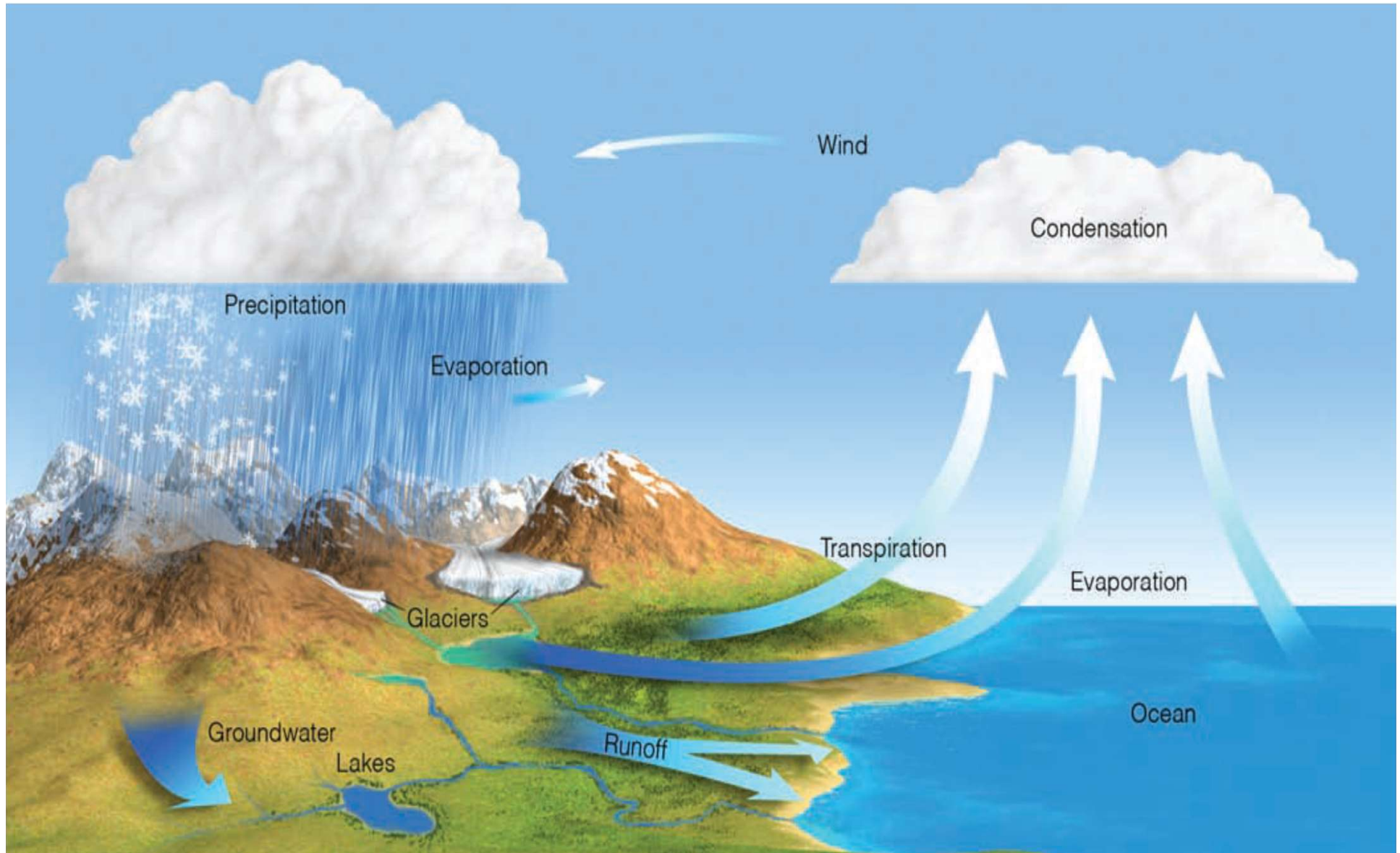


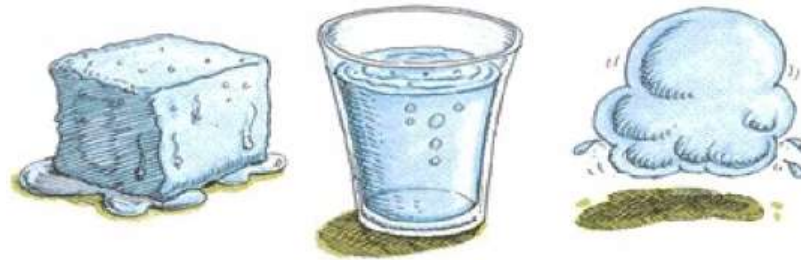
CHAPTER FIVE

5. ATMOSPHERIC HUMIDITY AND PRECIPITATION



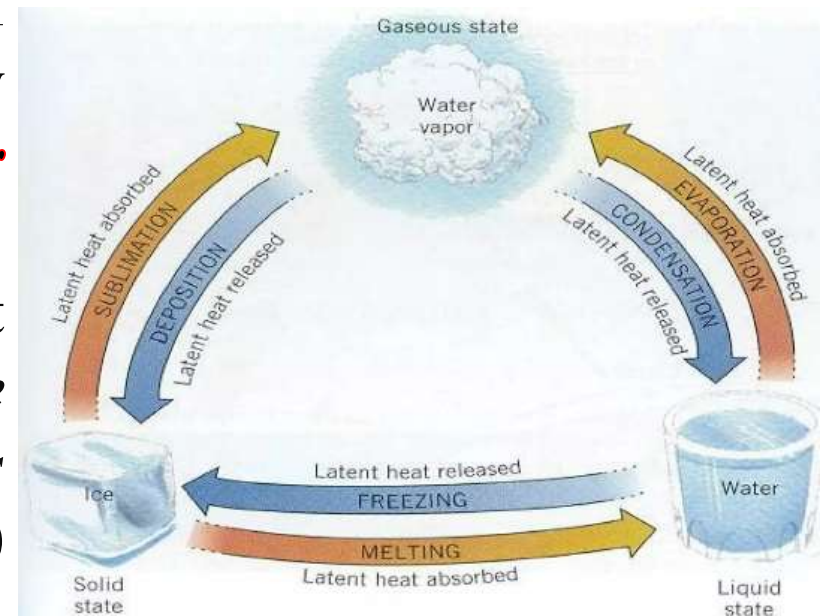
5.1. Atmospheric Moisture

- **Moisture** is a small amount of liquid that makes something **wet** or **moist**.
- **Water** is known to exist in three different **states**: as a **solid**, **liquid** or **gas**.



