Atmospheric Stability and Precipitation

June 30th, 2021

Adiabatic Cooling and Warming

Adiabatic means without the loss or gain of heat.

Expansion – Adiabatic Cooling

Compression – Adiabatic Warming

Saturated Air

The point at which some **water vapor molecules must become liquid because maximum vapor pressure** is exceeded.

The warmer the air, the more water vapor it can hold before becoming saturated.

Supersaturation - air contains more water vapor than is needed to cause saturation.

Water vapor begins to condense onto impurities (such as dust or salt particles) in the air as the RH approaches 100 percent, and a cloud or fog forms.

In air absolutely devoid of impurities, as sometimes exists above 25,000 feet but never at lower levels, the RH can climb well above 100 percent.

Condensation Nuclei

Ways to Reach Saturation

1. Mixing: warm air mixes with cold air. Examples are **evaporation fogs** and jet contrails

2. Cooling: a parcel of air is cooled until it reaches dew point

   A. **Diabatic cooling**: removal of energy from the air

   - **Warm wind over cold surface air loses energy to the ground**
   - Examples:
     - Advection fog – "wind" fog
     - Valley fog – a type of advection fog
     - Radiation fog – fog from longwave radiation and cool ground

   B. **Adiabatic cooling** – no energy is removed from the parcel of air in its cooling. Large masses of air can be cooled to dew point ONLY by expanding as they rise.

   Adiabatic cooling accounts for all significant cloud formations and precipitation

   Also: Orographic fog

Adiabatic Processes

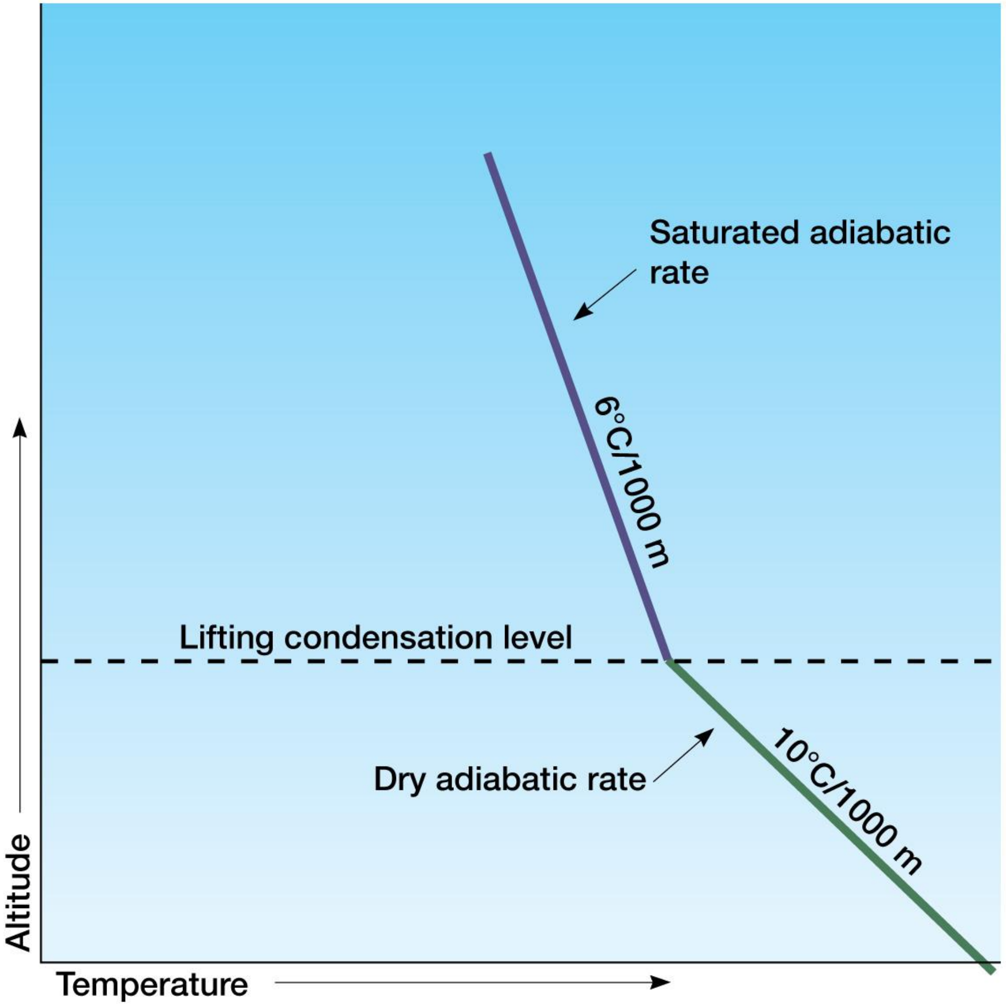
•**Dry adiabatic lapse rate**—the rate at which a parcel of ***unsaturated*** air cools as it rises; this rate is relatively steady (5.5°F per 1000 feet) (**10°C/km**) or **1°C/100m**.

•**Dry?**

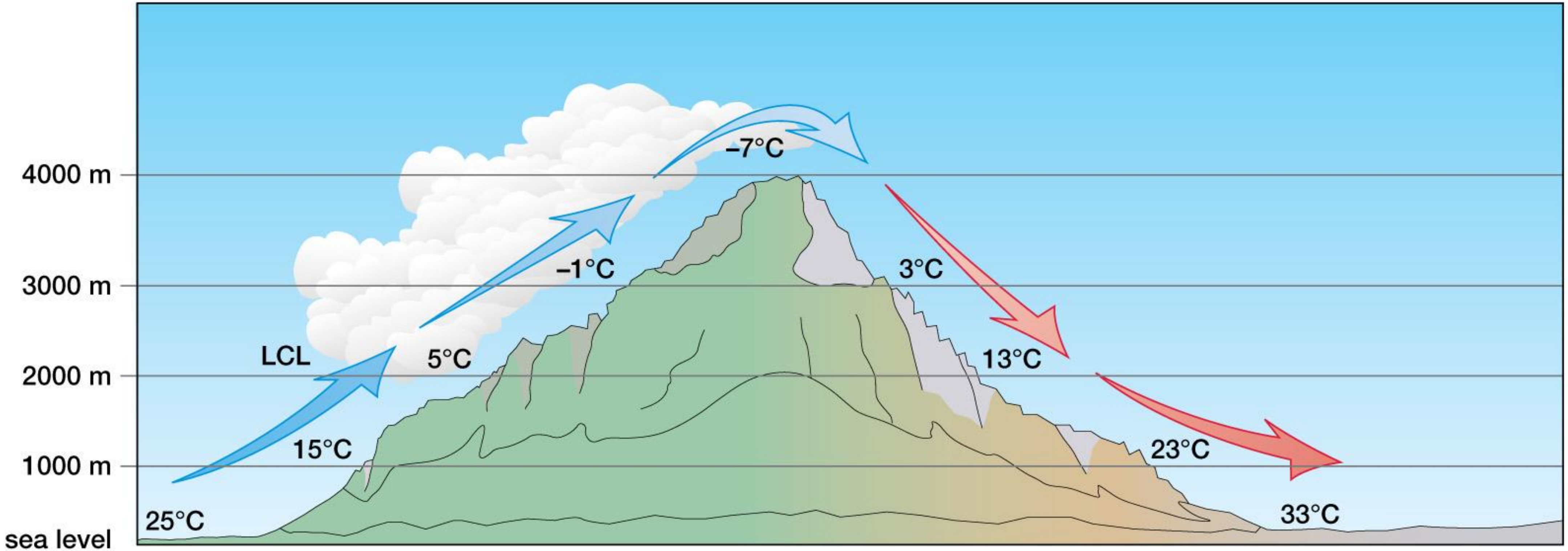
•Air is not necessarily "dry," just not saturated. Descending air warms, and it does so at the dry adiabatic lapse rate.

•**Lifting condensation level** (LCL) —the altitude at which rising air cools sufficiently to reach **100% relative humidity at the dew point temperature**, and **condensation begins**.

•**Saturated adiabatic lapse rate**—the diminished rate of cooling, which occurs when air rises above the lifting condensation level. It depends on temperature and pressure, but averages about 3.3°F per 1000 feet (**6.°C/km**) or **0.6°C/100m**.


Saturated adiabatic rate
6°C/1000 m
Lifting condensation level
Dry adiabatic rate
10°C/1000 m
Altitude
Temperature

Example....



4000 m
3000 m
2000 m
1000 m
sea level
–7°C
–1°C
3°C
LCL
5°C
13°C
15°C
23°C
25°C
33°C

Adiabatic Processes

Key physical geographic fact:

- **Large masses of air can ONLY be cooled to dew point by forcing them to expand and rise.**
  - Because of this limitation, adiabatic cooling is the only **prominent** mechanism for development of clouds and the production of rain.

What’s the difference between a cloud and fog?

Fog versus Cloud

Fog represents a minor form of condensation

There is no physical difference between a cloud and fog, but there are important differences in how they (fog and cloud) are formed.

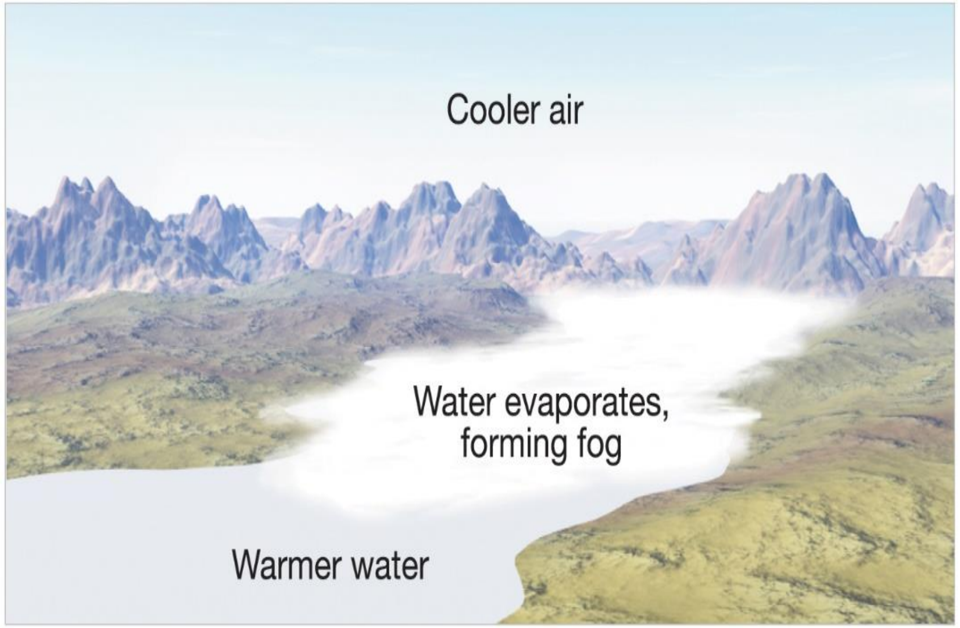
Most **clouds develop as a result of adiabatic cooling**, but **rarely is uplift involved in fog formation.**

Instead, most fogs are formed either when air at Earth's surface cools to below its **dew point temperature** or when **enough water vapor** is added to the air to saturate it (mixed).

