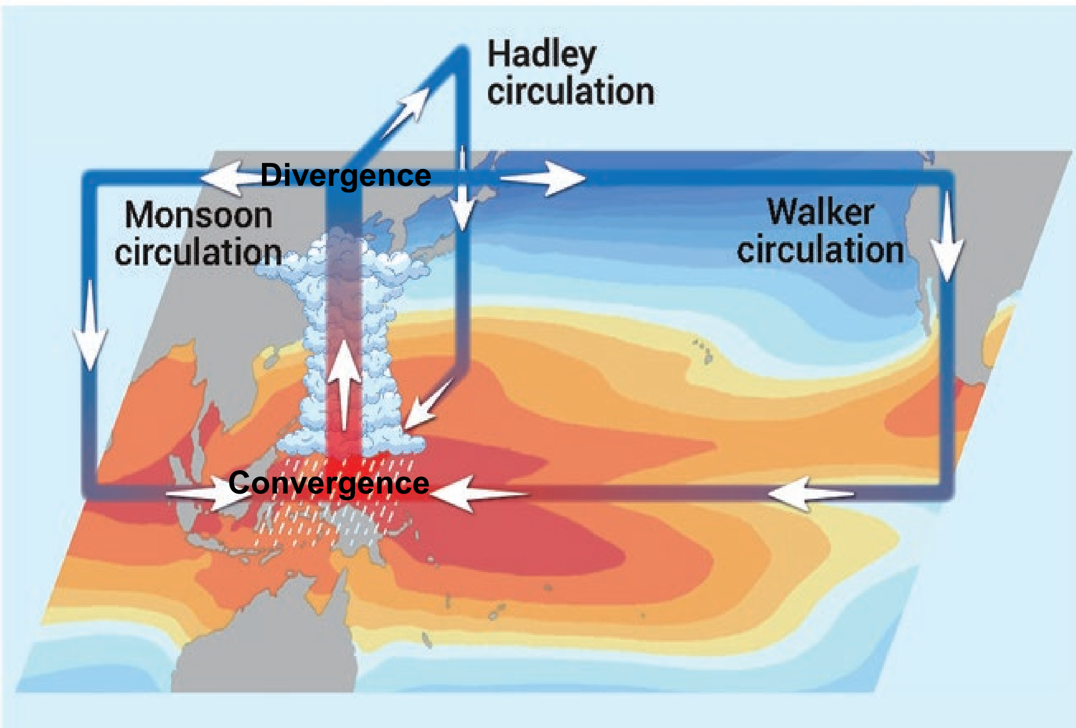
- Some weather systems are responsible for clear skies and light winds, Some develops dark clouds, precipitation, and strong winds.
- Some weather systems trigger brief showers, whereas others are accompanied by drizzle. Certain weather systems dominate the weather over thousands of square kilometers for weeks at a time.



Source: Global Effects of Climate Change in the South China Sea and Its Surrounding Areas, Volume: 3, DOI: (10.34133/olar.0038)

Different weather systems bring different types of weather depending on the air circulation (wind and vertical motions) and the thermodynamic characteristics of the atmosphere, such as temperature, humidity, and stability, which influence cloud development, precipitation, and storm intensity

What is Dynamic Meteorology ?

- the study of atmospheric motions that are associated with weather and climate.
- the smallest element of the atmosphere is defined as an air parcel (ignoring the discrete molecular and chemical nature of the atmosphere).
- atmospheric motions are governed by the fundamental physical laws
- - conservation of momentum
- - conservation of mass
- - conservation of energy

Why Dynamic Meteorology is necessary?

- Understanding atmospheric phenomena
- by <u>a small number of</u> physical principles
- Understanding atmospheric/hydrospheric/oceanic phenomena by <u>common</u> physical principles
- atmosphere ＋ hydrosphere ＋ ocean ⇒ climate
- Numerical weather/climate prediction- developing models based on systematic simplification of the fundamental governing equations
- Improving operational efficiency

Newton's Laws of Motion

- An object at rest will remain at rest and an object in motion will continue moving at a uniform speed in a straight line unless a force is exerted upon it.
- The acceleration of an object is directly proportional to the net force acting on that body

Can we apply the Newton's laws to the atmospheric motions ???

Newton's laws are valid in inertial frame of reference.

Inertial frame of reference : a non-accelerating frame of reference (fixed or moving at constant s

But the earth is rotating : Non-inertial frame of reference

Newton's laws can apply to the atmospheric motions with some modifications
There are some apparent forces in addition to fundamental forces

Fundamental Forces

1. Pressure gradient $$F = -\frac{1}{\rho}\nabla p$$

Pressure gradient - change in pressure measured across a given distance.

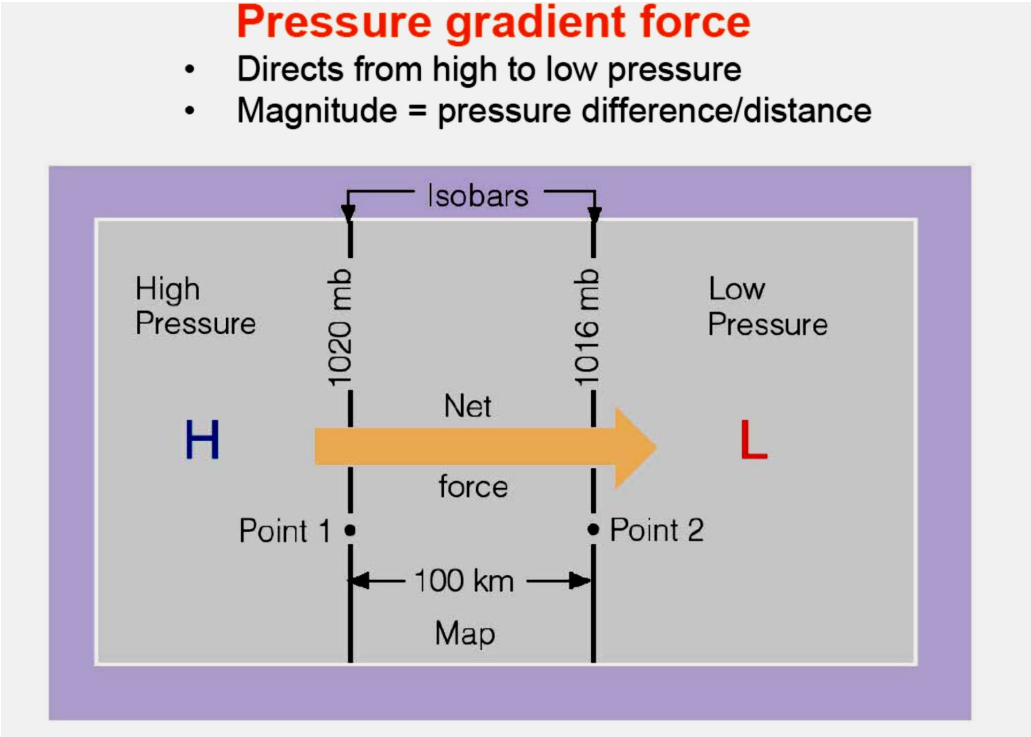
Net force that is directed from high to low pressure - "pressure gradient force".

2. Gravity $$g = -\left(\frac{GM}{a^2}\right)\left(\hat{r}\right)$$

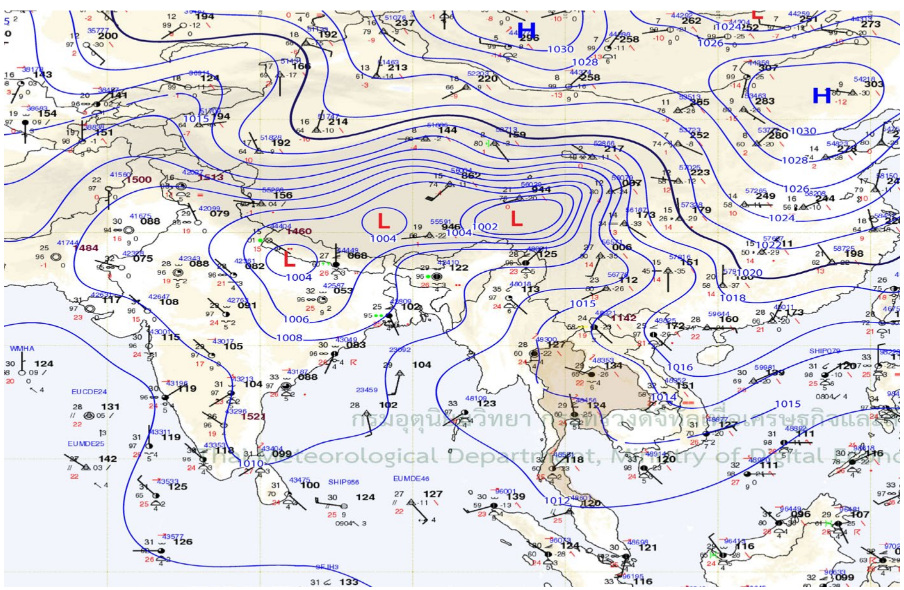
3. Viscous forces $$\frac{1}{\rho}\frac{\partial \tau_{zx}}{\partial z} = \frac{1}{\rho}\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right) = \nu\frac{\partial^2 u}{\partial z^2}$$

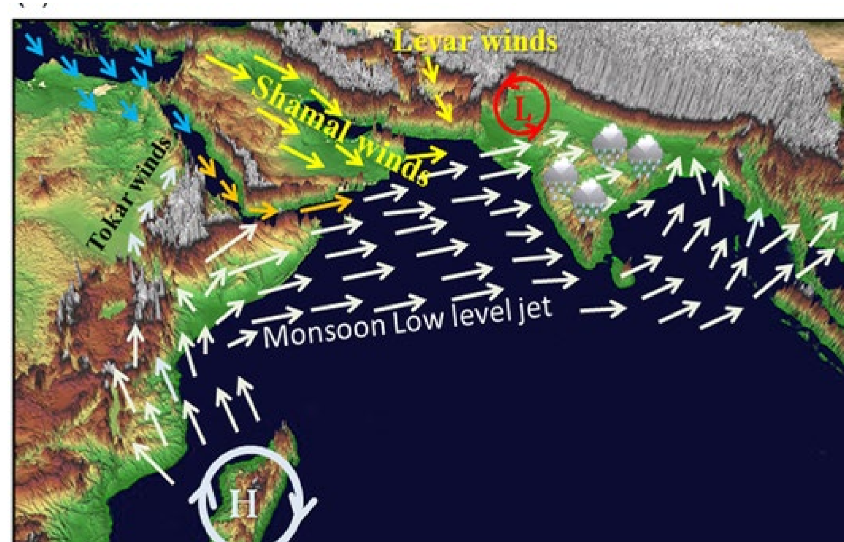
- Forces acting on air parcels either initiate or modify motion and are the consequence of
  - (1) an air pressure gradient,
  - (2) the centripetal force,
  - (3) the Coriolis Effect,
  - (4) friction, and
  - (5) gravity.

Actually, the centripetal force is not an independent force but occurs as a consequence of other forces.

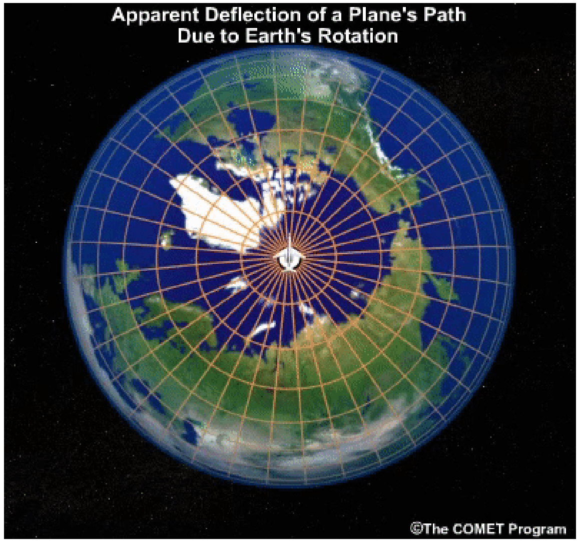


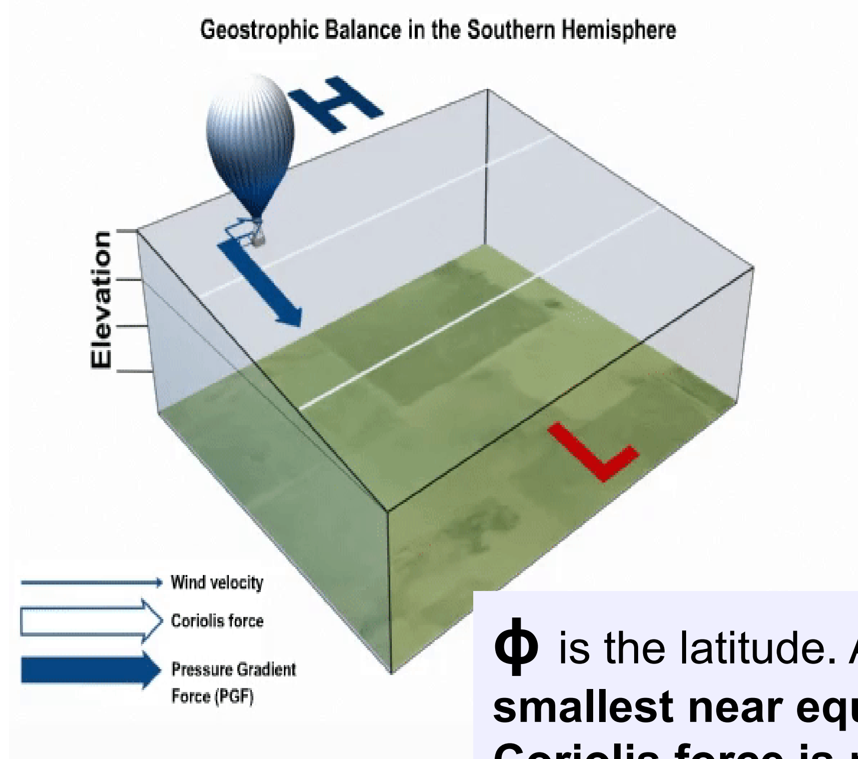
- A *gradient* is simply a change in some property over distance.
- An **air pressure gradient** exists whenever air pressure varies from one place to another
- Air pressure gradients occur both horizontally and vertically within the atmosphere.