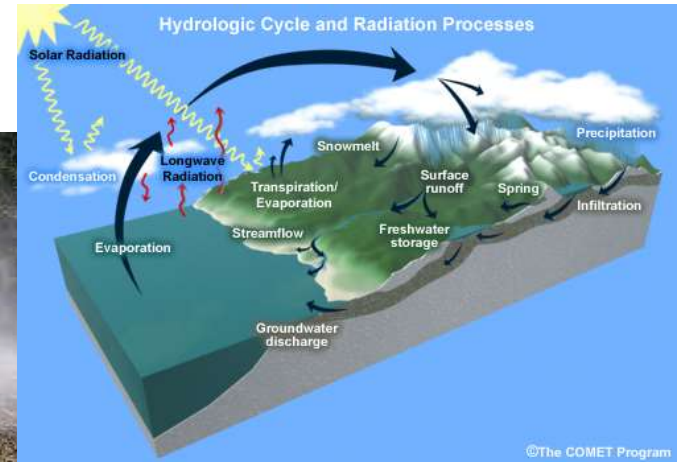
- When refereeing to the amount of moisture in the air, we are actually referring to the ***amount of water vapor***.

- If the air is described as **moist**, that means the air contains a ***large amount of water vapor-gaseous*** state, which occurs at a temp of 100 deg. Celsius.

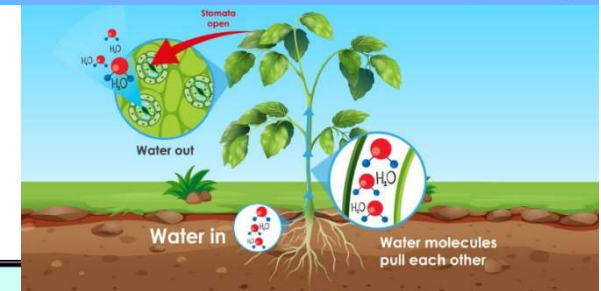


Sources of atmospheric moisture

Evaporation:

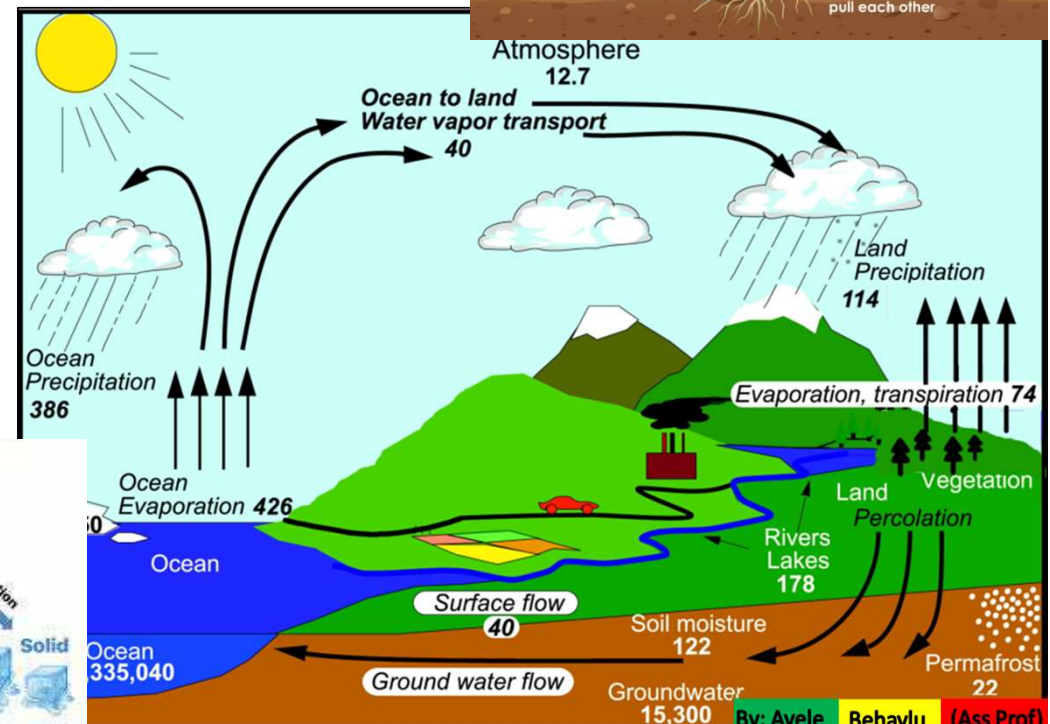
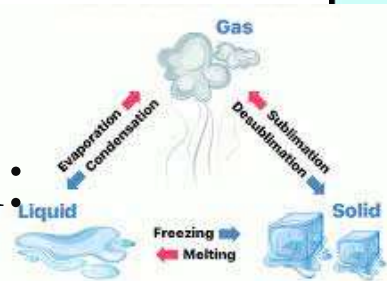


Transpiration:

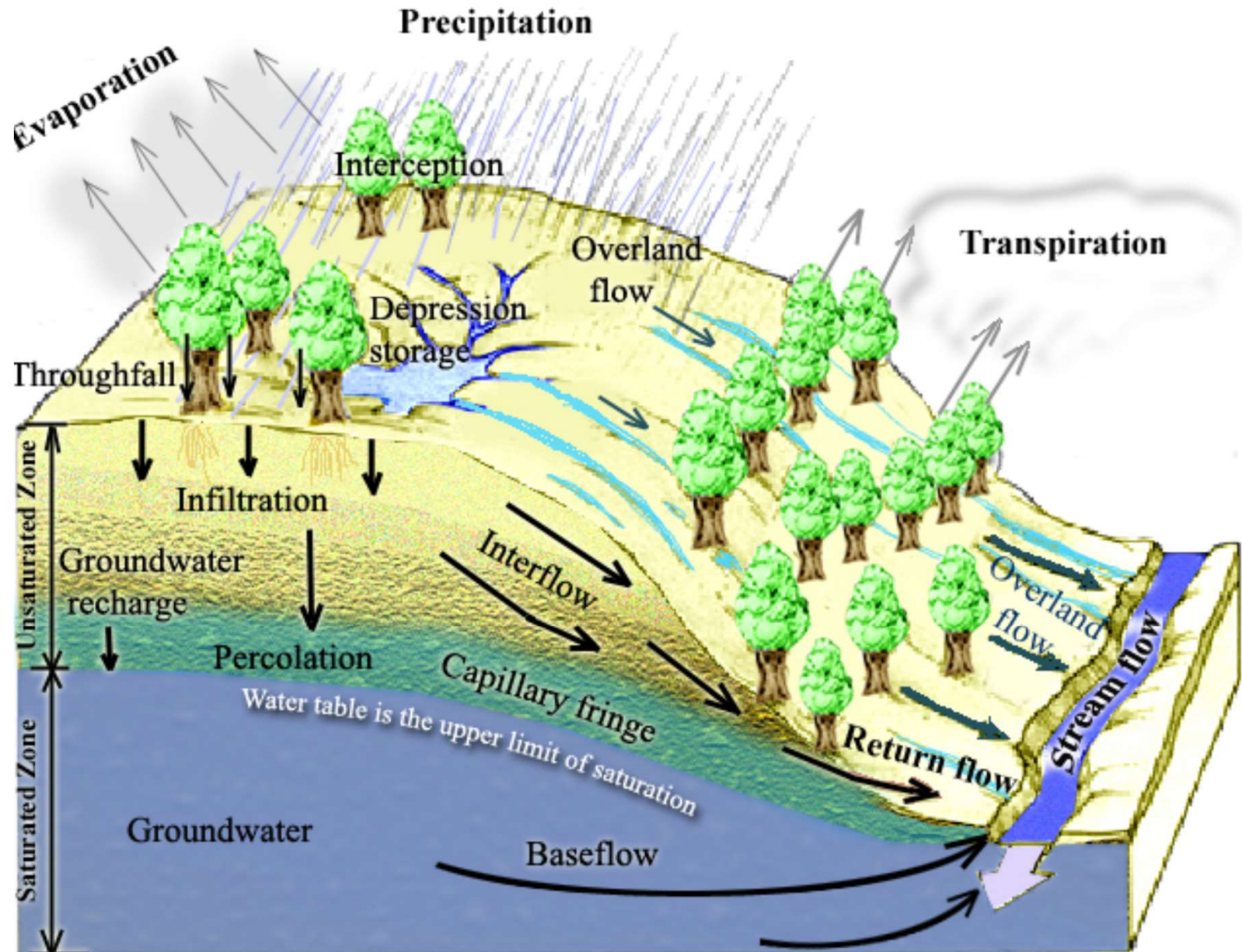


Respiration:

Sublimation:



- Evapotranspiration is one of the physical processes in the hydrological/water cycle.



5.2. Evapotranspiration

<https://youtu.be/5jJLfwTkGe8>

What is Evapotranspiration ?

Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation.

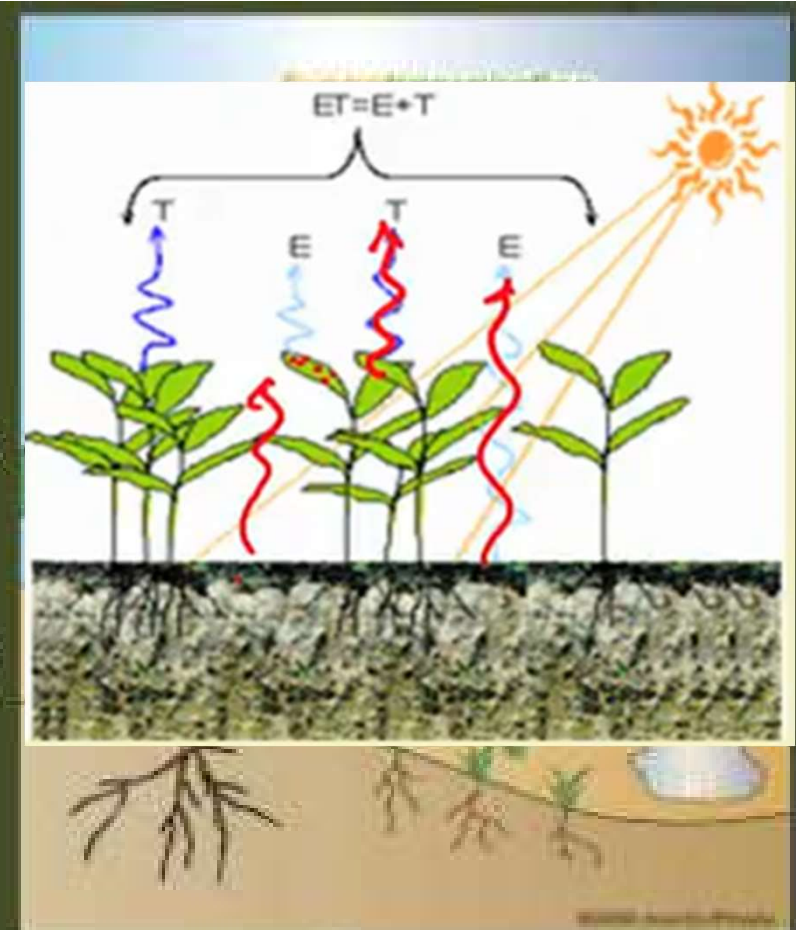
- It is a combination of two separate processes