Fog is simply a cloud on the ground

Evaporation Fog

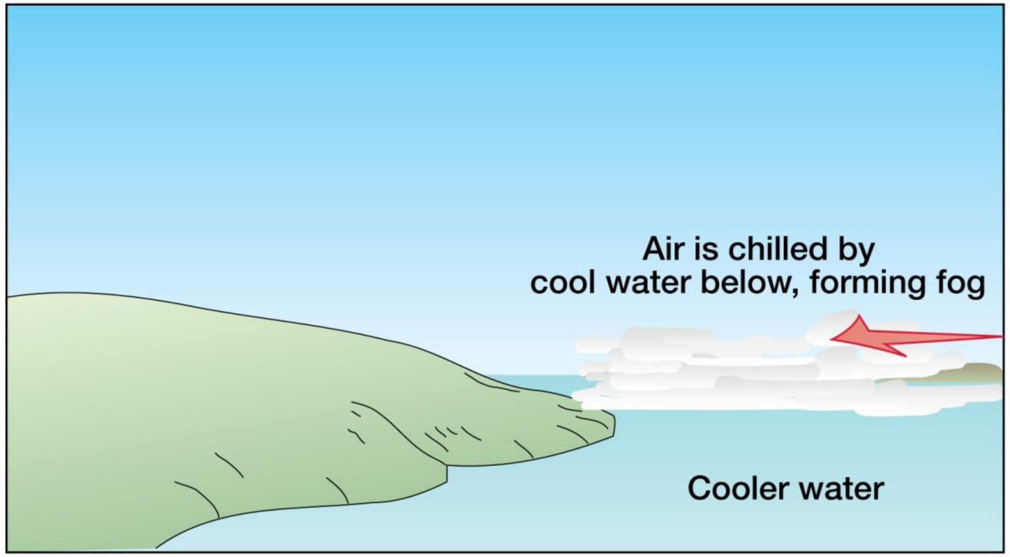
Evaporation fog — **when water vapor is added to cold air that is already near saturation**.
Cold air lying over the warm water of a lake, ocean surface, or **even a swimming pool**.
Also called *steam fog and frontal fog;* **forms as water molecules evaporate from the water surface into the cold overlying air**, effectively **humidifying the air to saturation followed by condensation to form a fog**.



(d) Evaporation

Advection Fog "wind fog"

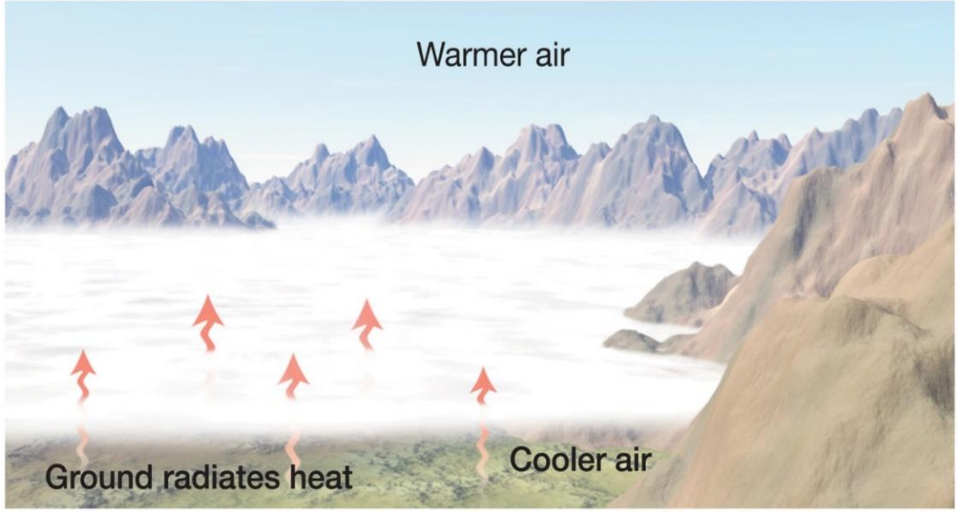
An advection fog develops when **warm, moist air moves horizontally over a cold surface**, such as snow-covered ground or a cold ocean current. Air moving from sea to land is the most common source of advection fogs.



(b) Advection

Radiation fog

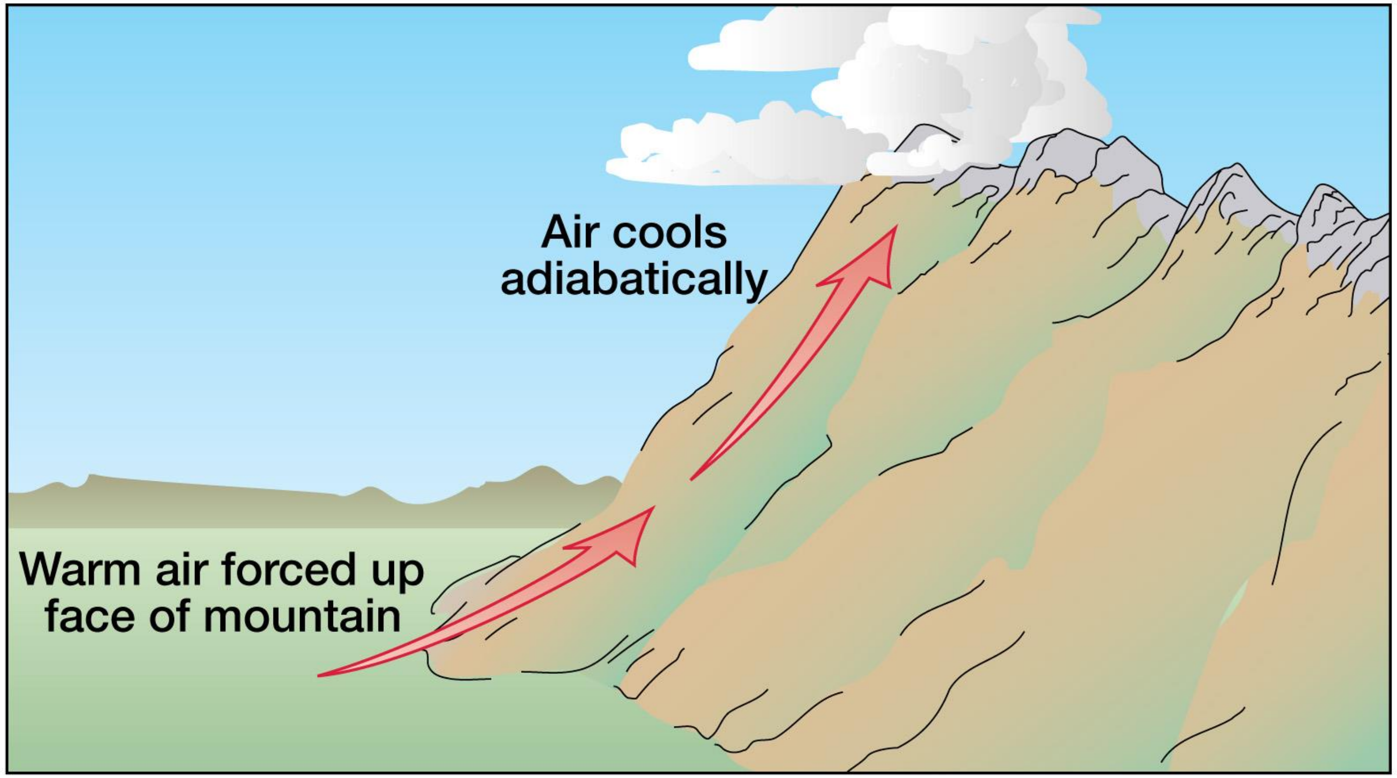
- **Forms at night and early mornings under clear skies with calm winds when heat absorbed by the earth's surface during the day is radiated into space**.
- As the earth's surface continues to cool, if there is a deep enough layer of moist air present near the ground, the humidity will reach 100% and fog will form.
- Radiation fog varies in depth from 3 feet to about 1,000 feet and is always found at ground level and usually remains stationary.
- **This type of fog can reduce visibility to near zero at times and make driving hazardous.**



(a) Radiation

Upslope Fog

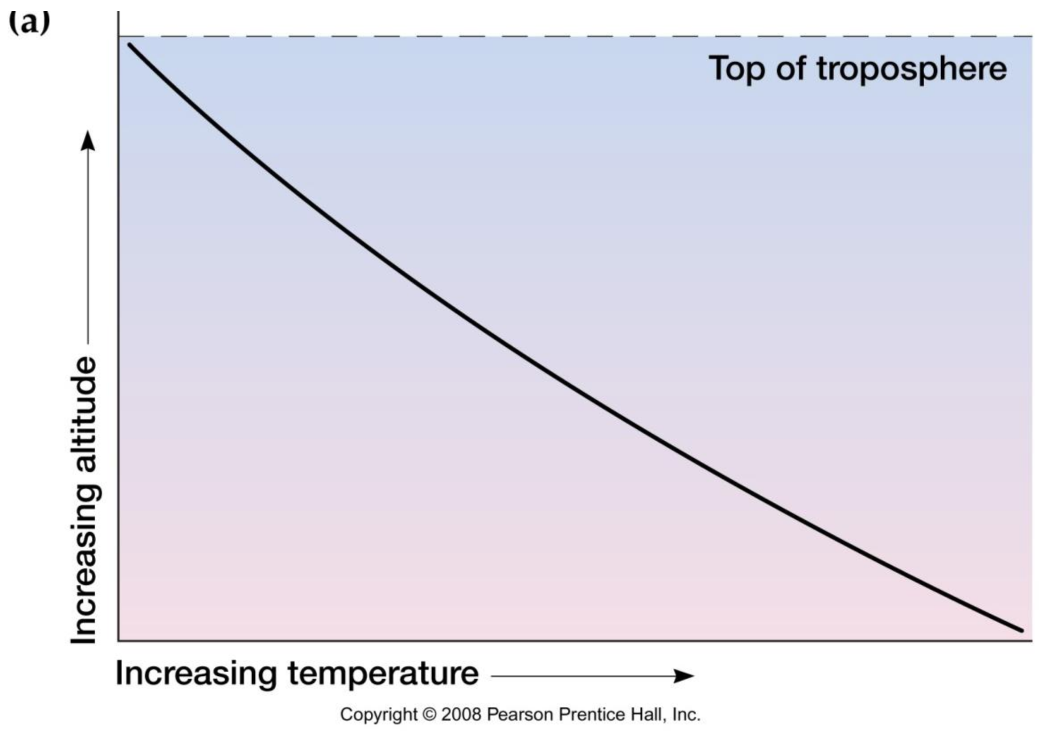
An upslope fog, or orographic fog (from the Greek *oro*, "mountain") is created by adiabatic cooling when humid air climbs a topographic slope



(c) Upslope (orographic)

Vertical Temperature Patterns

- **Average Lapse Rate**
  - normal vertical temperature gradient, with temperature dropping 3.6°F per 1,000 feet (6.5°C per kilometer)
- **Environmental Lapse Rate**
  - Rate at which temperature drops as altitude increases
  - can vary according to season, time of day, amount of cloud cover, and other factors.



This is typical, but…..