Coriolis force

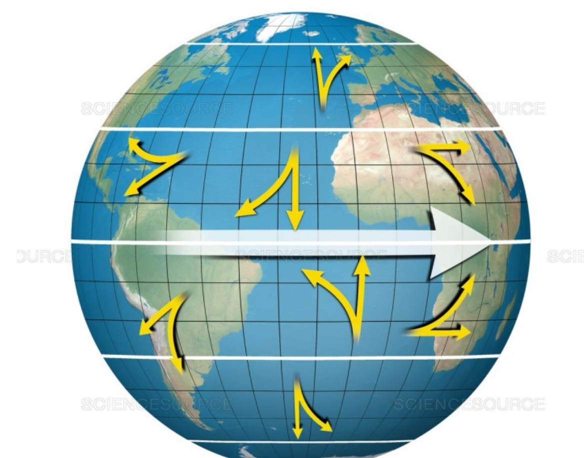




ϕ is the latitude. As sin ϕ is smallest near equator Coriolis force is negligible near Equator

Coriolis Force
= 2 × Earth Rotation Rate × sin(latitude) × velocity **$2\ \omega\ v\ \sin\ \phi$**
•Apparent force due to rotation of the earth
•Magnitude
– Depends upon the latitude and the wind speed
- The higher the latitude, the larger the Coriolis force
  – zero at the equator, maximum at the poles
- The faster the speed, the larger the Coriolis force

•Direction
– The Coriolis force always acts at right angles to the direction of movement
- To the right in the Northern Hemisphere
- To the left in the Southern Hemisphere



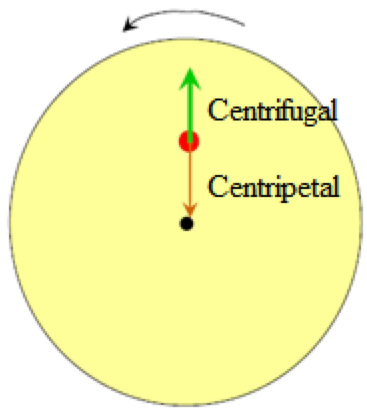
Source : COMET (https://www.meted.ucar.edu/education_training/)

CENTRIPETAL/CENTRIFUGAL FORCE

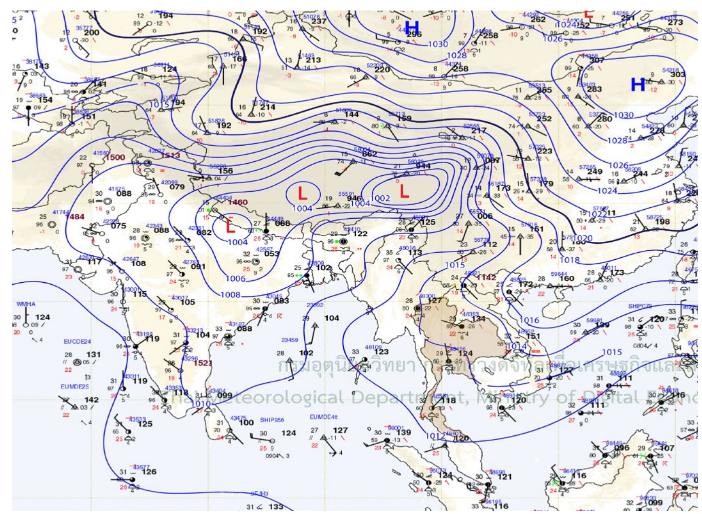
Centripetal/Centrifugal Force

= velocity^2 / radius

- Magnitude depends on
  - the radius from the center
  - the speed of the air parcel
- Direction
  - outward at right angles to the motion (Centrifugal)
  - ward at right angles to the motion (Centripetal)



Isobars plotted on a surface weather map are almost always curved, indicating that the pressure gradient force changes direction from one place to another. Consequently, the horizontal wind blows in curved paths. Curved motion indicates the influence of the centripetal force



3 D Momentum equation

$$\left(\frac{d\vec{r}}{dt}\right)_{inertial} = \left(\frac{d\vec{r}}{dt}\right)_{rotating} + \vec{\Omega}\times\vec{r}$$

$$\frac{d\vec{V}}{dt} = -2\vec{\Omega}\times\vec{V} - \frac{1}{\rho}\nabla p + \vec{g} + \vec{F}_r$$

Total Differentiation

$$\underbrace{\frac{dT}{dt}}_{} = \underbrace{\frac{\partial T}{\partial t}}_{} + \left(\underbrace{u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}}_{} \right)$$

total derivative ;the rate of change of a field variable following the motion

local derivative : the rate of change at a fixed point

Advection by winds

The conversation laws contain expressions of the rates of charge per unit volume following the motion of particular fluid parcels. In order to apply these laws , it is necessary to derive a relationship between the rate of change of a field variable following the motion and the rate of change at a fixed point.

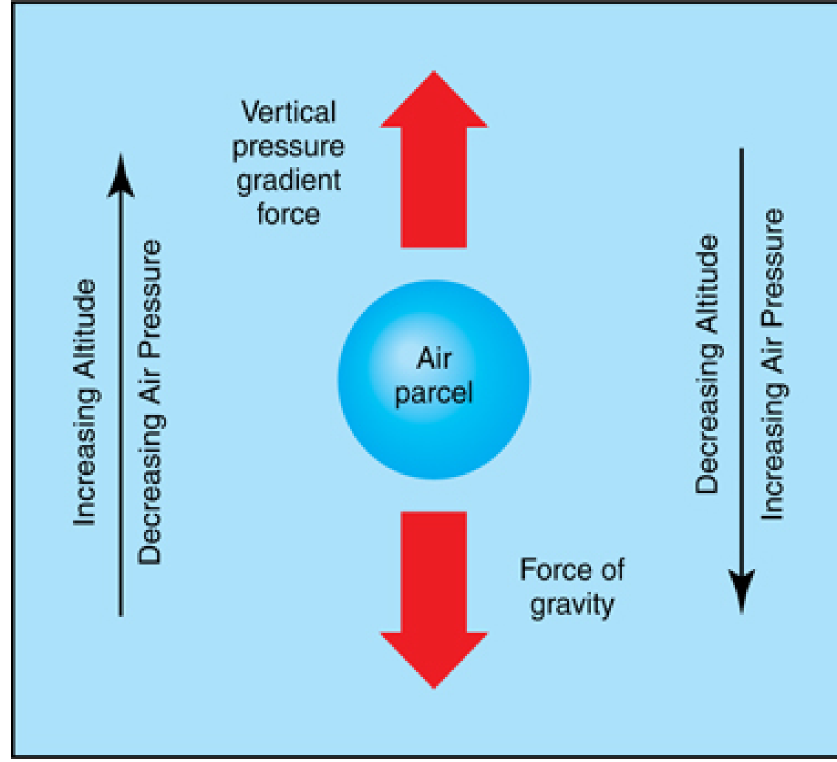
$$or$$

$$\frac{\partial T}{\partial t} = \frac{dT}{dt} - V.\nabla T$$

$$where V = (u, v, w)$$

Hydrostatic Balance

$$\boxed{\frac{dp}{dz} = -\rho g}$$



Source : Moran, J.M., 2009. *Weather studies*

- In the absence of atmospheric motions the gravity force must be exactly balanced by the vertical component of the pressure gradient force.
- Because vertical accelerations are very small for large-scale atmospheric motions, this is an excellent approximation for the vertical dependence of pressure in the real atmosphere.

Horizontal momentum equation scaled for midlatitude large-scale motions.

$$\frac{dV}{dt} = -2\Omega \times V - \frac{1}{\rho}\nabla p$$

Rate of change of velocity following the fluid motion.

Coriolis acceleration

Pressure gradient force (per unit mass)

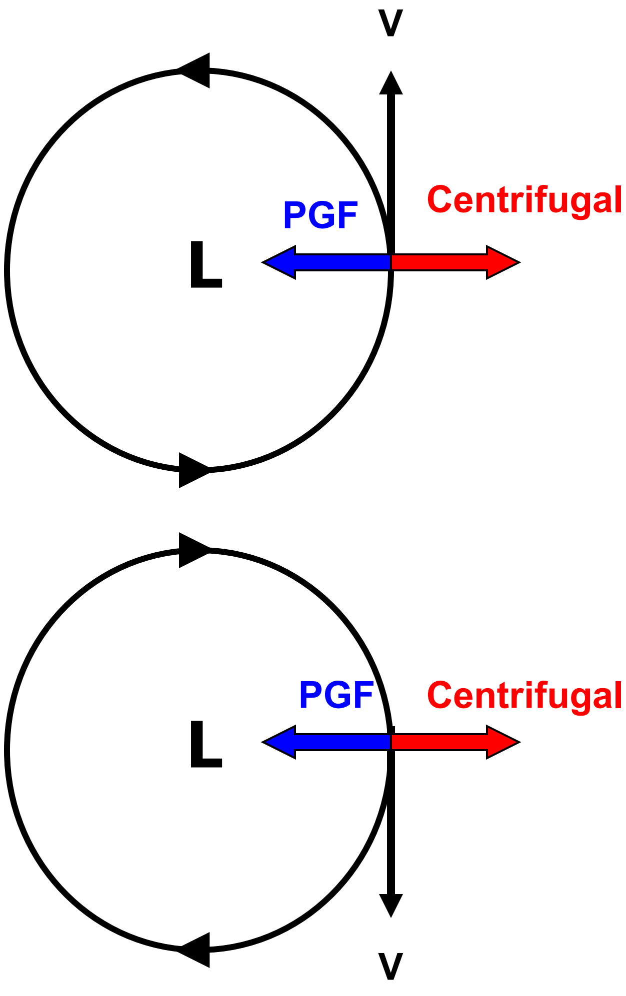
Balanced flows

Inertial flow	$\frac{V^2}{R} = fV$	Balance between coriolis force and centrifugal force
Geostrophic flow	$fV_g = -\frac{1}{\rho}\nabla p$	Balance between coriolis force and pressure gradient force
Cyclostrophic flow	$\frac{V^2}{R} = -\frac{1}{\rho}\nabla p$	balance between the centrifugal and pressure gradient force
Gradient flow	$\frac{V^2}{R} + fV = -\frac{1}{\rho}\nabla p$	Balance between coriolis force pressure gradient force, and centrifugal force

Cyclostrophic Flow

balance between the centrifugal and pressure gradient force
Coriolis force is negligible : eg. Tornados