Evaporation:

Loss of water from the soil surface or any other open water body

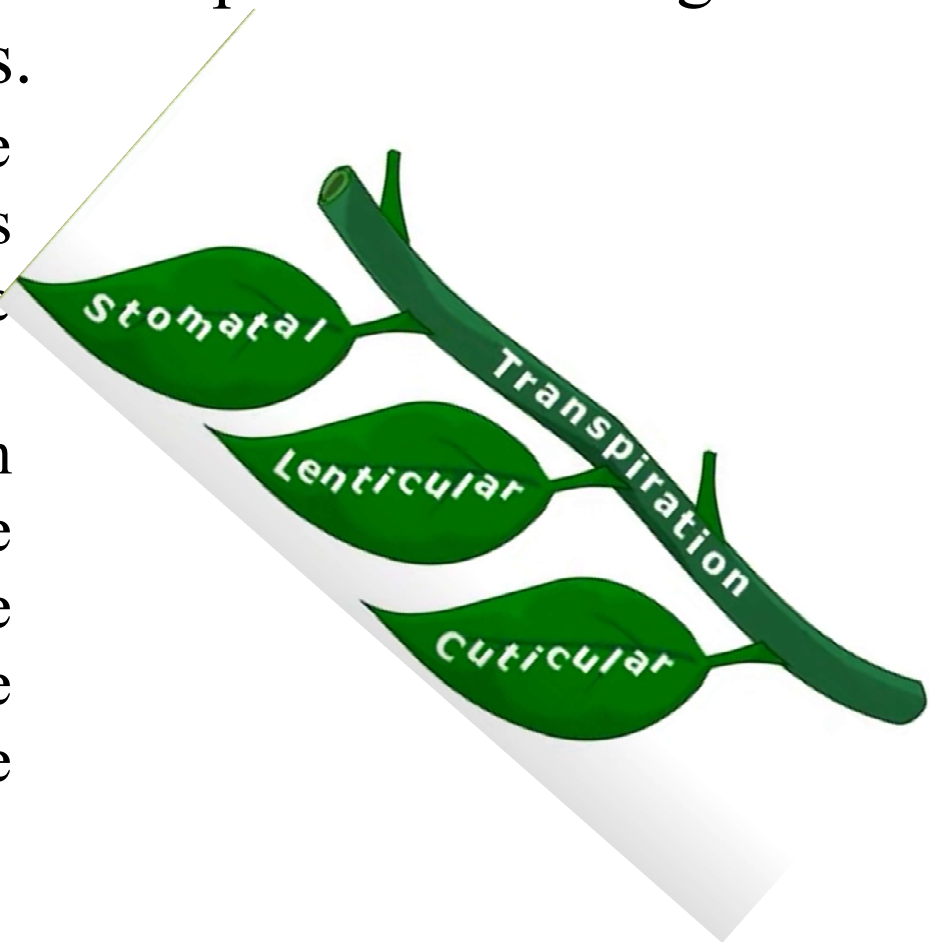
Transpiration:

from plant surface



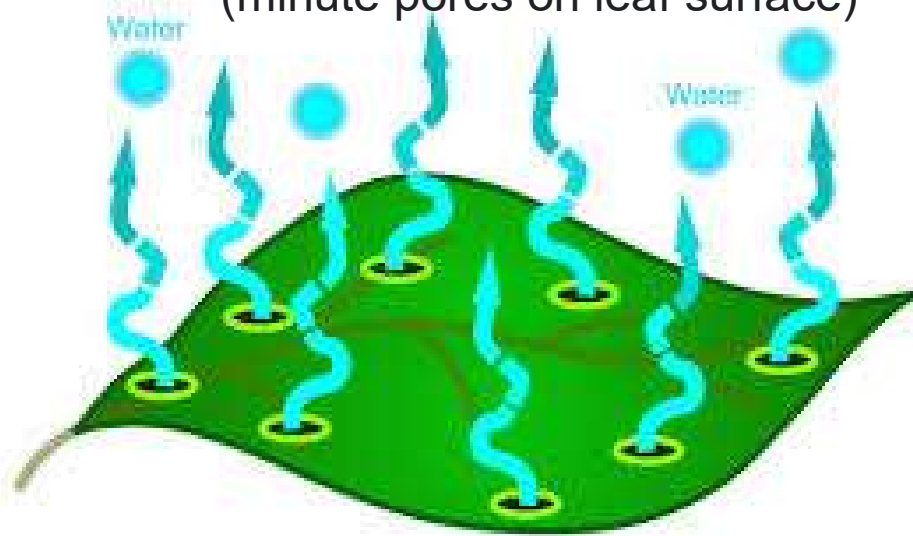
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- Transpiration consists of the vaporization of liquid water contained in *plant tissues* and the *vapor removal to the atmosphere*.
- Crops predominately lose their water through **stomata**. These are **small openings** on the plant leaf through which *gases* and *water vapor* pass.
- The water, together with some nutrients, is taken up by the roots and transported through the plant.
- The vaporization occurs within the leaf, namely in the intercellular spaces, and the vapor exchange with the atmosphere is controlled by the **stomatal aperture/hole**.