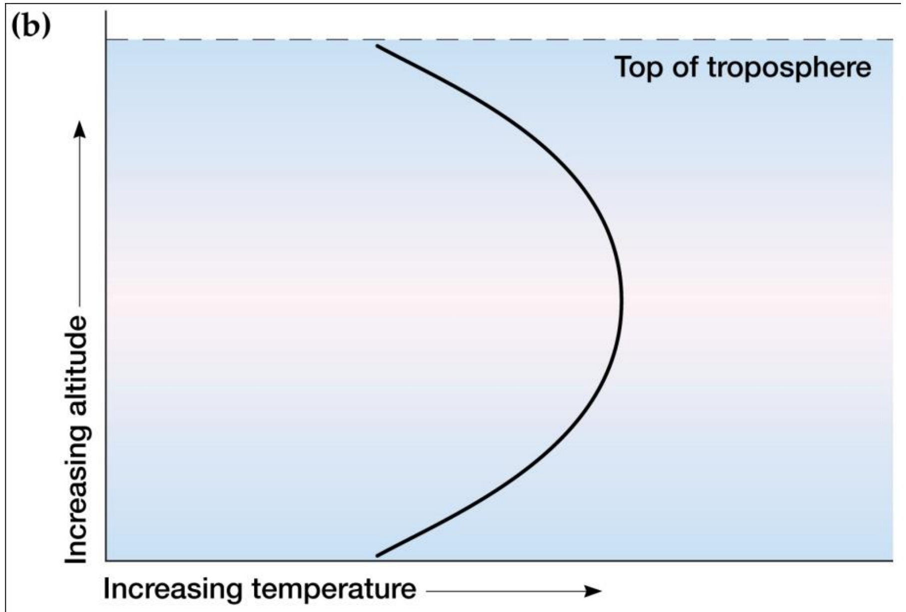
Temperature Inversions

Temperature inversions—prominent exception to average lapse rate, in which temperature increases with increasing altitude.

- Common but usually brief and only to a restricted depth.
- Affect weather by cutting possibility of precipitation and creating stagnant air conditions.

Surface Inversions—there are three kinds of surface inversions:

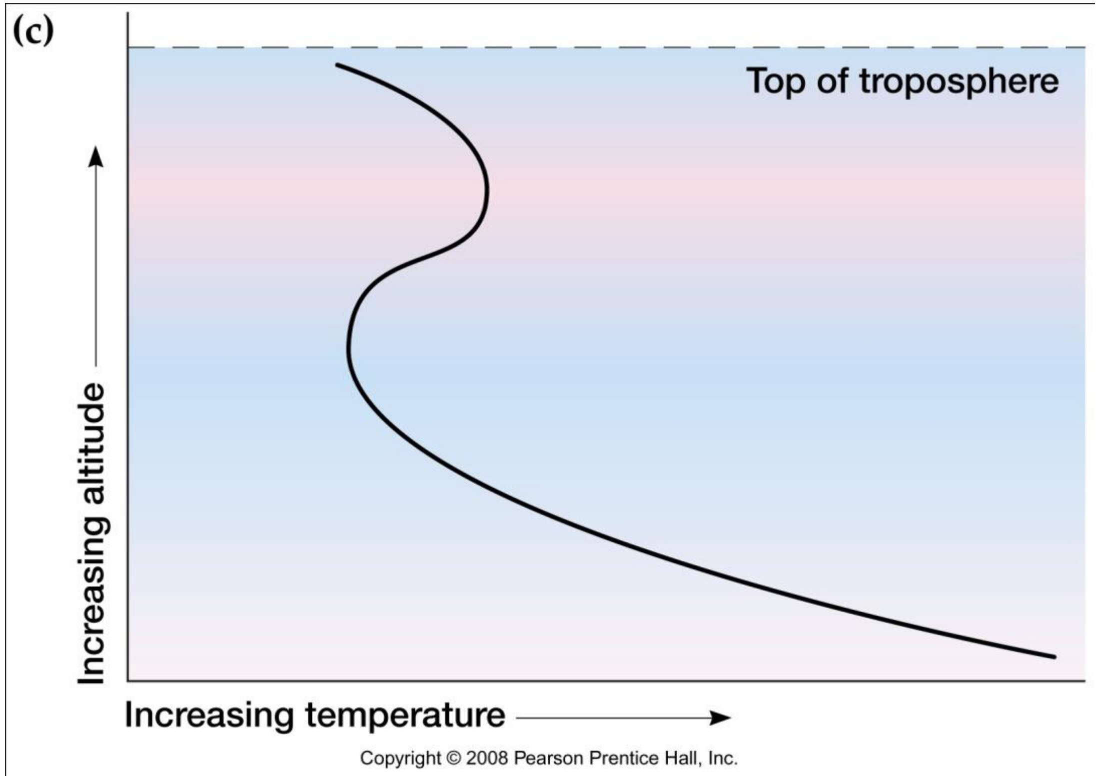
- **Radiational inversions**—surface inversion that results from rapid radiational cooling of lower air, typically on cold winter nights (and thus in high latitudes);
- **Advectional inversions**—surface inversion caused by a horizontal inflow of colder air into an area (as in cool maritime air blowing onto a coast); usually short-lived and shallow and can occur any time of year, but are more common in winter than in summer;
- **Cold-air-drainage inversions**—surface inversion caused by cooler air sliding down a slope into a valley; fairly common during winter in some midlatitude regions.



Temperature Inversions

Upper-Air inversions

- **AKA Subsidence inversions—** temperature inversions that occur well above Earth's surface as a result of air sinking from above.



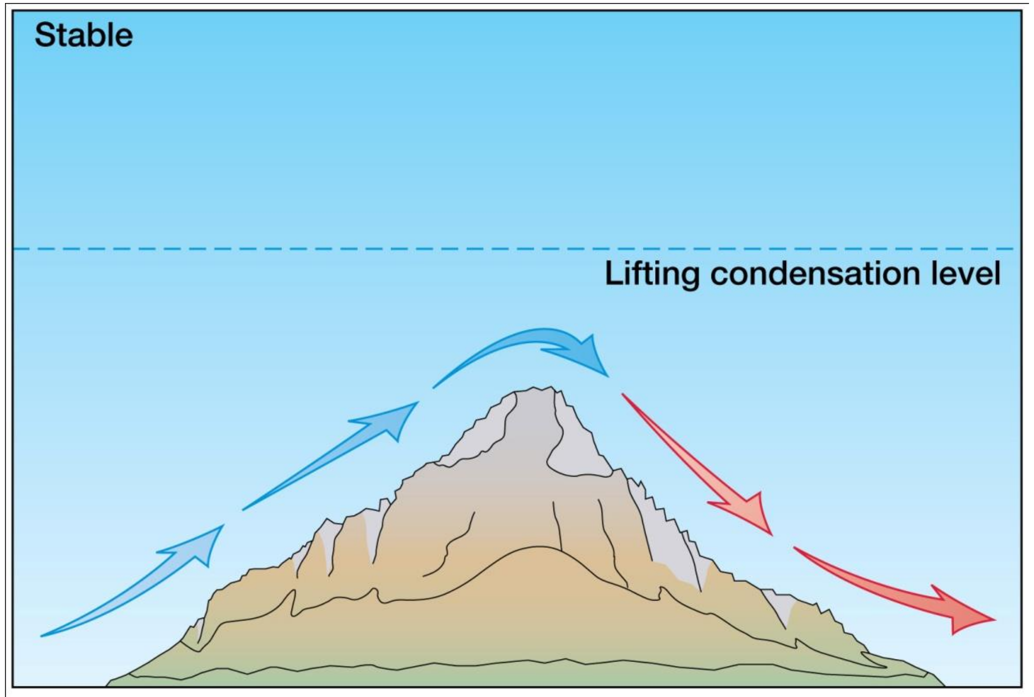
The Buoyancy of Air

- **Buoyancy**—the tendency of an object to rise in a fluid.
- Because most condensation and precipitation are the result of rising air, the conditions that promote or hinder upward air movement in the troposphere are very important to weather and climate.
- Depending on the buoyancy of air, it may rise more freely and extensively under different circumstances

Atmospheric Stability

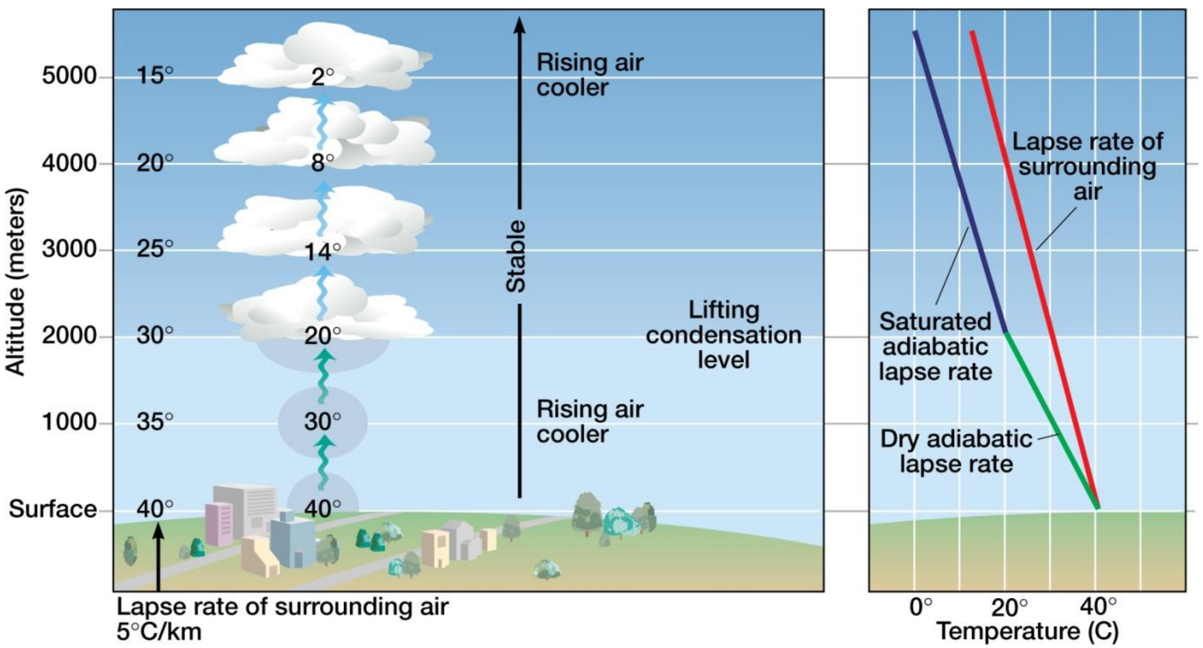
- Picture a given parcel of air, one having imaginary boundaries, as being an “object” and the surrounding air as being the fluid.
- As with other gases (and liquids, too) a parcel of air moves vertically until it reaches a level at which the surrounding air is of equal density (equilibrium level).
- Therefore, if a parcel of air is warmer, and thus less dense, than the surrounding air, it tends to rise.
- If a parcel is cooler, and therefore denser, than the surrounding air, it tends either to sink or at least resist uplift.
- **Thus we tend to say that warm air is more buoyant than cool air.**

•If a parcel resist uplift, we say it is ***stable.***
•**Stable air**—resists vertical movement