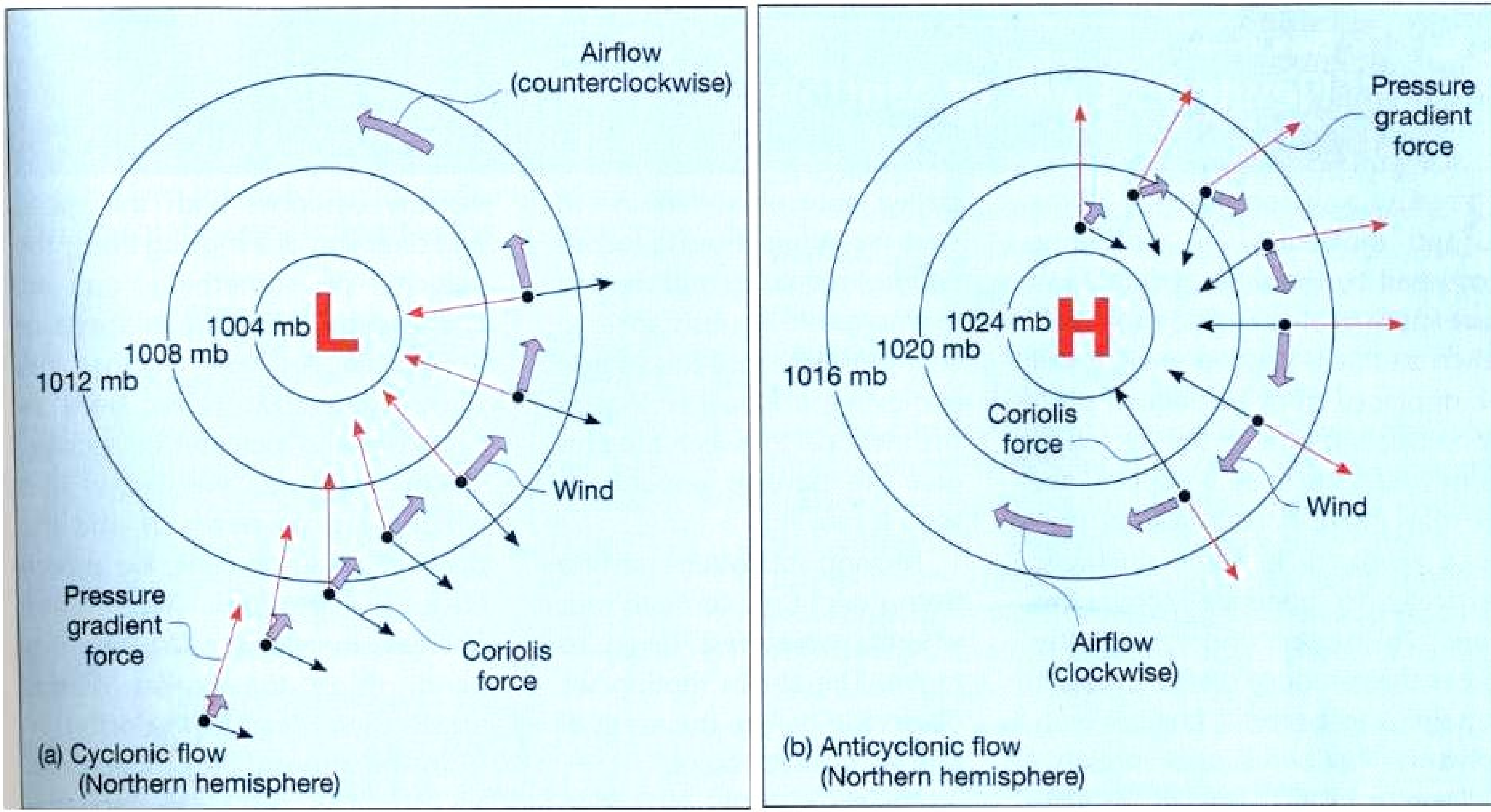
If the horizontal scale of a disturbance is small enough Coriolis force may be neglected

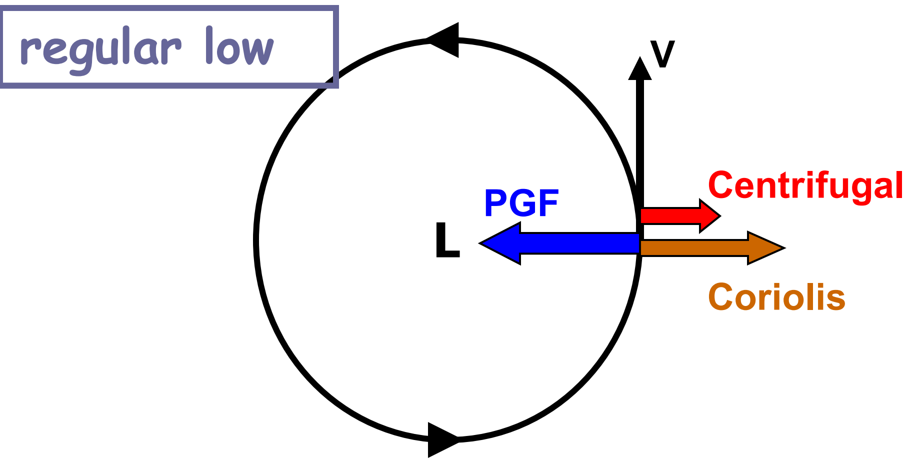


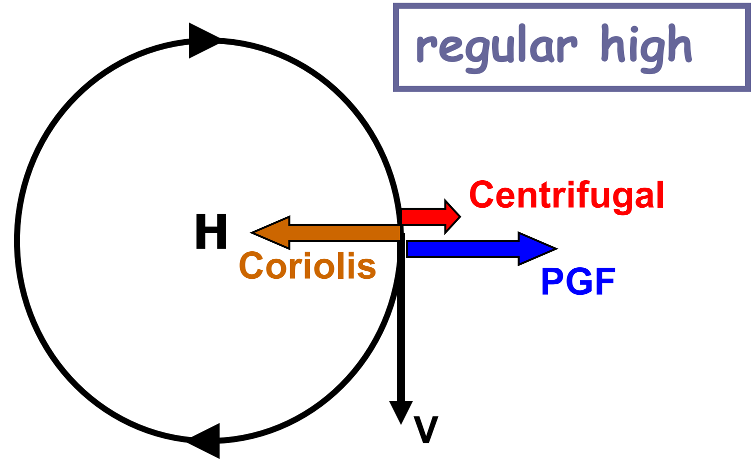
Cyclostrophic flow can either be clockwise or counterclockwise.

Only low pressure systems (Small scale) acting in thunderstorms/tornados can have cyclostrophic flow.

Gradient Wind

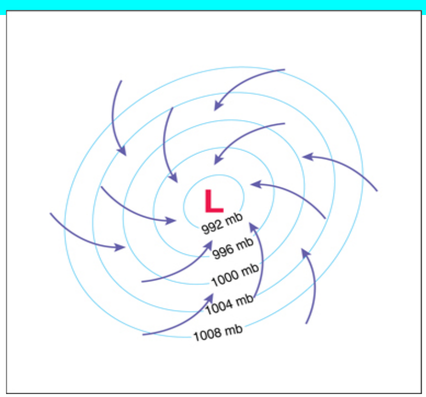


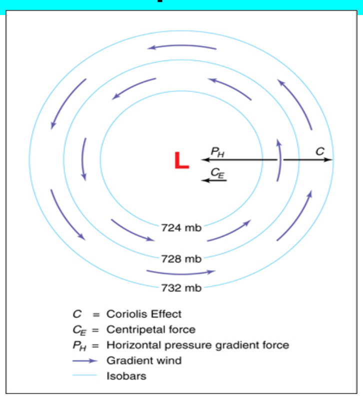


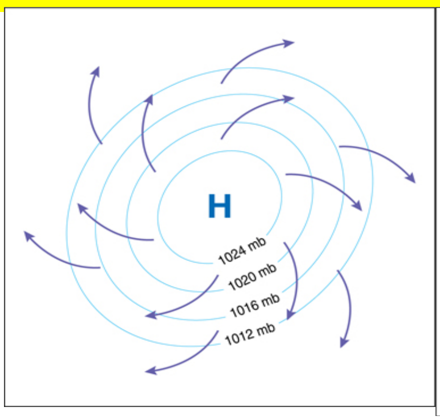


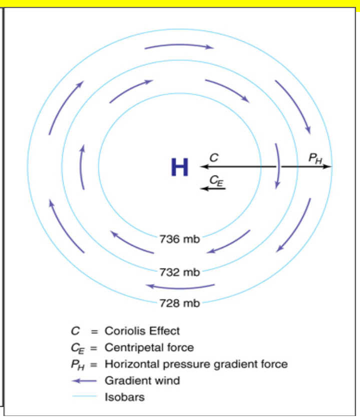
Regular Low - Always directed counter-clockwise in Northern Hemisphere

Regular High - Always directed clockwise in Northern Hemisphere









Gradient Wind - balance between coriolis force, pressure gradient force, and centrifugal force

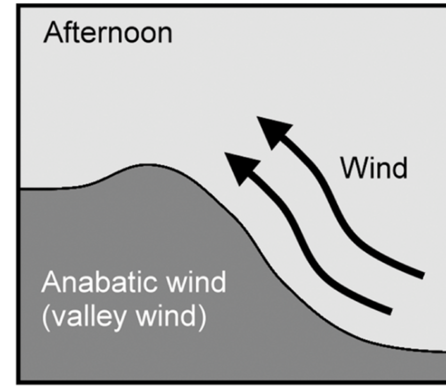
Gradient wind is often a better approximation to the actual wind than the geostrophic wind

Local Winds

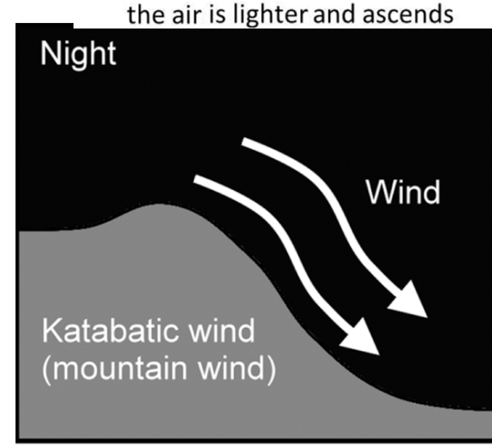
- An **anabatic wind**, from the Greek meaning "moving upward," is a wind that blows upslope along a steep hill or mountainside. It is also known as an upslope flow and typically occurs during the day when the sun heats the mountain surface, causing air to rise.

- A **katabatic wind**, from the Greek meaning "going downhill," is a wind that carries cooler, denser air from higher elevations down a slope under the force of gravity. These winds, also referred to as fall winds, most commonly occur at night when the elevated surfaces cool rapidly.

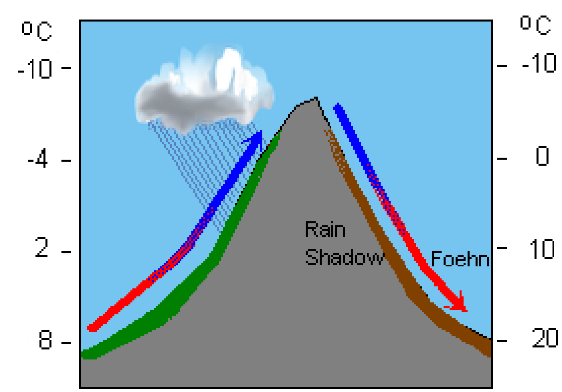
- However, not all downslope winds are katabatic. Winds such as the **Föhn, Chinook, or Kachchan** are examples of rain shadow winds. These occur when moist air ascends the windward side of a mountain, loses its moisture through precipitation (due to orographic lift), and then descends the leeward side as a warm, dry wind due to adiabatic warming.



The sun warms the mountain, the air is lighter and ascends



The mountain cools down, the air becomes heavier so it descends

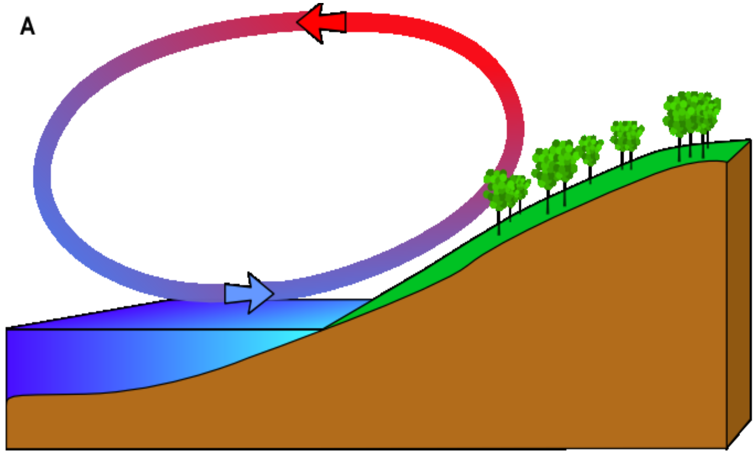


Sea Breeze & Land Breeze

- A sea-breeze (or onshore breeze) is a wind from the sea that develops over land near coasts. It is formed by increasing temperature differences between the land and water which create a pressure minimum over the land due to its relative warmth and forces higher pressure, cooler air from the sea to move inland.

- At night, the land cools off quicker than the ocean due to differences in their specific heat values, which forces the dying of the daytime sea breeze. If the land cools below that of the adjacent sea surface temperature, the pressure over the water will be lower than that of the land, setting up a land breeze as long as the environmental surface wind pattern is not strong enough to oppose it. If there is sufficient moisture and instability available, the land breeze can cause showers or even thunderstorms, over the water.