Stomatal opening

(minute pores on leaf surface)



Lenticular



→ Lenticels

Lenticular



Minute opening
s on the
stem

→ Lenticels

The cuticles are protective, hydrophobic, waxy coverings produced by the epidermal cells of leaves, young shoots, and all other aerial plant organs. Cuticles minimize water loss and effectively reduce pathogen entry due to their waxy secretion.

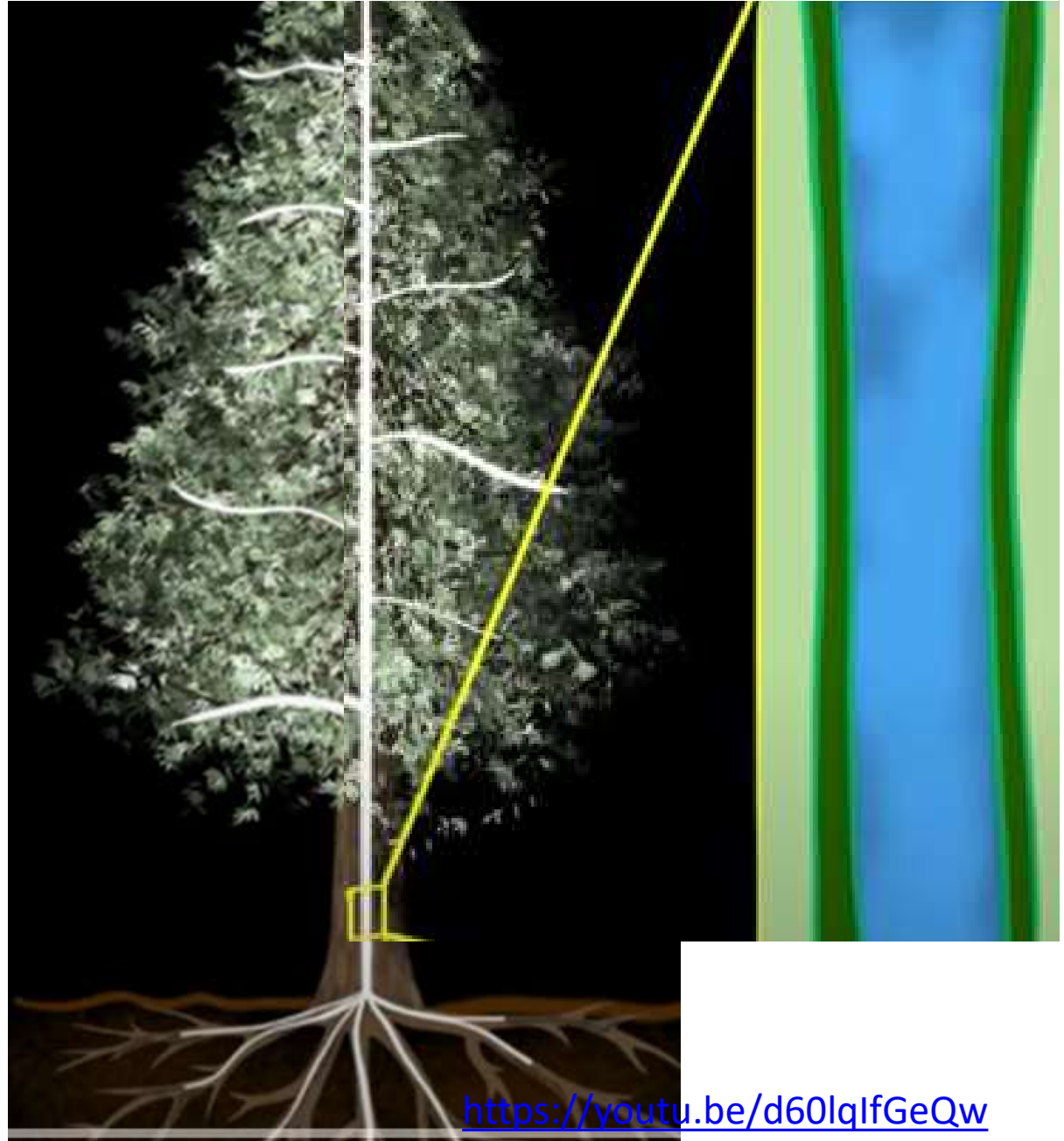


Cuticular

- Nearly all water taken up is lost by **transpiration** and *only a tiny fraction is used within the plant.*

How transpiration works

Xylem- made of dead cells used to transport water sucked from the soil or by root pressure



<https://youtu.be/d60lqlfGeQw>

- **Evaporation** and **transpiration** occur *simultaneously* and there is *no easy way of distinguishing* between the two processes.
- Apart from the water availability in the topsoil, the evaporation from **cropped soil** is mainly determined by the fraction of the solar radiation reaching the soil surface.
- This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area.