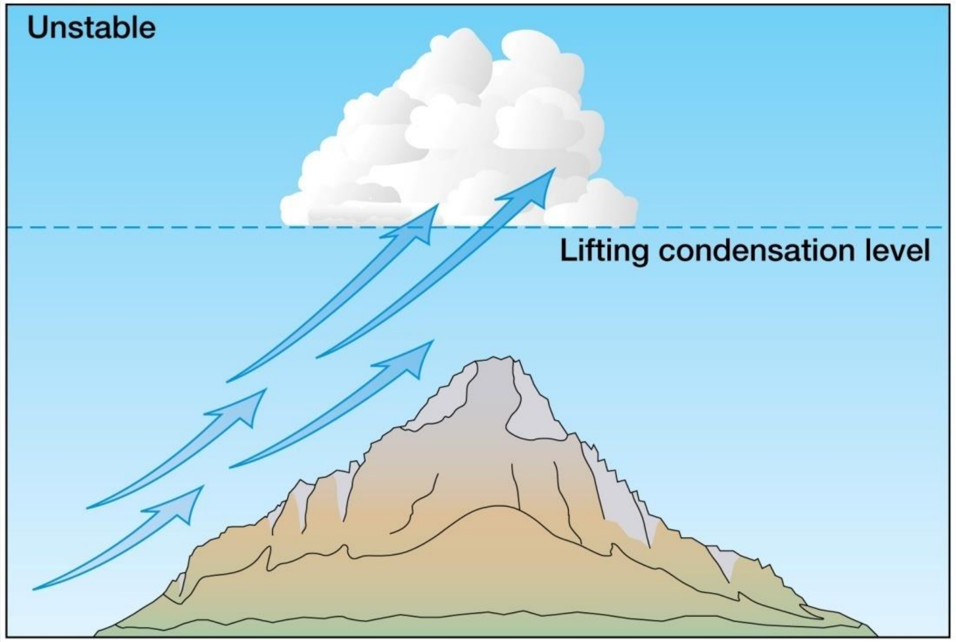
(a)

As stable air blows over a mountain, it rises only as long as it is forced to do so by the mountain slope. On the leeward side, it moves downslope



(a)

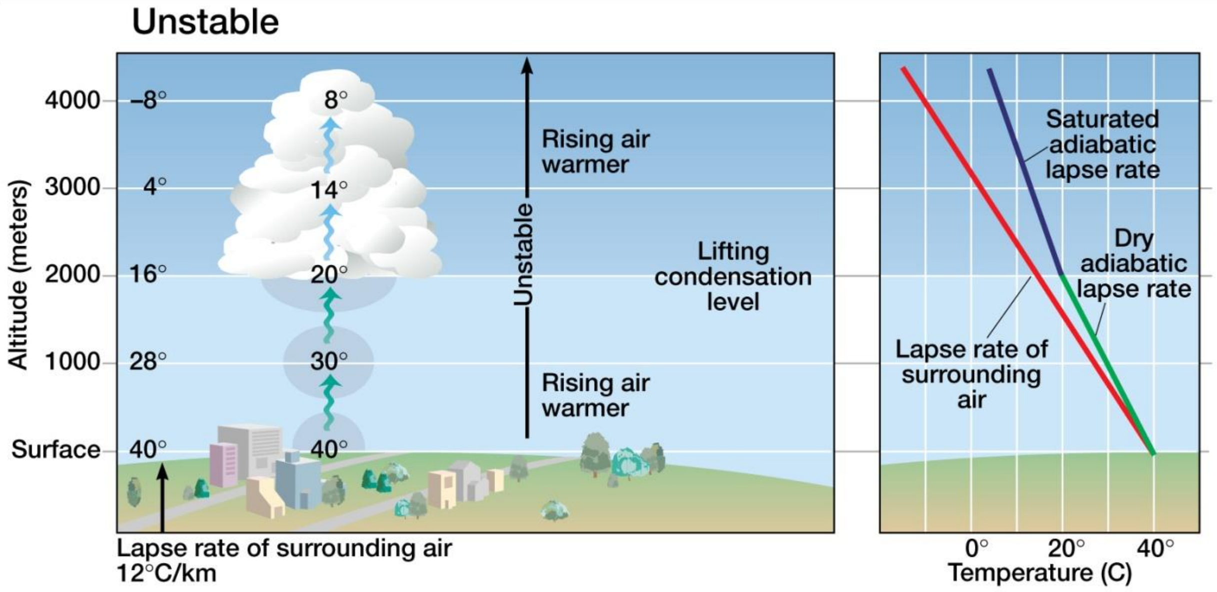
At all elevations, the rising parcel of air is cooler than the surrounding air, so the parcel is stable and will rise only if forced



(b)

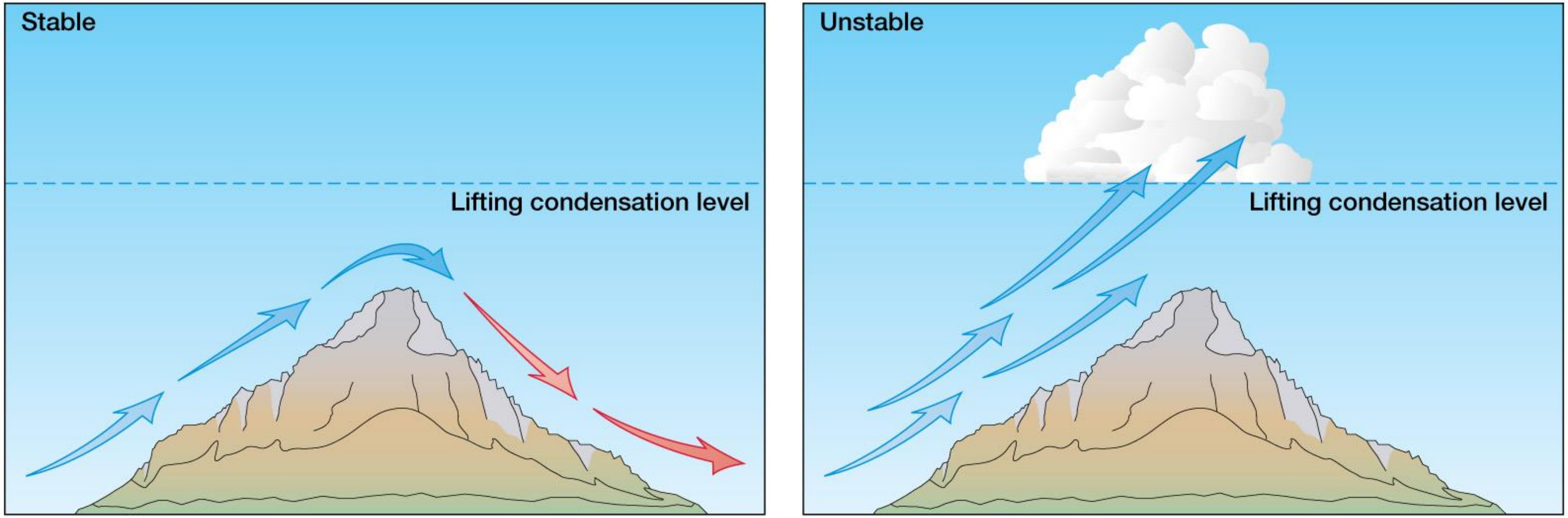
•**Unstable air**—buoyant, will rise without external force or will continue to rise after force is removed.

When unstable air is forced up a mountain slope, it is likely to continue rising of its own accord until it reaches surrounding air of similar temperature and density; if it rises to the lifting condensation level, clouds form



(b)

At all elevations, the rising parcel of air is warmer than the surrounding air, so the parcel is unstable and will rise because of its buoyancy


Stable
Lifting condensation level
Unstable
Lifting condensation level

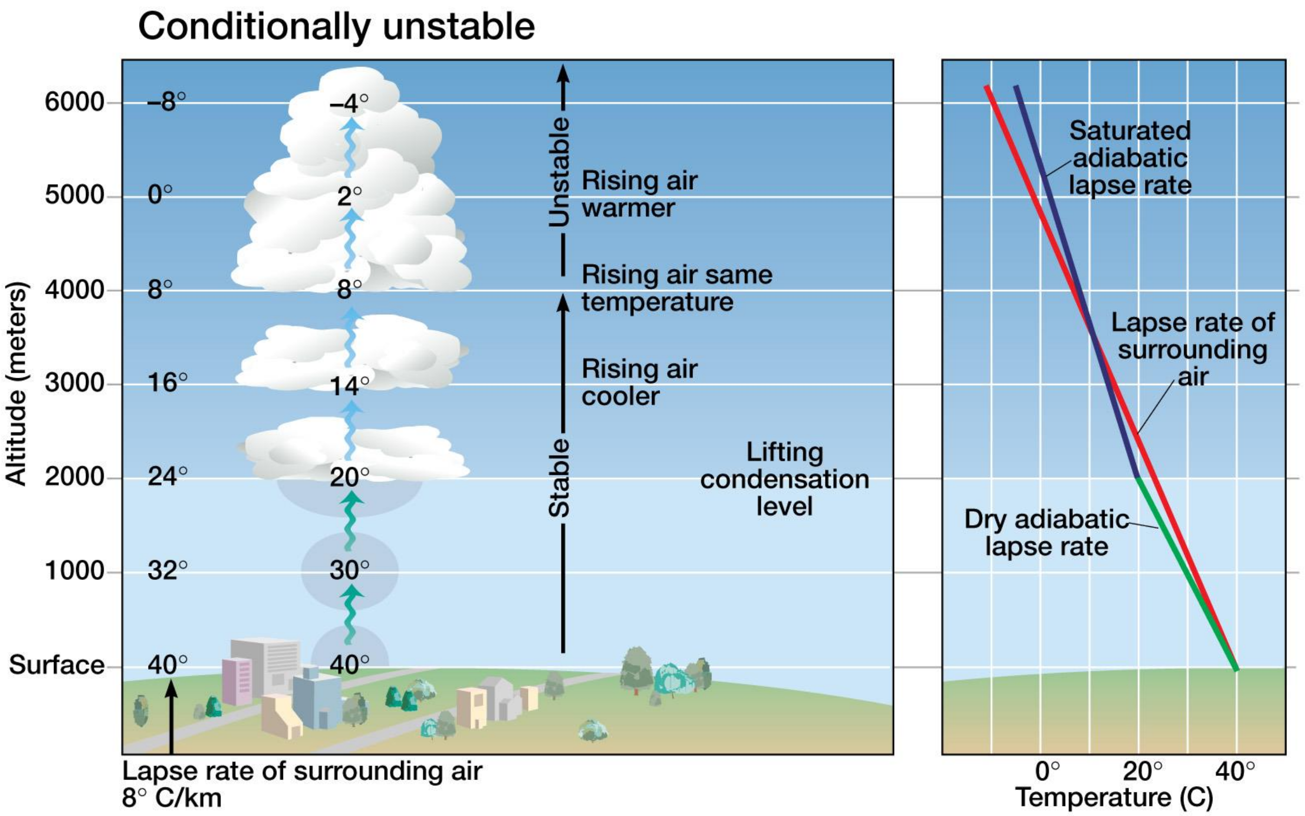
(a) (b)

Conditional instability

Condition between absolute stability and absolute instability.

occurs when an air parcel's adiabatic lapse rate is somewhere between the dry and wet adiabatic rates.

Acts like stable air until an external force is applied; when forced to rise, it may become unstable if condensation occurs (release of latent heat provides buoyancy).