A



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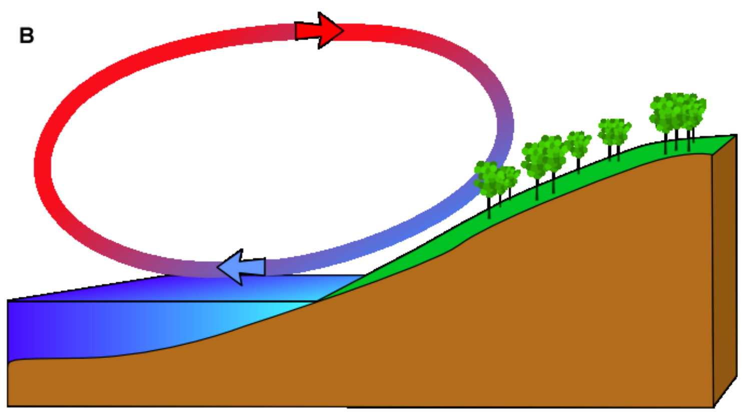
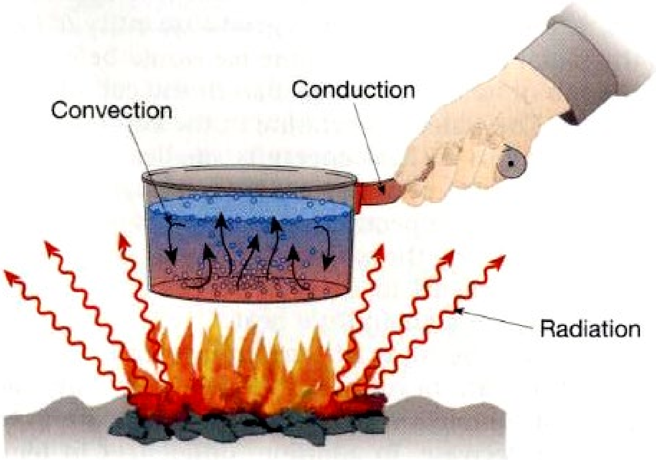
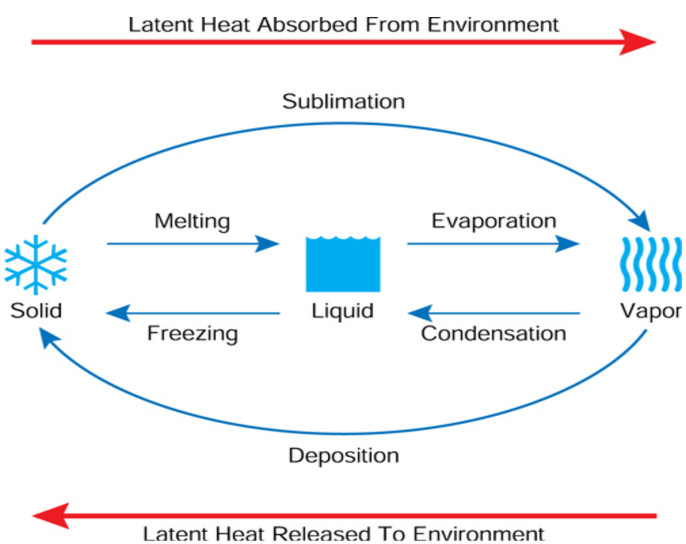


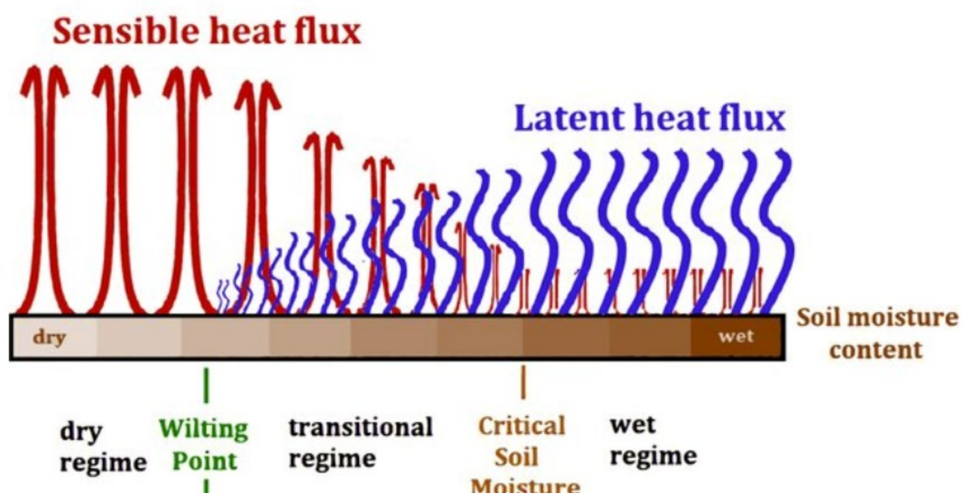
Mechanisms of Heat Transfer

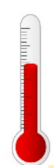
- Within the Earth-atmosphere system, heat is transferred via radiation (emission and transmission of energy in the form of electromagnetic waves), conduction (thermal energy is transported through a material without the actual movement of the material itself), and convection (the transport of heat within a fluid via motions of the fluid itself).
- Also, when water changes phase, heat is either absorbed from or released to the environment





Source : Moran, J.M., 2009. *Weather studies*





The quantity of heat that is involved in phase changes of water is known as **latent heat**, where the term "latent" refers to heat that is "hidden" until released.

In the troposphere, conduction and convection work together in transferring heat. The combination of conduction and convection is known as **sensible heating**, as we can *sense* a change in temperature in response to such heating.

THERMAL INERTIA

- Water's exceptional capacity to store heat has important implications for weather and climate.
- A large body of water (such as the ocean or Great Lakes) can significantly influence the climate.
- The most persistent influence is on air temperature.
- Compared to an adjacent landmass, a body of water does not warm as much during the day (or in summer) and does not cool as much at night (or in winter).
- Resistance to temperature change, called **thermal inertia**
- In other words, a large body of water exhibits a greater resistance to temperature change, called **thermal inertia**, than does a landmass.
- Greater specific heat of water versus land is the major reason for this contrast in thermal inertia, differences in heat transport also contribute.
- The input (or output) of equal amounts of heat energy causes a land surface to warm (or cool) more than the equivalent surface area of a body of water.

VAPOR PRESSURE, MIXING RATIO, & SPECIFIC HUMIDITY

- Humidity measurements help quantify the amount of water vapor in the atmosphere, using different approaches such as vapor pressure, mixing ratio, relative humidity and specific humidity.
- Vapor pressure refers to the partial pressure exerted by water vapor within the atmosphere, following Dalton's Law. Higher water vapor content increases vapor pressure. Water vapor is a variable component of air but generally does not exceed 40 mb at sea level, given the total atmospheric pressure of about 1000 mb.
- Mixing ratio quantifies humidity as the mass of water vapor per mass of dry air, usually measured in grams per kilogram.
- Specific humidity represents the ratio of water vapor mass to the total air mass, including water vapor.

Relative humidity(RH) compares the actual amount of water vapor in the air with the amount of water vapor that would be present if that same air were saturated. RH is expressed as a percentage and can be computed from either the vapor pressure or mixing ratio

$$RH = \frac{\text{(vapor pressure)}}{\text{(saturation vapor pressure)}} \times 100\%$$

or

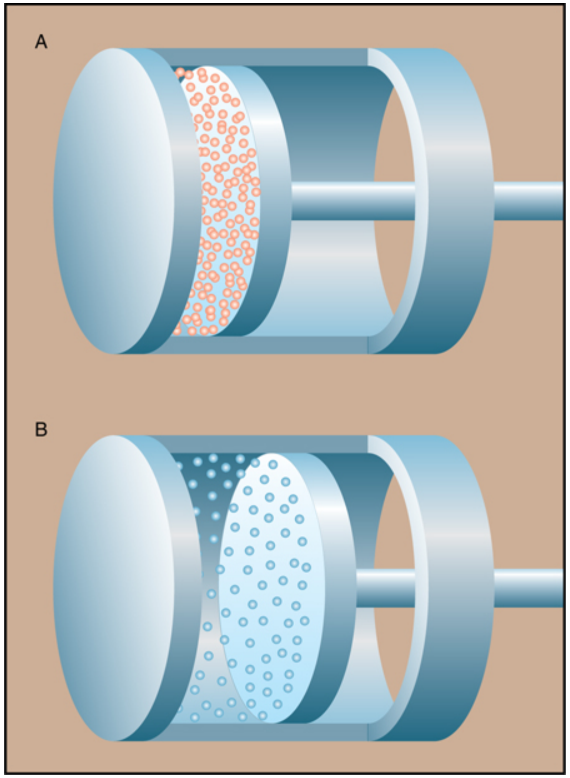
$$RH = \frac{\text{(mixing ratio)}}{\text{(saturation mixing ratio)}} \times 100\%$$

How Air Becomes Saturated

- The relative humidity is variable and as it approaches 100%, condensation or deposition of water vapor becomes more and more likely.
- Condensation or deposition within the atmosphere produces clouds so the probability of cloud development increases as the relative humidity nears saturation.
- A **cloud** is a visible aggregate of tiny water droplets and/or ice crystals suspended in the atmosphere. (Under special circumstances, the relative humidity can rise slightly higher than 100% without water vapor changing phase; in that case air is *supersaturated*.)

Expansional cooling and **compressional warming**

- *Expansional cooling* is the principal means whereby clouds form in the atmosphere.
- Ascending air expands and cools whereas descending air is compressed and warms.
- As ascending currents of unsaturated (clear) air cool, the relative humidity increases and approaches saturation.
- At or near saturation, clouds usually form.
- On the other hand, descending currents of air warm, the relative humidity decreases, and existing clouds vaporize.
- Within the atmosphere, expansional cooling and compressional warming of unsaturated air are essentially *adiabatic processes*.



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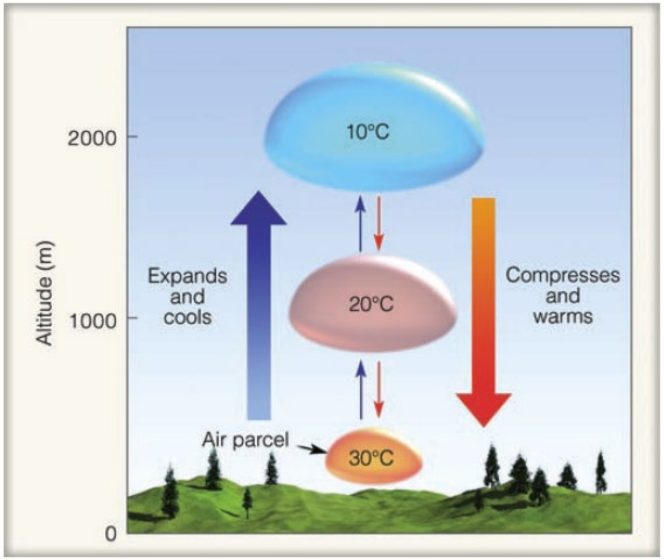
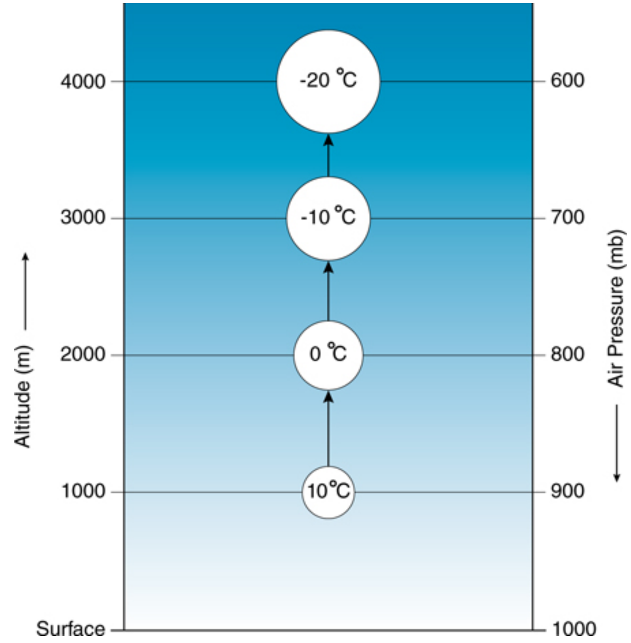


During an **adiabatic process**, no heat is exchanged between an air parcel and its surroundings.
Because air often moves vertically relatively rapidly in large quantities, it can be assumed to behave adiabaticaly.