- When the **crop is small**, *water is predominately lost by soil evaporation*, but once the crop is well developed and completely covers the soil, **transpiration** becomes the **main process**.

- In the partitioning of *evapotranspiration* into *evaporation* and *transpiration* is plotted in correspondence to the *leaf area per unit surface* of soil below it.
- At *sowing*, nearly *100%* of *ET* comes from *evaporation*, while at *full crop cover*, more than *90%* of *ET* comes from *transpiration*.

5.2.1. Factors that affect the evapotranspiration rate

- Current environmental conditions, plant type, soil conditions (soil chemistry and soil salinity), and geographical location are the primary factors affecting *ET* rates.
 - Environmental factors
 - Plant/crop factor
 - Geographical factor
 - Soil factors

1. Environmental factors

- **Several factors** affect the plants' rate of transpiration and hence evapotranspiration.

Air temperature: as temperature increase, evapotranspiration also goes up.

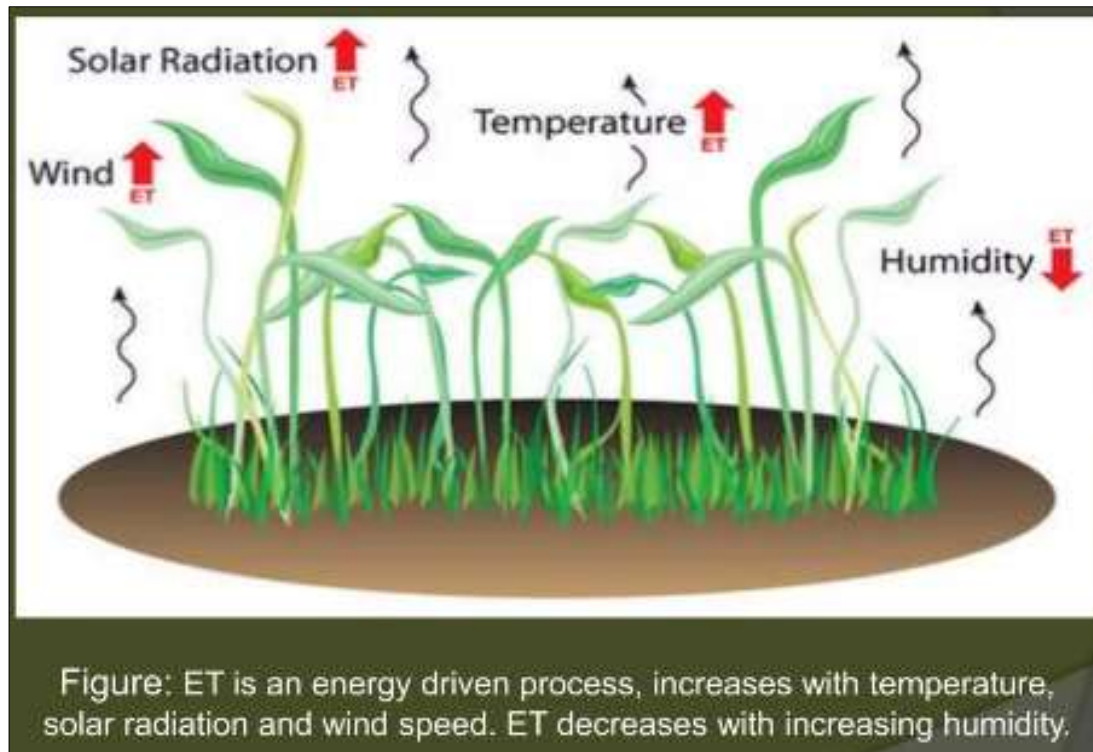
Humidity: as the air becomes more and more saturated, less water is able to evaporate into that air.