(c)

Precipitation

Precipitation

- Most clouds do not yield precipitation, but a lot of them do.
- Condensation alone is insufficient to produce raindrops.
- *The Processes*
  - Still not well understood why most clouds do not produce precipitation.
  - Two mechanisms are believed to be principally responsible for producing precipitation:
    - Collision and coalescence of water droplets
    - Ice-crystal formation

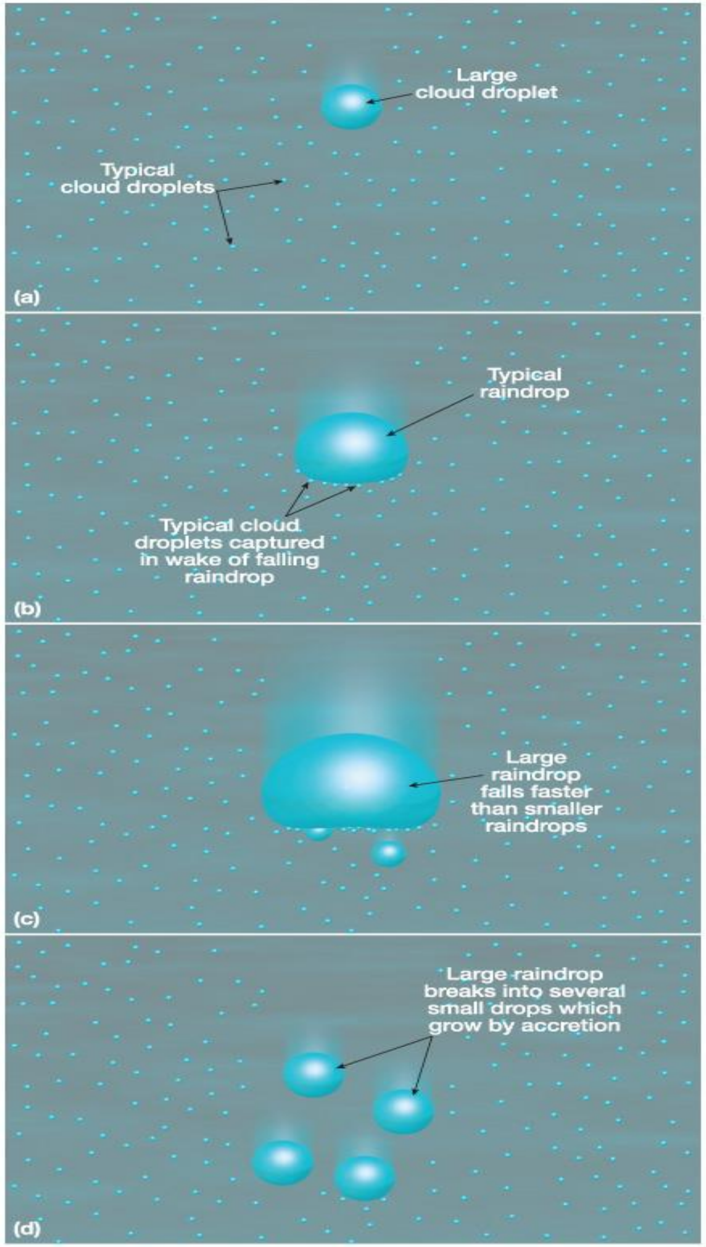
Collision/Coalescence

Most responsible for precipitation in the tropics and produces much precipitation in the middle latitudes.

At these latitudes, cloud temperatures are greater than 0°C (32° F); these are known as ***warm clouds.***

Under these conditions rain is produced by the collision and coalescing (merging) of water droplets.

Condensation alone cannot give rain because it produces lots of small droplets but no large drops



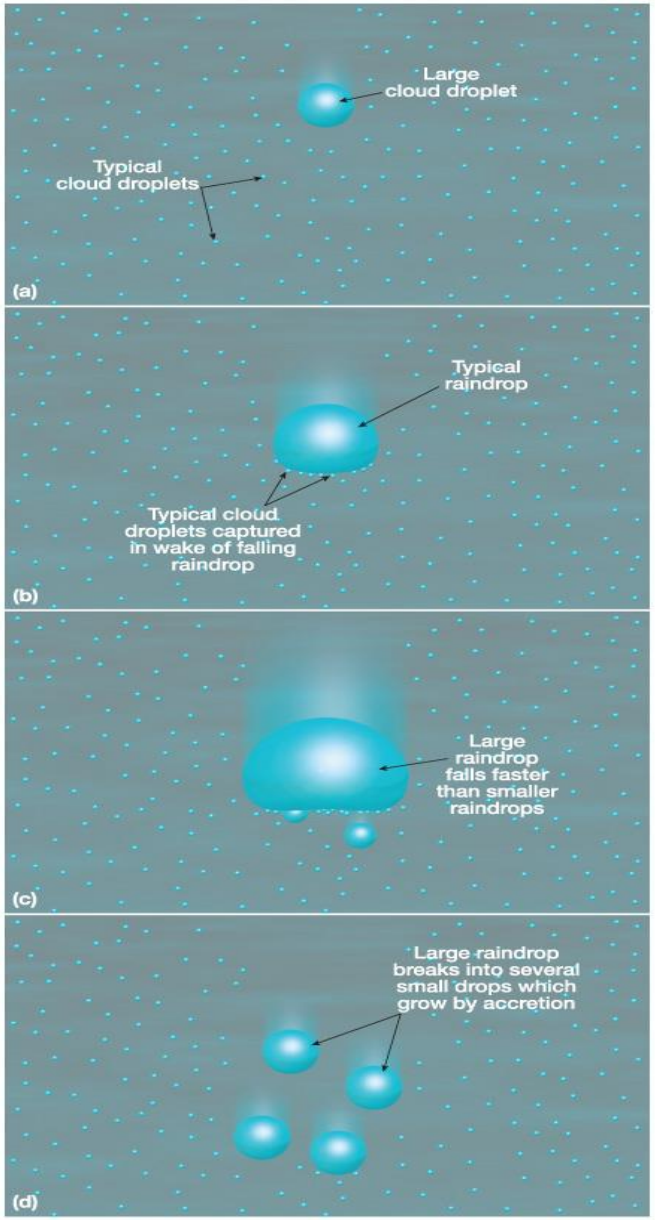
Collision/Coalescence

Must coalesce enough that the droplets become large enough to fall.

<u>No ice crystals because cloud temperatures are too high.</u>

Coalescence is assured only if atmospheric electricity is favorable, so that positively charged droplets collide with negatively charged ones ==polarity of water important.

- **Typical cloud droplets = 0.02 mm**
- **Large cloud droplet = 0.05 mm**
- **Typical rain drop = 2 mm**
- **Large rain drop = 4 mm**

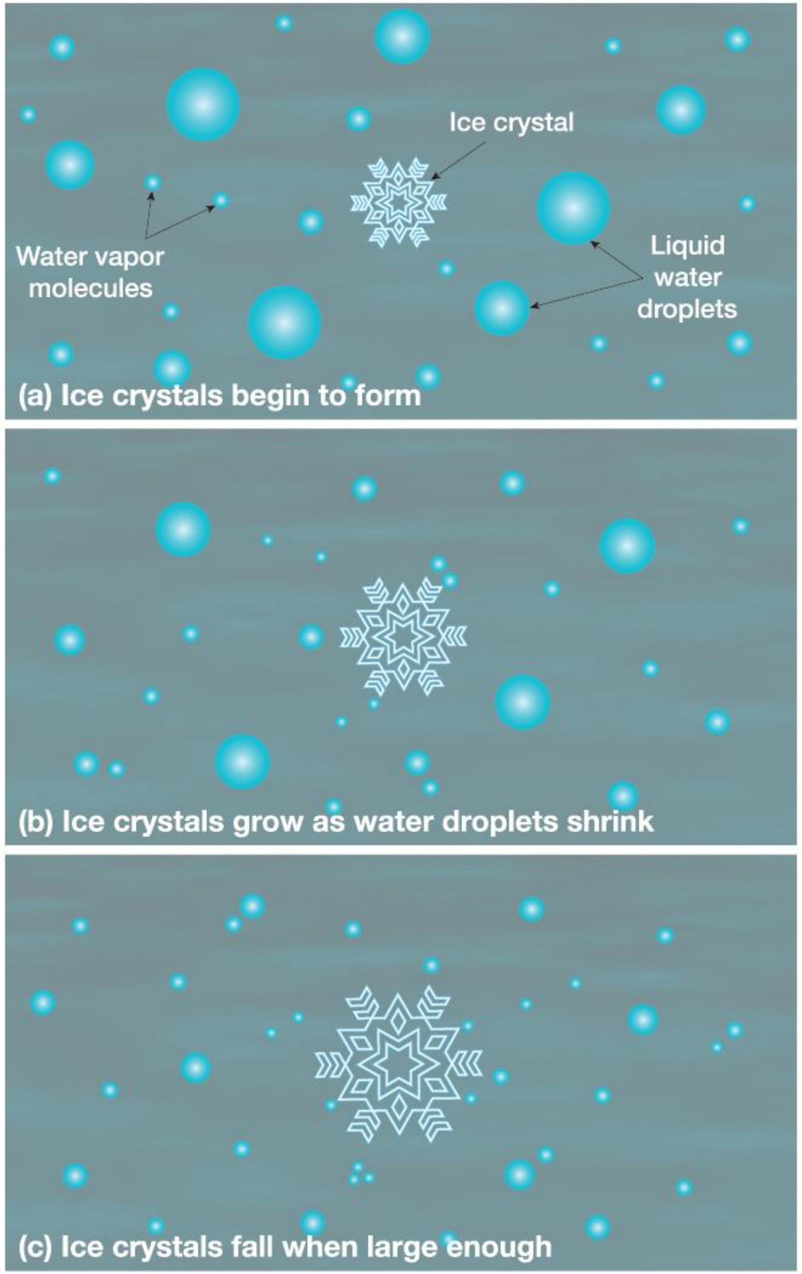


Bergeron process – Tor Bergeron

Process by which ice crystal formation occurs; is believed to account for the majority of precipitation outside of tropical regions.

Clouds or portions of clouds extend high enough to have temperatures well below freezing point of liquid (***called cool or cold clouds***).

Ice crystals and supercooled water droplets often coexist in the cloud and are in direct "competition" for water vapor not yet condensed.



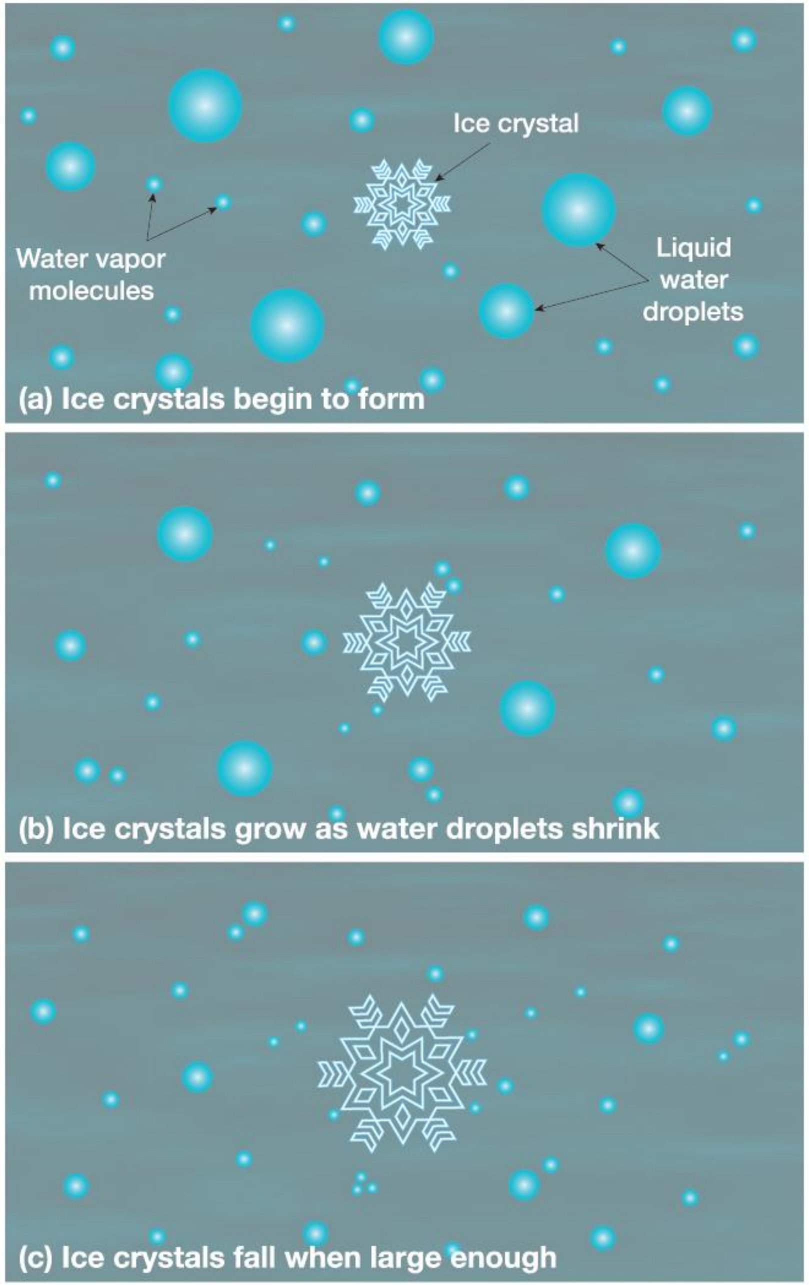
Bergeron process – Tor Bergeron

Ice crystals attract most of the water and the liquid water evaporates to replenish diminishing vapor.