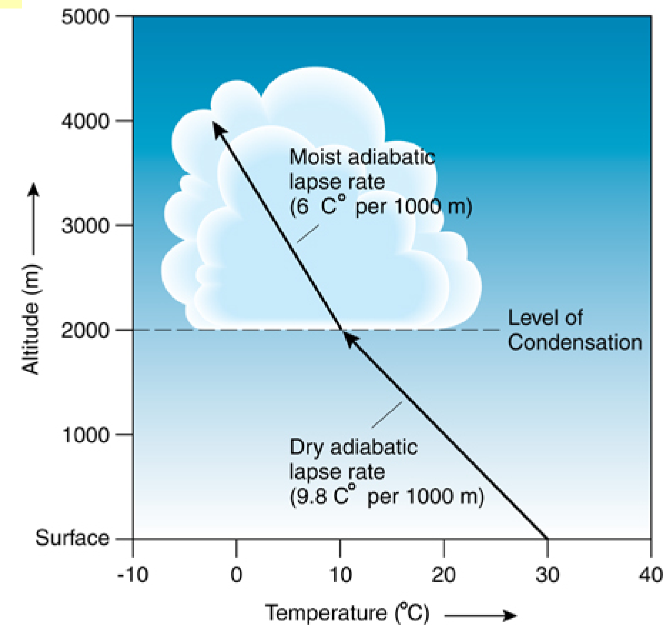
Dry adiabatic lapse rate

- The dry adiabatic lapse rate describes the expansional cooling of ascending unsaturated (clear) air parcels. Here, the magnitude of the dry adiabatic lapse rate is rounded off to 10 Celsius degrees per 1 km.
- The dry adiabatic lapse rate applies to any parcel that is not saturated with water vapor (because no condensation or evaporation can take place during a dry adiabatic process).
- Hence, the dry adiabatic lapse rate describes the temperature change of unsaturated air as it moves vertically (up or down) within the atmosphere.



Moist adiabatic lapse rate

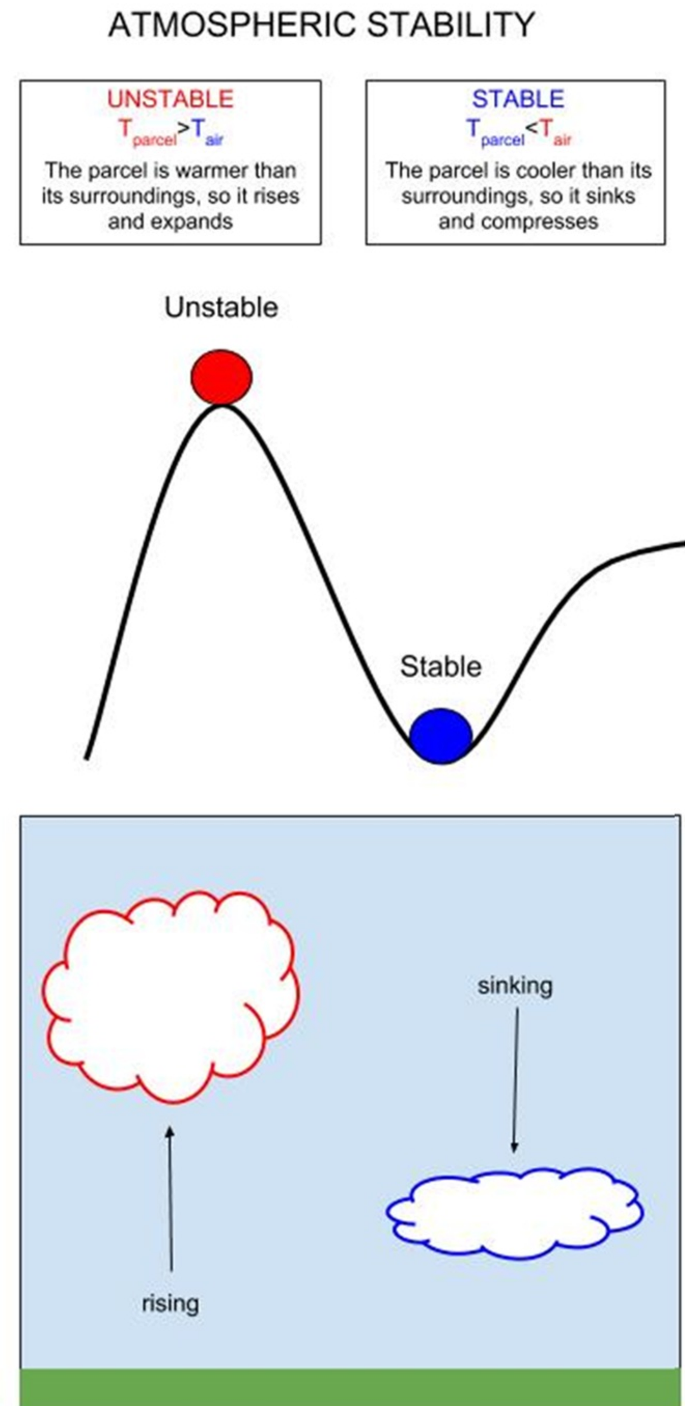
- Rising air parcels cool to the point that the relative humidity reaches 100% (saturation) and condensation or deposition occurs
- Latent heat that is released to the environment during ongoing condensation or deposition
- Consequently, an ascending saturated (cloudy) air parcel cools at a lower rate than an ascending unsaturated (dry) air parcel.
- Rising saturated air parcels cool at the **moist adiabatic lapse rate**



Source : Moran, J.M., 2009. *Weather studies*

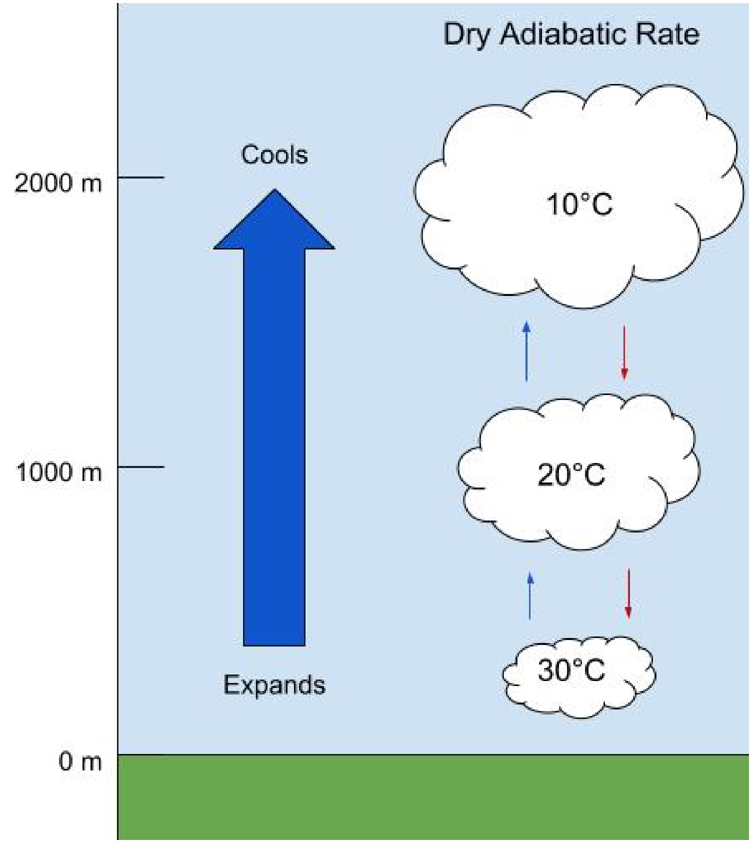
Stability of Atmosphere

- Our atmosphere is in constant motion. The rotation of the earth on its axis, together with large and small scale variations in pressure and temperature produce wind, which is the horizontal and vertical movement of air in the atmosphere.
- Stability is simply the resistance of the atmosphere to vertical motion.
- More precisely, it is the degree to which vertical motion in the atmosphere is enhanced or suppressed.
- Atmospheric stability is described in terms of the effects of the environment on vertical motion.
- An **unstable atmosphere** will enhance or encourage the vertical movement of air.
- A **stable atmosphere** will suppress or resist vertical motion.



Rising Air Parcel

- the atmospheric pressure rapidly decreases as altitude increases in the atmosphere.
- As an air parcel rises, the surrounding pressure decreases.
- To equalize the pressure, the air molecules inside the parcel will push outward, making it expand.
- This will increase the volume of the air parcel but decrease its density – the same number of molecules now occupies a larger volume.

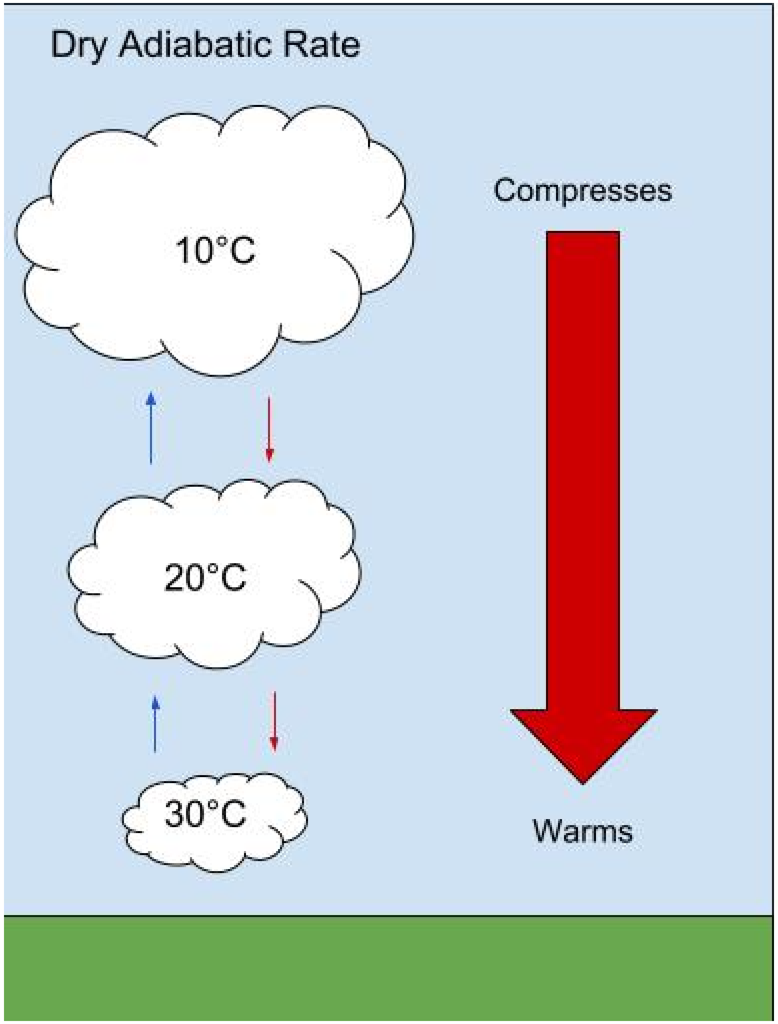


- Because the molecules use their own energy for this process, their speed will decrease, which lowers the temperature of the parcel.
- Thus, rising air parcels will always expand and cool.

Source : Moran, J.M., 2009. *Weather studies*

Sinking Air Parcel

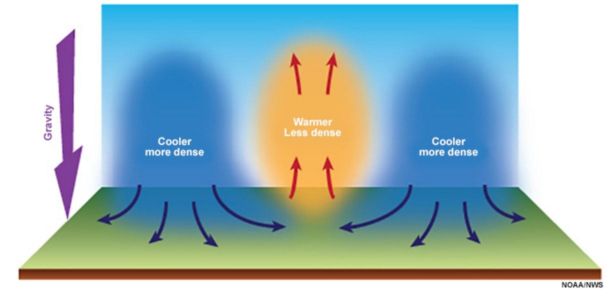
- As an air parcel descends through the lower atmosphere, the external pressure increases causing the parcel to compress.
- This compression diminishes the parcel's volume and moves the air molecules closer together.
- As a result, the density of the parcel increases and its temperature will rise as the molecules hit each other thereby increasing their speed.
- Thus, sinking air parcels always compress and warm.

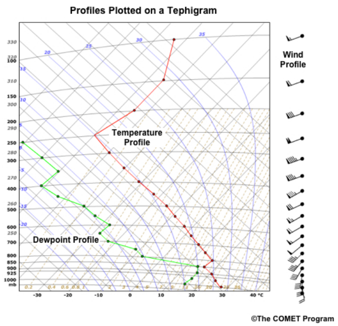


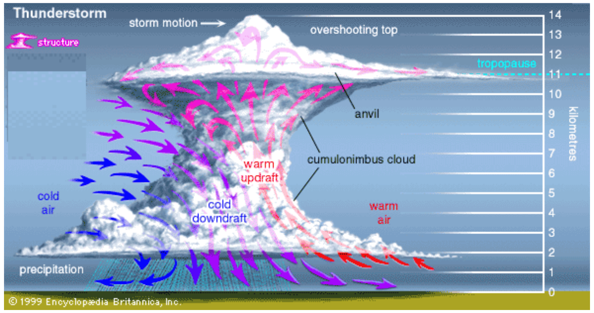
Source : Moran, J.M., 2009. *Weather studies*

Atmospheric Stability

- The weather patterns begin at very local scales and are related to the atmosphere's capacity for vertical motion.
- Weather occurs because air is constantly moving vertically and horizontally.
- Warm air is less dense than cooler air, and therefore will tend to rise.
- Atmospheric stability controls the ability of air to rise or sink, which in turn influences weather.
- If a rising air parcel has a lower temperature than the surrounding environment, the rising parcel is denser, and will tend to sink. In this case, the atmosphere is said to be stable.
- If a rising air parcel has a higher temperature than the surrounding environment, the rising parcel is less dense, and will tend to rise. In this case, the atmosphere is said to be unstable.



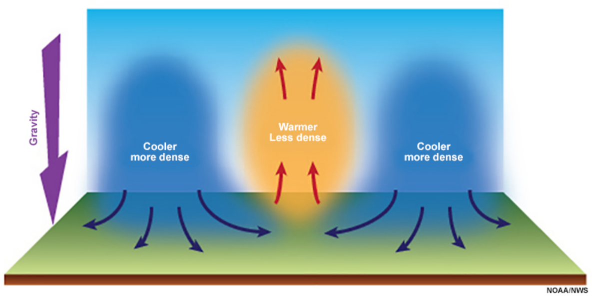


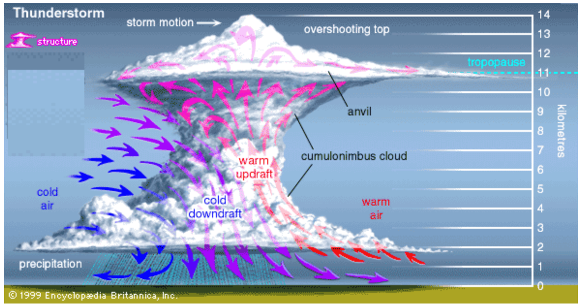


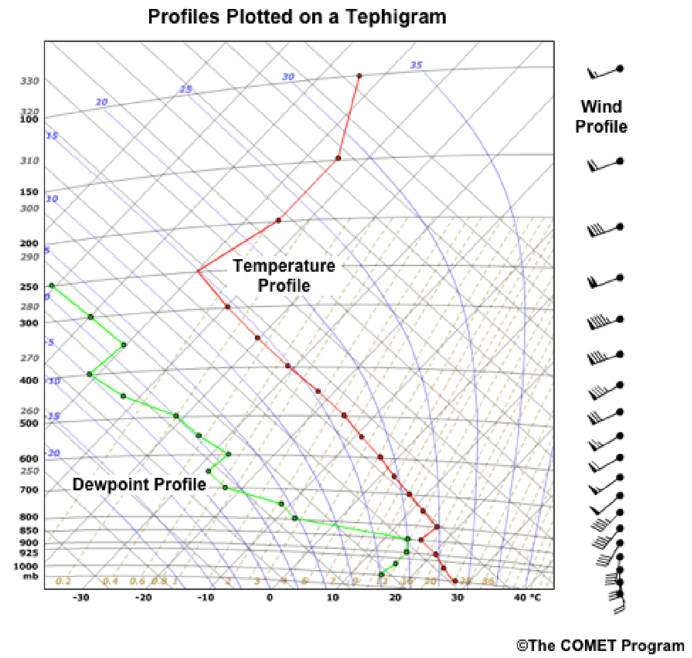
Source : COMET (https://www.meted.ucar.edu/education_training/)

Determining Stability

- **Environmental Lapse Rate**
- In order to determine the stability of the atmosphere, meteorologists compare the temperature of a rising air parcel with the temperature of the air around it at the same level.
- The environmental lapse rate is simply the change in temperature with a change in altitude.



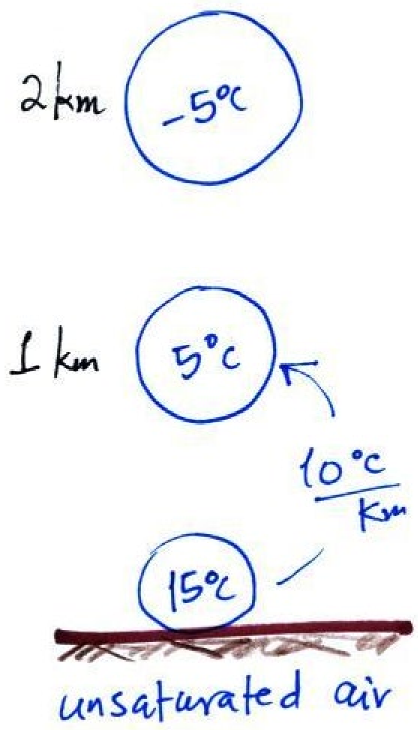




Source : COMET (https://www.meted.ucar.edu/education_training/)

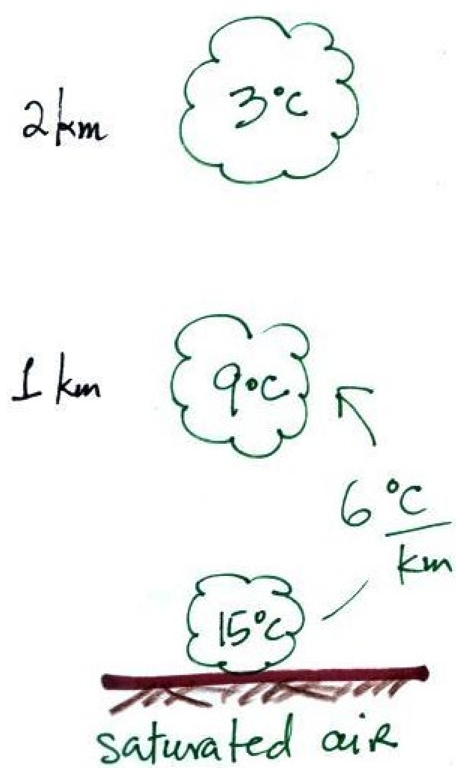
Dry Adiabatic Lapse rate

- The Dry Adiabatic Lapse Rate (DALR) is the rate of change in temperature with altitude for a parcel of dry or unsaturated rising under adiabatic conditions.
- Unsaturated air has less than 100% relative humidity
- The dry adiabatic lapse rate for the Earth's atmosphere equals -**10° C per kilometre**.

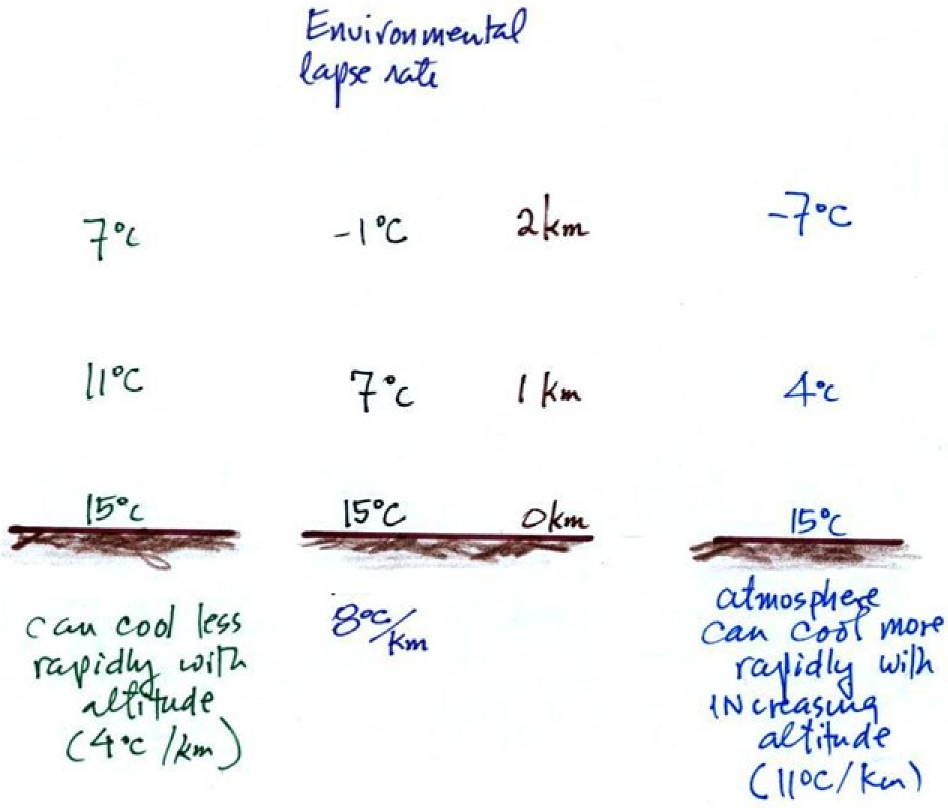


Saturated Adiabatic Lapse rate (Moist Adiabatic Lapse rate)

- When an air parcel that is saturated with water vapour rises, some of the vapour will condense and release latent heat. This process causes the parcel to cool more slowly than it would if it were not saturated.
- The moist adiabatic lapse rate varies considerably because the amount of water vapour in the air is highly variable. The greater the amount of vapour, the smaller the adiabatic lapse rate [because the condensation process keeps on adding more latent heat of condensation]. On an average it is taken as **6 C per kilometre**.
- As an air parcel rises and cools, it may eventually lose its moisture through condensation; its lapse rate then increases and approaches the dry adiabatic value.



Environmental lapse rate

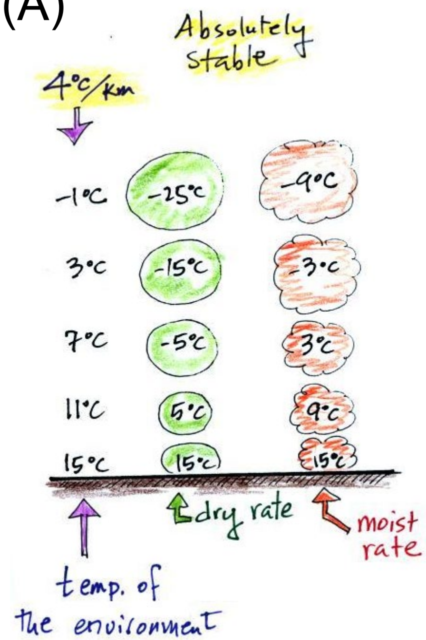


In order to determine the stability of the atmosphere, meteorologists compare the temperature of a rising air parcel with the temperature of the air around it at the same level.

The environmental lapse rate is simply the change in temperature with a change in altitude.

Determining Stability

(A)



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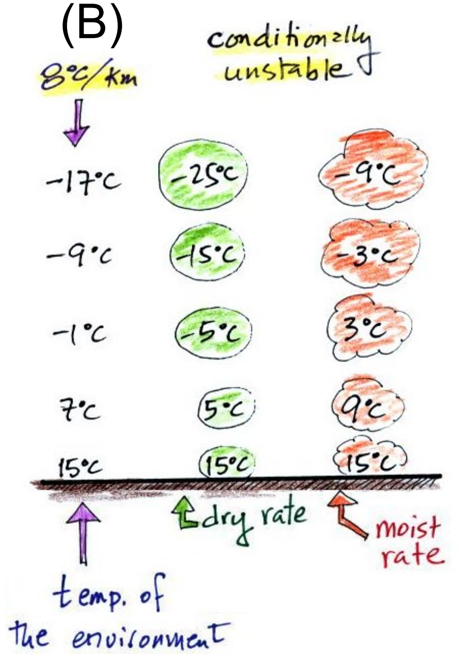
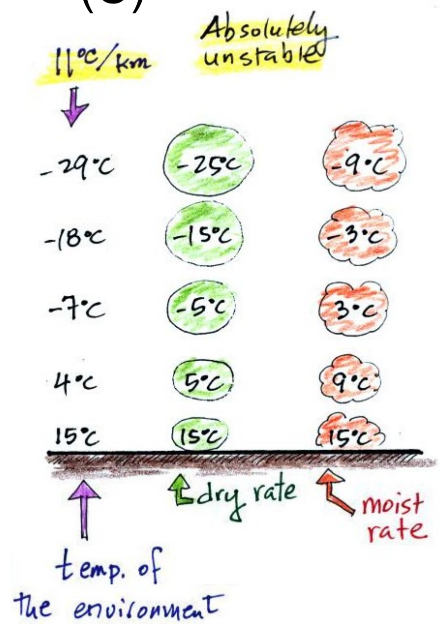
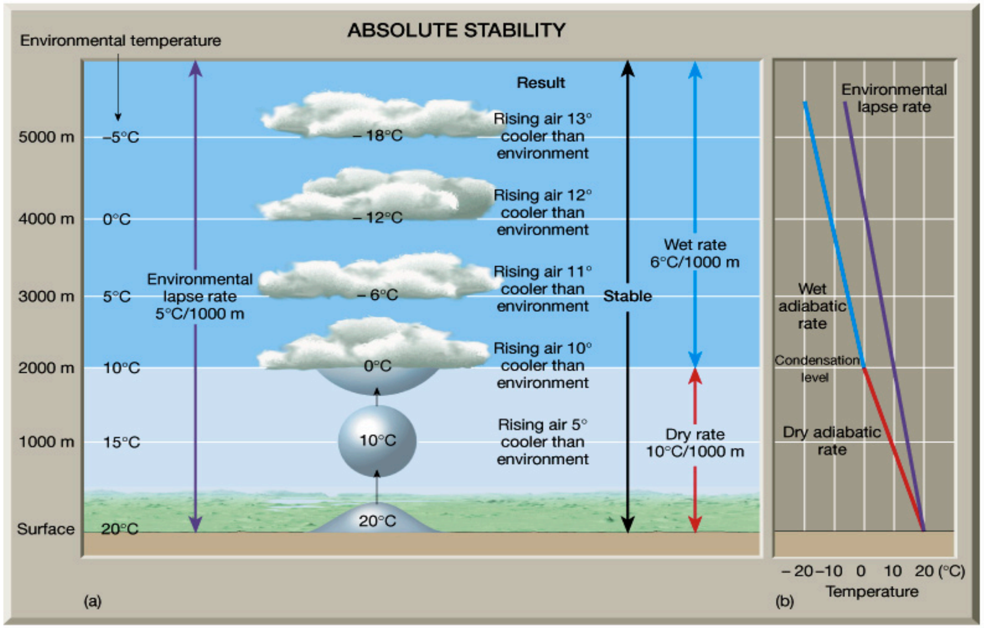