Therefore ice crystals grow at expense of water droplets, until the crystals are large enough to fall.

As they descend, they grow warmer and pick up more moisture, growing still larger.

They then either precipitate as snowflakes or melt and precipitate as raindrops.



Forms of Precipitation

The type of precipitation we get **depend on the environmental lapse rate and temperature at which the droplet was formed (typical situation, <u>but see hail</u>).**

- Once a parcel of air reaches the lifting condensation level, clouds begin to form.
- If conditions are unstable, it will continue to rise.
- There are several types of precipitation and most are driven by temperature and turbulence.

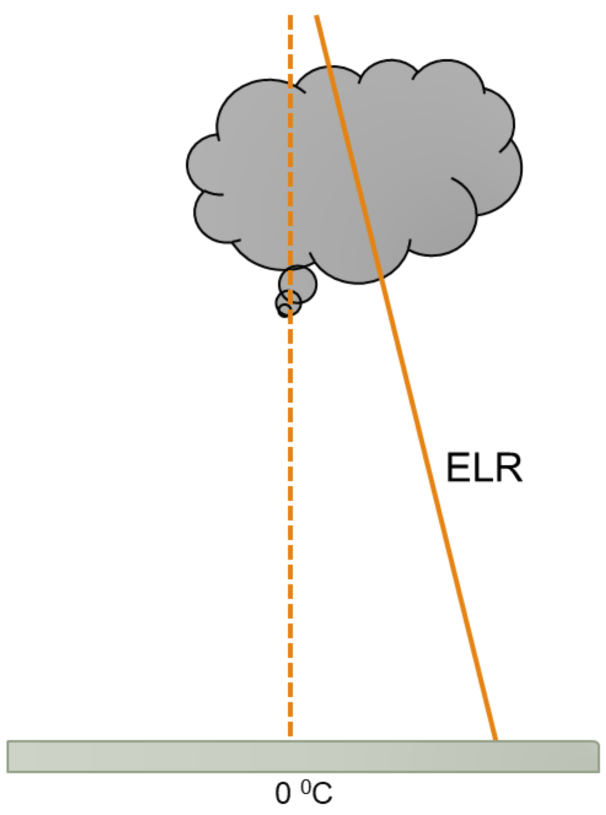
Rain

The most common and widespread form of precipitation, consisting of drops of liquid water.

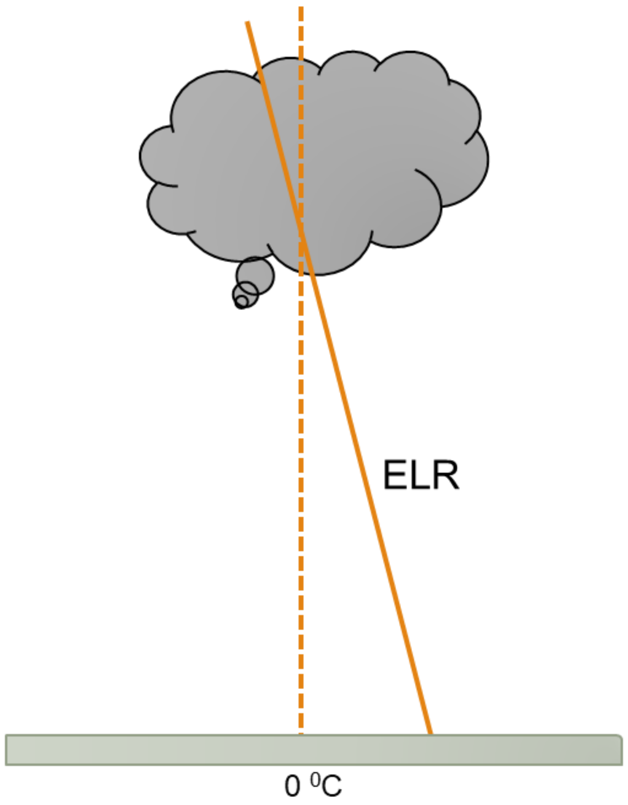
Most rain is the result of condensation and precipitation in ascending air that has a temperature above freezing, but some result from thawing of ice crystals.

ELR = Environmental Lapse Rate

Temperature at cloud formation is above freezing:
Vapor >Water >Rain



Temperature at cloud formation is below freezing:
Vapor >Ice > Water>Rain

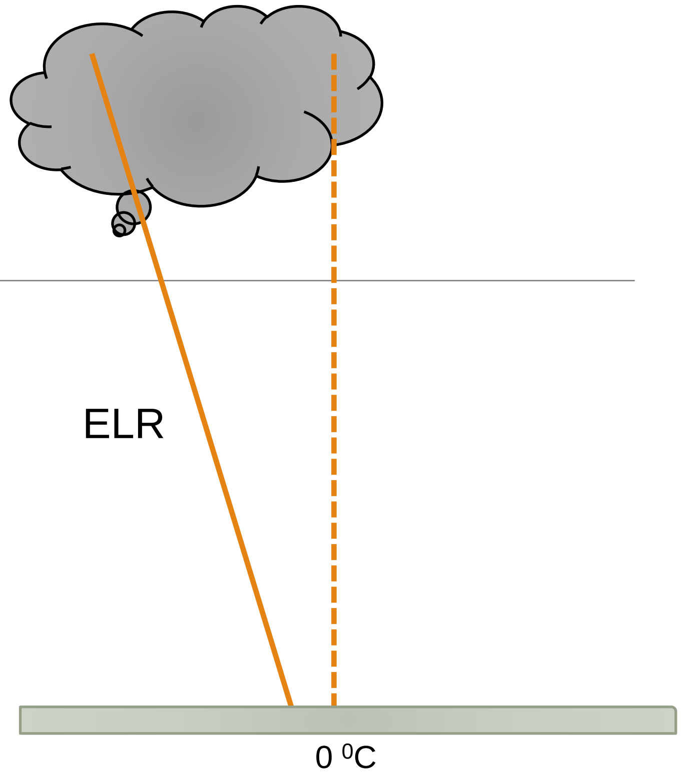


Snow

Solid precipitation in the form of ice crystals, small pellets, or flakes

Is formed by the direct conversion of water vapor to ice without an intermediate liquid stage.

But, water vapor may have evaporated from supercooled liquid cloud droplets inside cold clouds

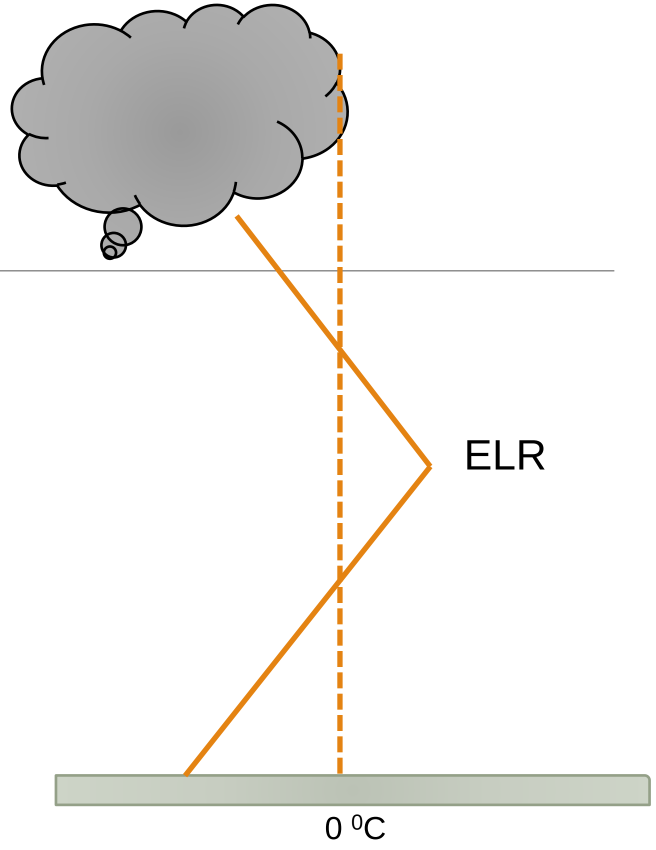


Temperature at cloud formation is below freezing:
Vapor > Ice > Snow

Sleet

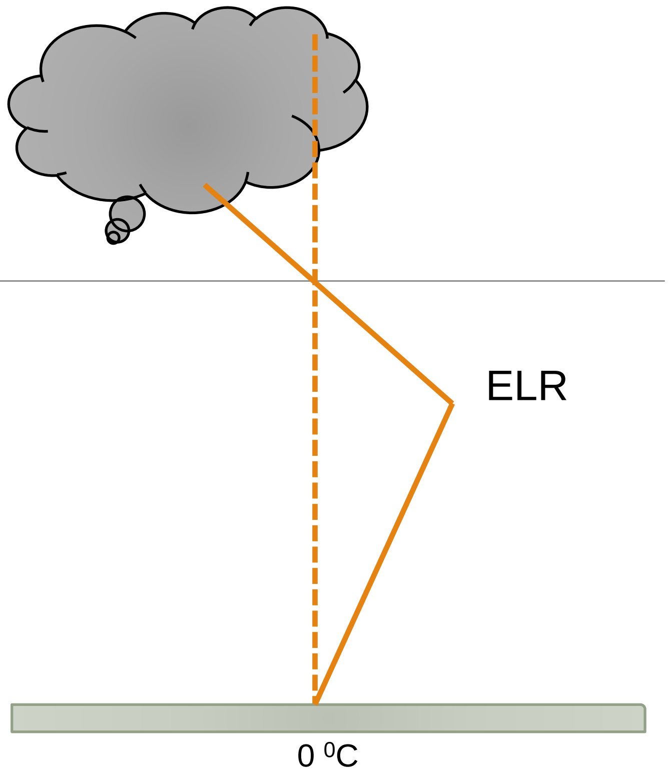
In the United States, sleet refers to small raindrops that freeze during decent, reaching ground as small pellets of ice.

In other parts of the world, the term is often applied to a mixture of rain and snow



Temperature at cloud formation is below freezing:
Vapor > Ice > Water> Ice

Glaze or Freezing Rain



Rain that turns to ice the instant it collides with a solid object.

Raindrops fall through a shallow layer of subfreezing air near to the ground.