(C)



environmental lapse rate	atmospheric stability
less than the MALR (eg. 4° C/km)	absolutely stable
between the DALR & the MALR (eg. 8° C/km)	conditionally unstable
greater than the DALR (eg. 11° C/km)	absolutely unstable

conditional instability—Property of an ambient air layer that suppresses vertical motion for unsaturated (dry) air parcels and enhances vertical motion for saturated (cloudy) air parcels. The *sounding* in a conditionally instable layer of air lies between the *dry adiabatic lapse rate* and the *moist adiabatic lapse rate*.



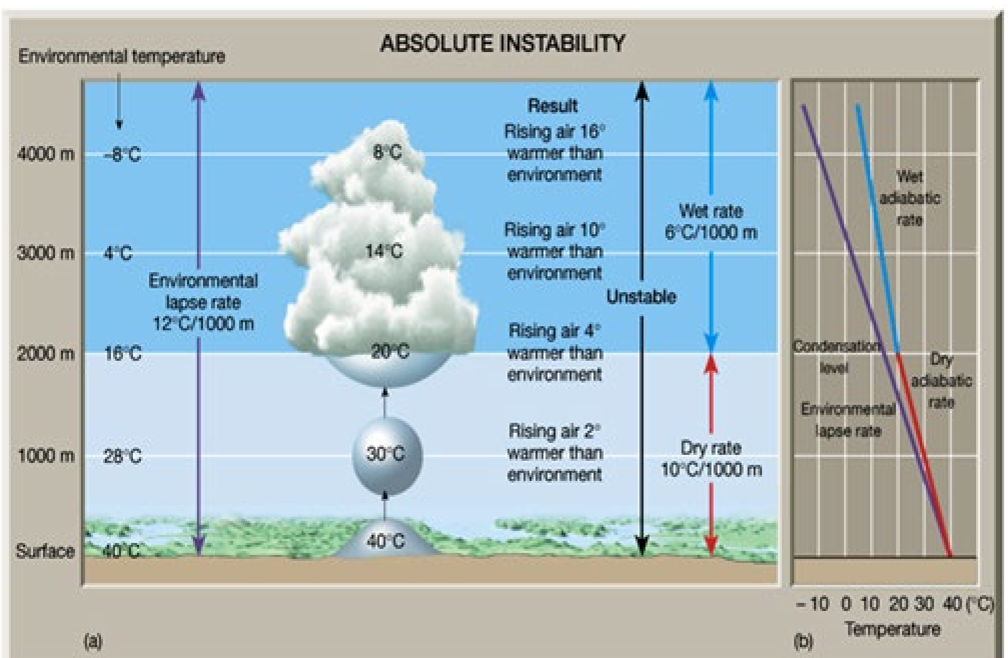
Source : https://www.eiu.edu/

Stable Atmosphere

Envorenmental Lapse rate is less than Dry Adiabatic Lapse Rate and Moist Adiabatic Lapse Rate

Ex : Envorenmental Lapse rate (5^0C/km) less than Dry Adiabatic Lapse Rate (10^0C/km) and Moist Adiabatic Lapse Rate (6^0C/km)

Sunny Weather, Very less clouds, mostly clear sky



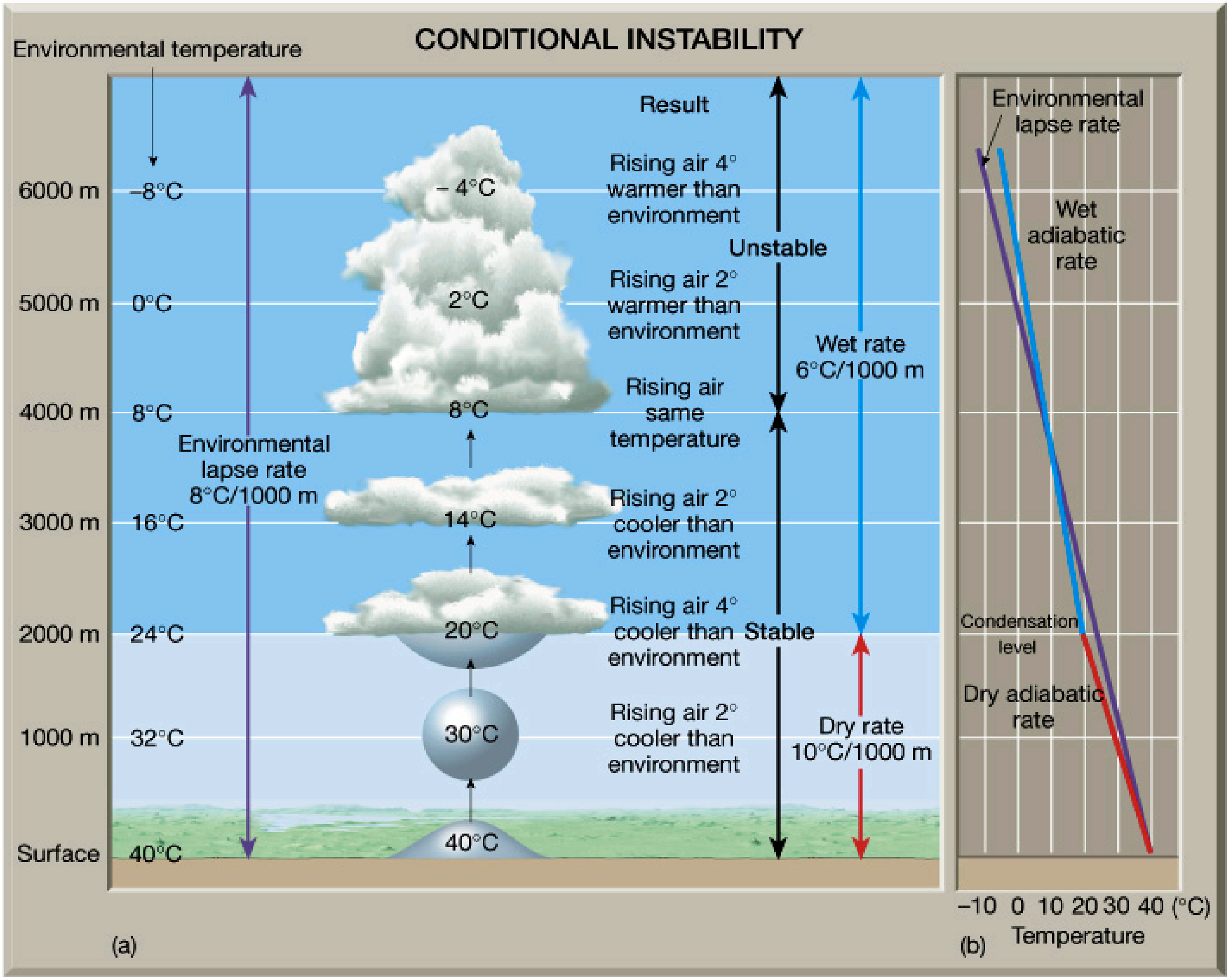
Unstable Atmosphere

Envorenmental Lapse rate is greater than Dry Adiabatic Lapse Rate and Moist Adiabatic Lapse Rate

Ex :Envorenmental Lapse rate (12^0C/km) less than Dry Adiabatic Lapse Rate (10^0C/km) and Moist Adiabatic Lapse Rate (6^0C/km)

Rainy Weather mostly cloudy sky

Conditional Unstable



Source : https://www.eiu.edu/

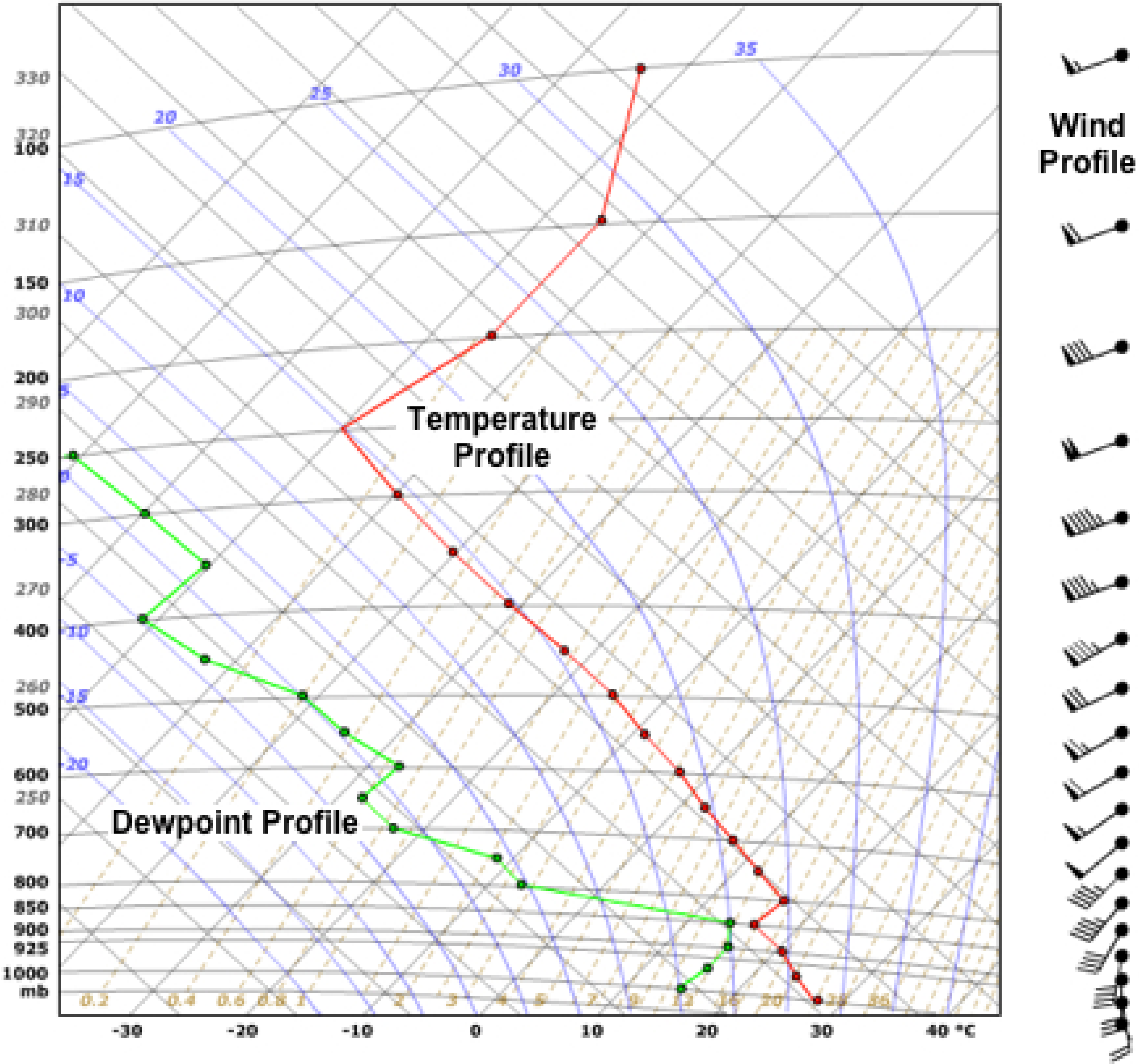
suppresses vertical motion for unsaturated (dry) air parcels and enhances vertical motion for saturated air parcels.

The *Environmental Lapse rate* in a conditionally instable layer of air lies between the *dry adiabatic lapse rate* and the *moist adiabatic lapse rate*.