Although the drops do not freeze in the air (in other words, they do not turn to sleet), they become supercooled while in this cold layer and are instantly converted to an icy surface when they land.

The result can be a thick coating of ice that makes both travel hazardous as well as damage tree limbs.

Temperature at cloud formation is below freezing:
Vapor > Ice > Water> Freeze at surface > Freezing rain

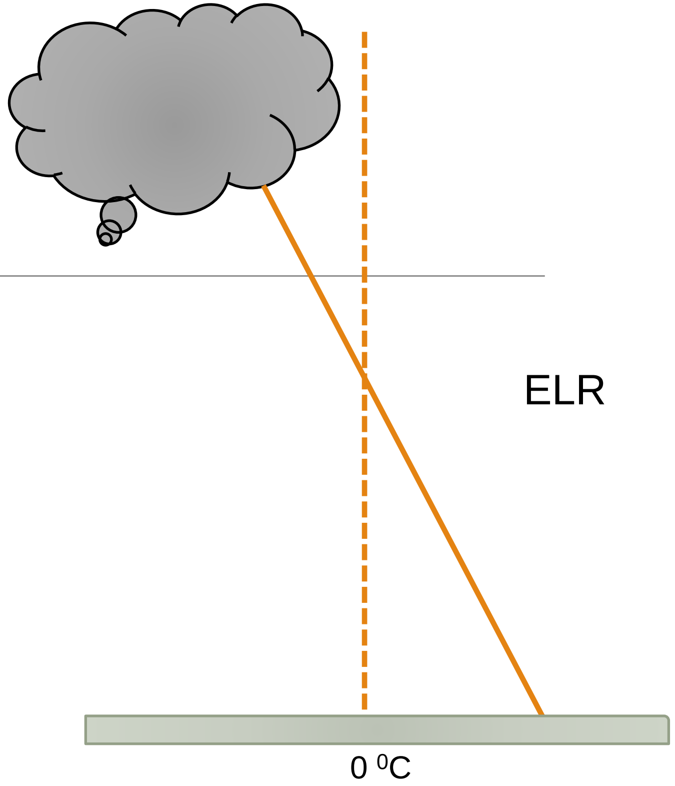
Hail

The precipitation form with the most complicated origin is hail

Hailstones are usually composed of roughly concentric layers of clear and cloudy small pellets or larger lumps of ice.

The cloudy portion contain numerous tiny air bubbles among small crystals of ice, whereas the clear parts are made up of large ice crystals

Hail is produced in cumulonimbus clouds as a result of great instability and strong vertical air currents (updrafts and downdrafts)



Hail cannot be predicted based on ELR, but may look a bit like this

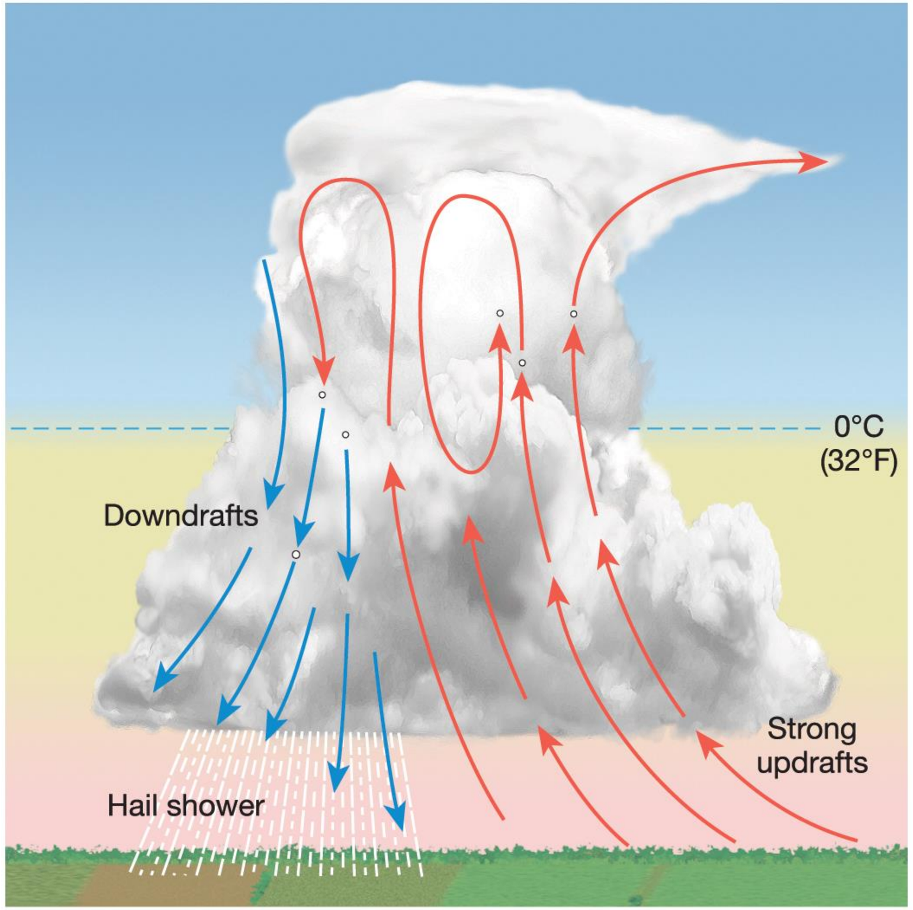
Hail

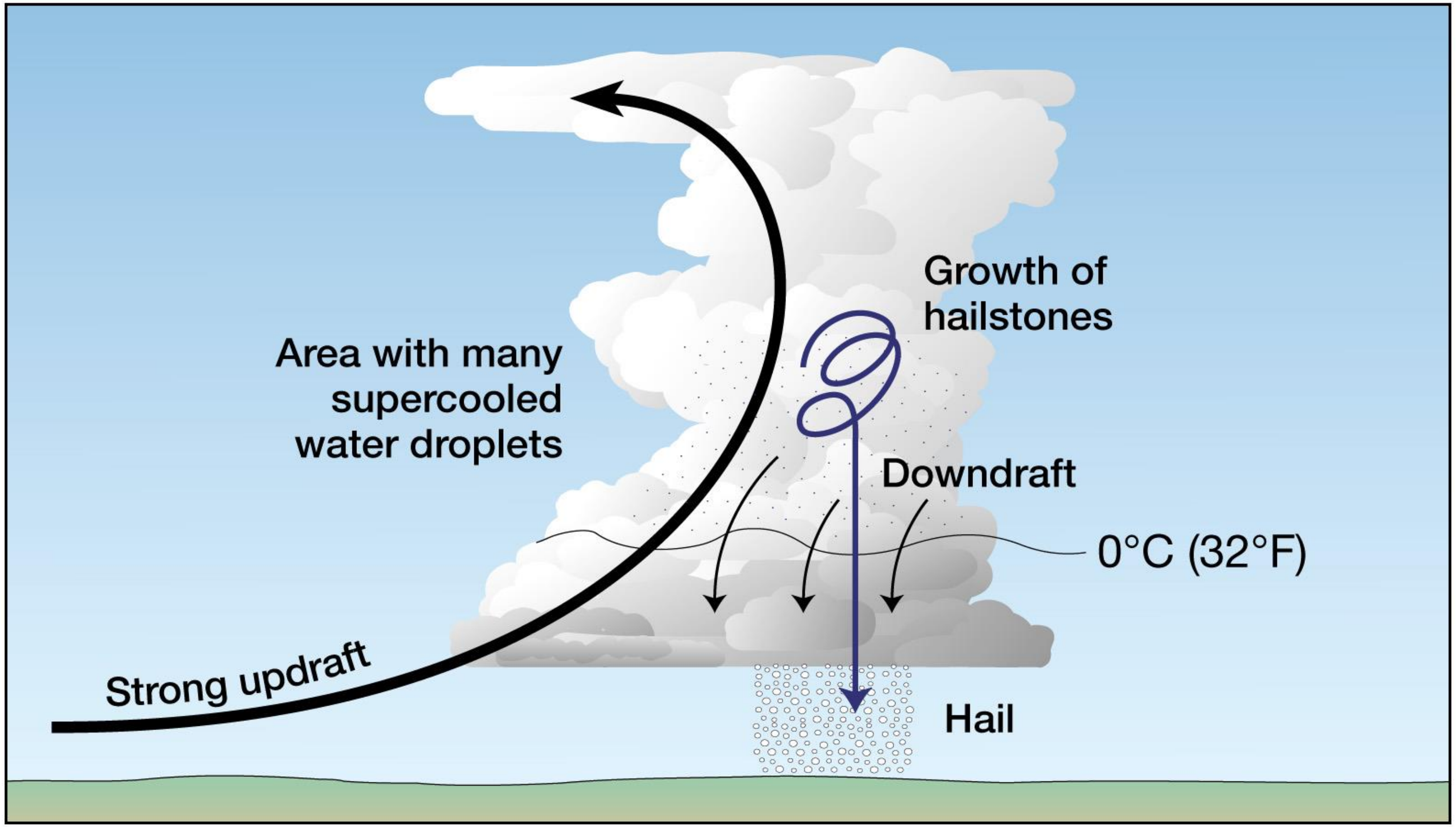
Updrafts carry water from the above-freezing layer or small ice particles from the lowest part of the below freezing layer upward, where they grow by collecting moisture from the supercooled cloud droplets

When the particles become too large to be supported in the air, they fall, gathering more moisture on the way down.

If they encounter a sufficiently strong updraft, they may be carried skyward again, only to fall another time

This sequence may be repeated several times.




Growth of hailstones
Area with many supercooled water droplets
Downdraft
0°C (32°F)
Strong updraft
Hail

Mechanisms of Uplift

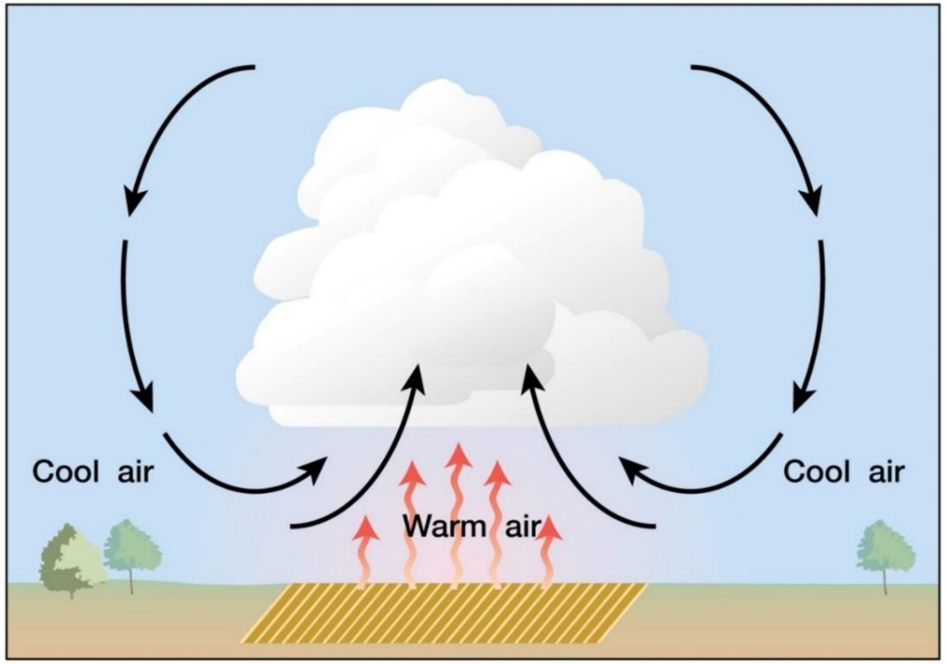
Atmospheric Lifting

- Significant amounts of precipitation can originate only by rising air and adiabatic cooling.
- **There are four principal types of atmospheric lifting**:
  1. Convective lifting
  2. Orographic lifting
  3. Frontal lifting
  4. Convergent lifting; and
  - Also Dynamic lifting – see midlatitude cyclones

More often than not, the various types operate in conjunction.