Ex :

Envorenmental Lapse rate (8^0C/km) is less than Dry Adiabatic Lapse Rate (10^0C/km) and more than Moist Adiabatic Lapse Rate (6^0C/km)

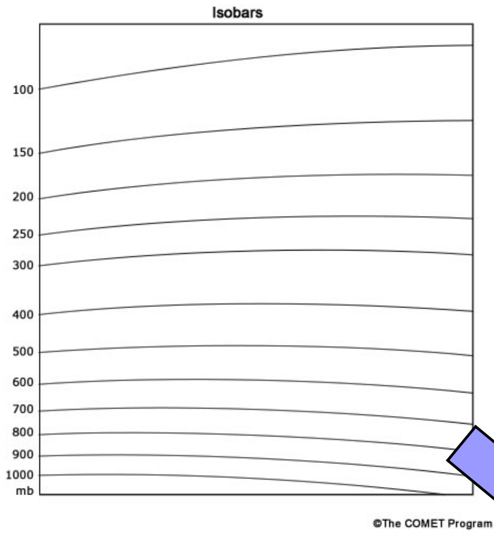
Profiles Plotted on a Tephigram

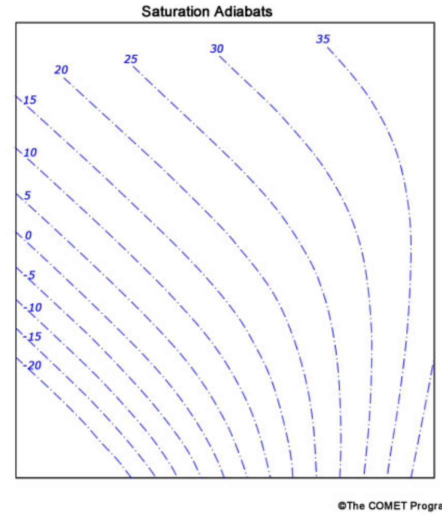


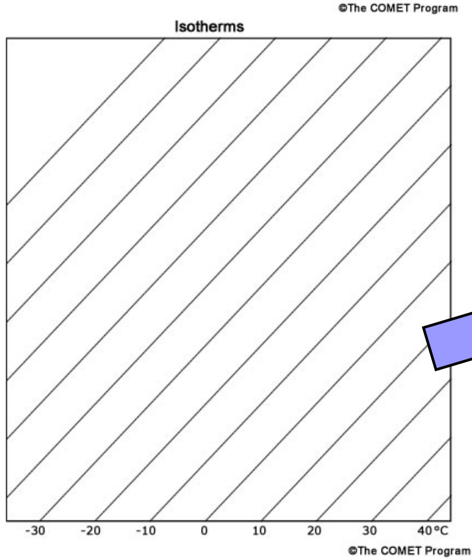
- The tephigram is a thermodynamic diagram used to plot vertical profiles of atmospheric temperature, moisture, and wind

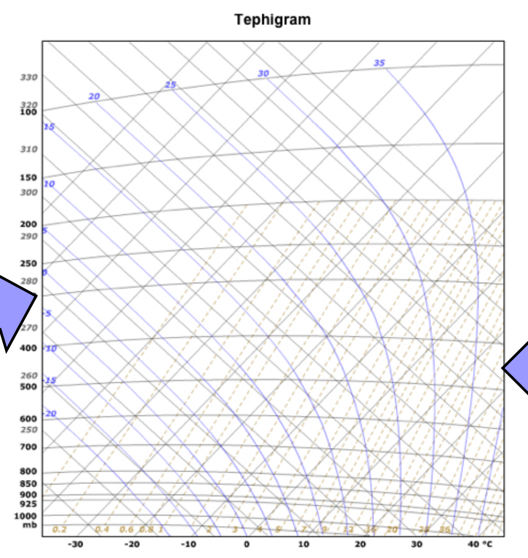
Source : COMET (https://www.meted.ucar.edu/education_training/)

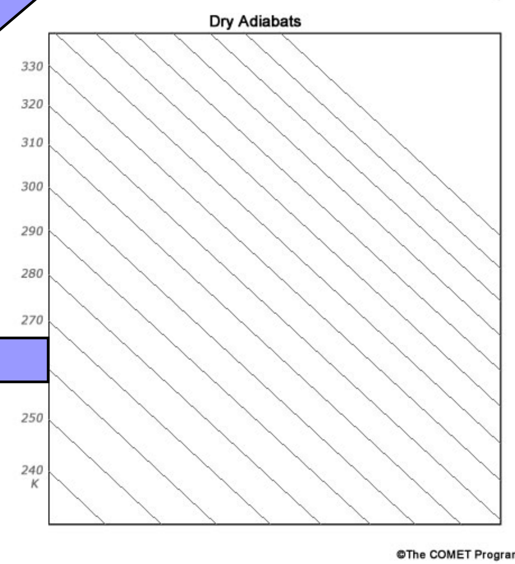
ISOBAR -Equal Pressure lines











Tephigram

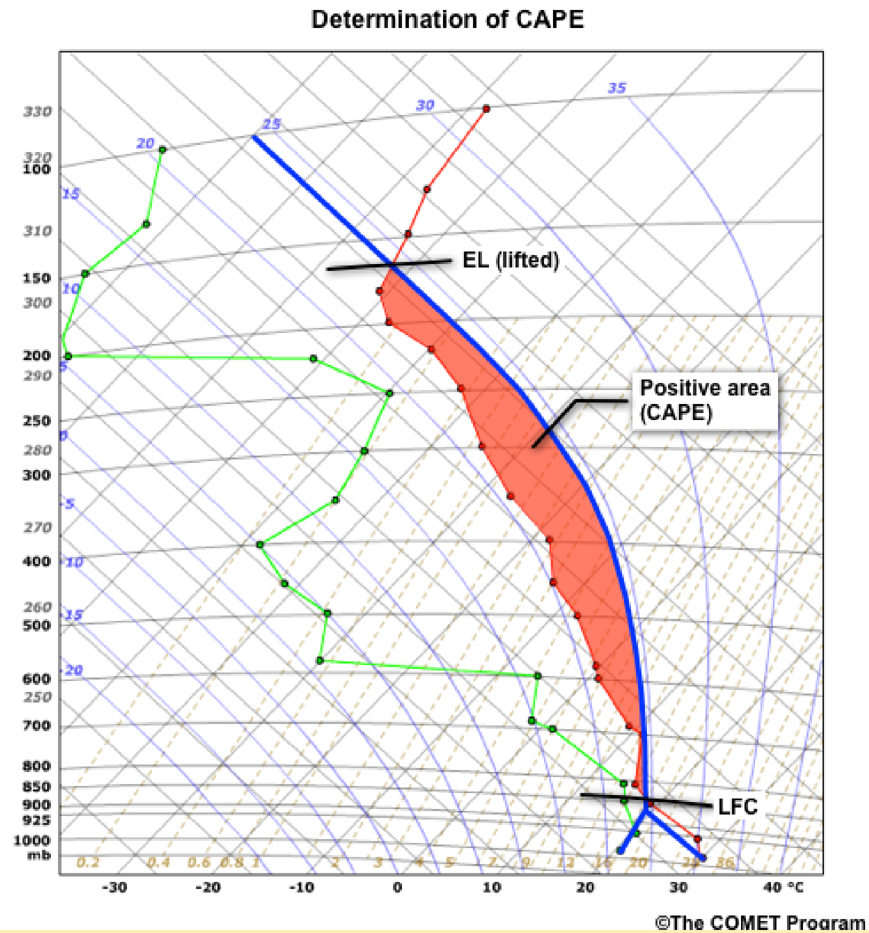
ISOTHERM
-Equal TEMPERATURE lines

Source : COMET (https://www.meted.ucar.edu/education_training/)

Convective Available Potential Energy (CAPE)

The altitude at which the rising air becomes saturated and clouds form is known as the **lifting condensation level (LCL)** and usually corresponds to the base of the clouds.

The **level of free convection (LFC)** is the altitude in the atmosphere where an air parcel lifted adiabatically until saturation becomes warmer than the environment at the same level, so that positive buoyancy can initiate self-sustained convection



The **equilibrium level (EL)** is the height where the temperature of a buoyantly rising parcel again equals the temperature of the environment.

The **convective available potential energy (CAPE)** is represented by the area on a tephigram enclosed by the environmental temperature profile and the saturation adiabat running from the LFC to the EL. This area, depicted in the diagram below, indicates the amount of buoyant energy available as the parcel is accelerated upward. CAPE is measured in units of joules per kilogram (J/kg).

convective inhibition (CIN)

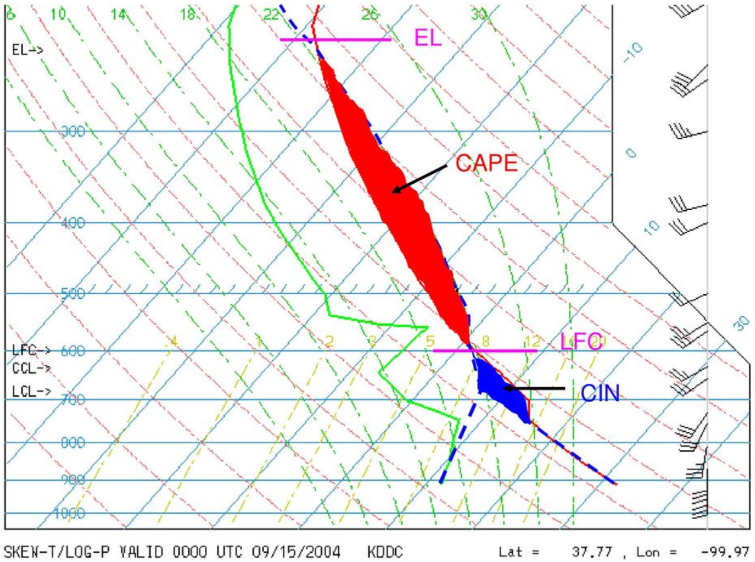
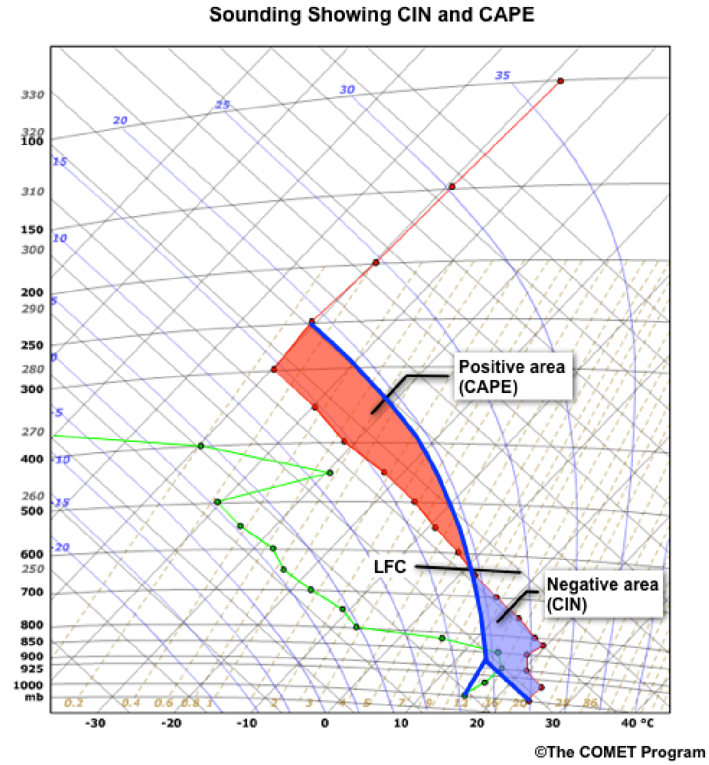


Figure 3: Skew-T Ln-P plot from Dodge City, KS at 0000 UTC on 15 September 2004



Source : COMET (https://www.meted.ucar.edu/education_training/)

- CIN represents the amount of negative buoyant energy available to inhibit or suppress upward vertical acceleration, or the amount of work the environment must do on the parcel to raise the parcel to its level of free convection (LFC). The energy needed to lift an air parcel upward adiabatically to the lifting condensation level (LCL) and then from the LCL to its LFC.

Quiz for Stability

Determine whether the following soundings obtained from radiosonde launches are stable, unstable, or neutral for both saturated and unsaturated air parcels

1). −7 C°/1000 m

(a) stable (b) unstable (c) conditionally unstable

2). -3C°/1000 m

(a) stable (b) unstable (c) conditionally unstable

3). −15C°/1000 m

(a) stable (b) unstable (c) conditionally unstable

4). −4C°/1000 m

(a) stable (b) unstable (c) conditionally unstable

The dry adiabatic lapse rate for the Earth's atmosphere equals -**10° C per kilometre**.

The moist adiabatic lapse rate is **6 C per kilometre**

Answers (1) (c), (2) (a) , 3) (b), 4) (a)