Convective Lifting

- Showery precipitation with large raindrops falling fast and hard
- caused by convective lifting, **which occurs when unequal heating of different air surface areas warms one parcel of air and not the air around it by conduction**
- The density of the heated air is reduced as the air expands, and so the parcel rises to a lower-density layer.
- The parcel cools adiabatically to dew point and forms clouds.
- **This is the only spontaneous of the four lifting types; the other three require an external force.**

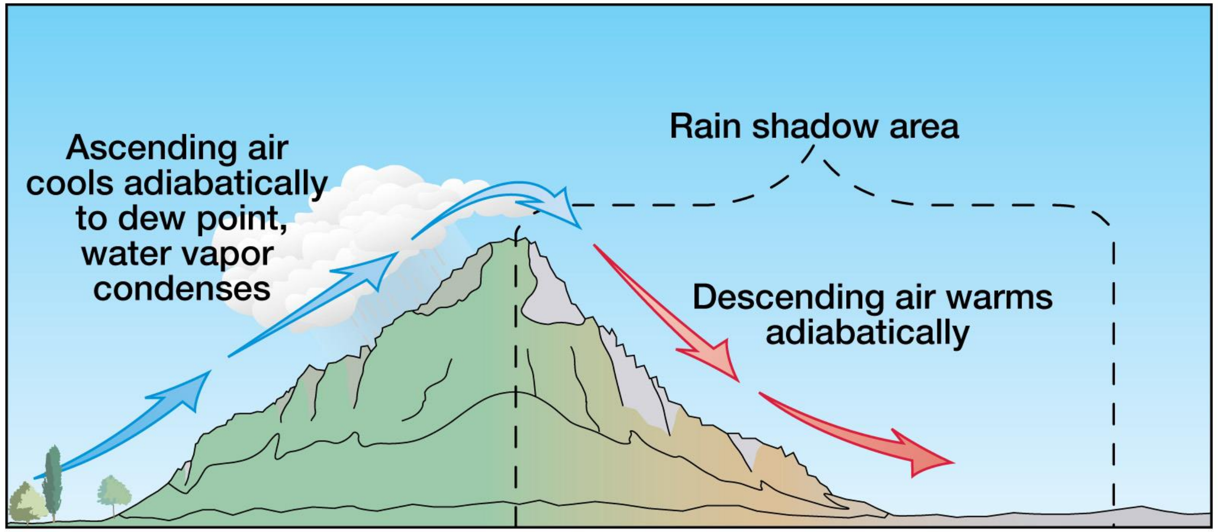


(a) Convective

Orographic Lifting

Topographic barriers, such as mountains, force air to ascend upslope. This causes the ascending air to cool to its dew point, forming a cloud.

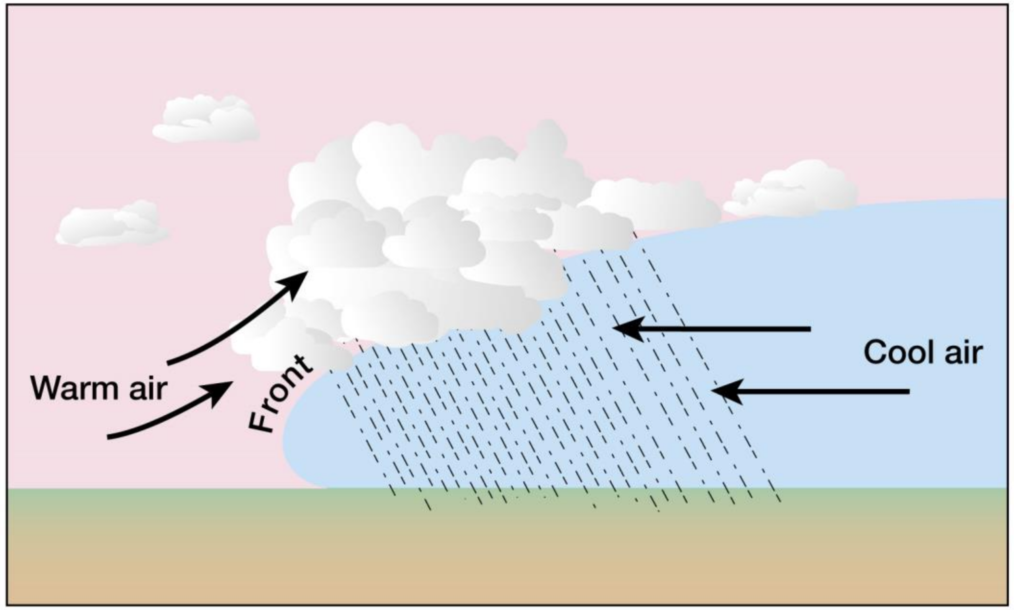
•**Rain shadow**—area of low rainfall on the leeward side of a topographic barrier; can also apply to the area beyond the leeward side, for as long as the drying influence continues.



(b) Orographic

Frontal Lifting

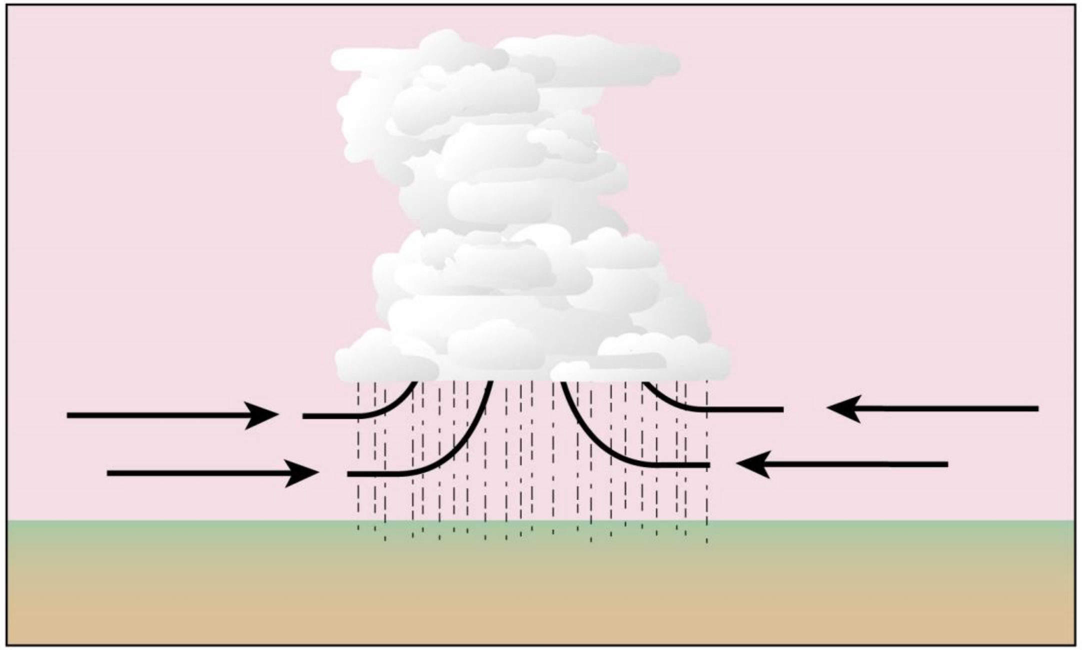
- **Unlike air masses do not mix**
- Occurs when air is cooled to the dew point after **unlike air masses meet**, creating a zone of discontinuity (front) that forces the warmer air to rise over the cooler air (frontal lifting).



(c) Frontal

Convergent Lifting

Showery precipitation caused by convergent lifting, which occurs when air parcels converge and the crowding forces uplift, which enhances instability. This precipitation is particularly characteristic of low latitudes.

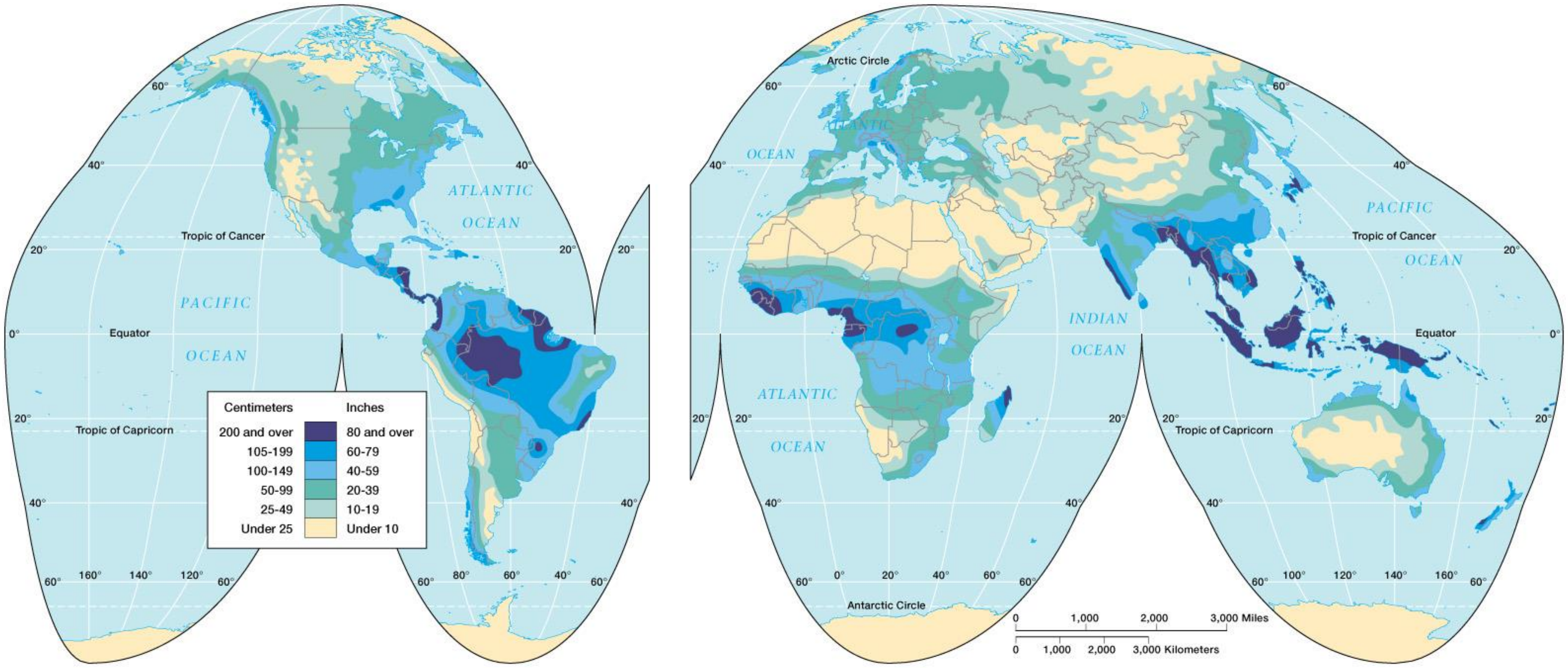


(d) Convergent

Dynamic Uplift

The Jet Streams lead to uplift and thus precipitation.

Will be discussed further with midlatitude cyclones



Average annual precipitation over the land areas of the world