Movement of wind and air: it increases evapotranspiration. because moving air is less saturated than stagnant air.

- Air movement such as wind can aid with transpiration. When the air is still or there is no wind, humidity may build up around the plant from transpiration eventually decreasing the amount of water being released. When there is wind present, this causes the air to be replaced constantly allowing the plant to transpire.

Moisture available in the soil: less water available means plants begin to transpire less water in an effort to survive. This in turn decreases evapotranspiration.

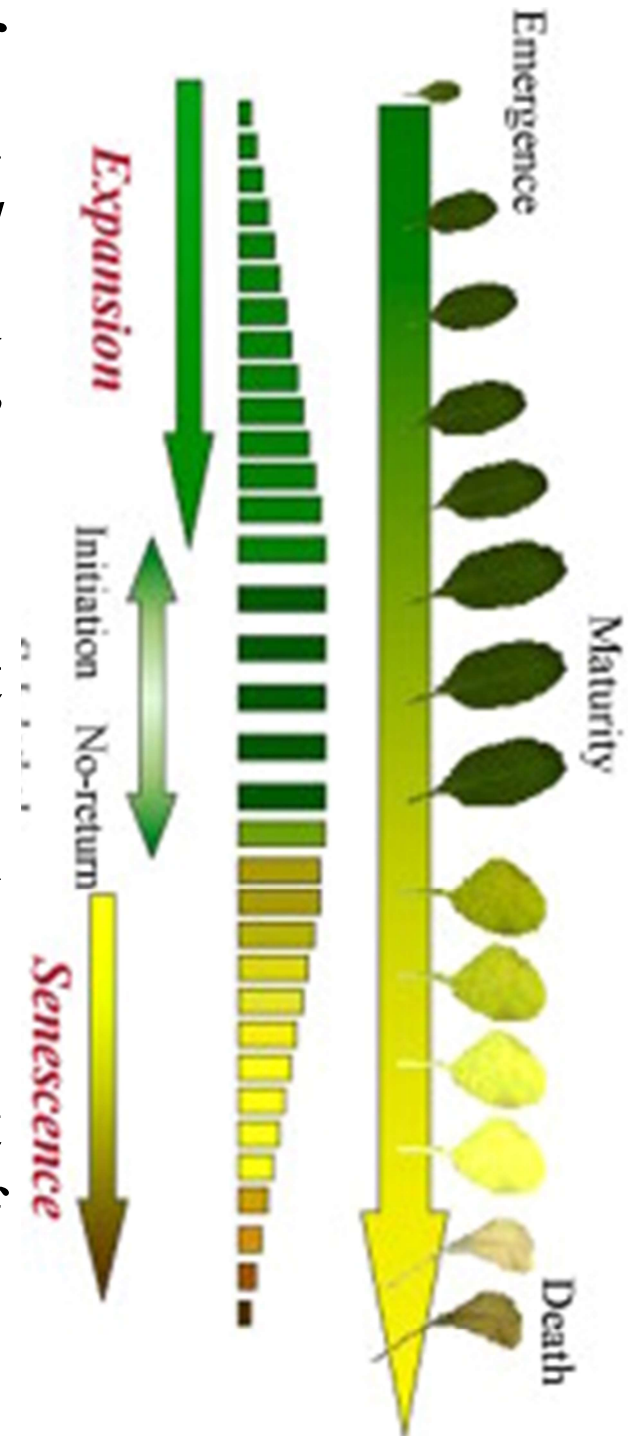
Solar radiation: the more solar radiation the more will be the rate of evapotranspiration.



2. Plant and crop factors:-

- Plants with deep-reaching roots can transpire water more constantly because water transpired through leaves comes from the roots.
 - The ET rates between different plant species can vary greatly.
-
- Most transpiration takes place through the leaf (stomata), therefore actual transpiration depends on the;
 - **Total leaf surface area;**
 - **Plant height, and;**
 - The aerodynamic drag and ‘**roughness**’ of leaves (which influences the turbulence of the air).

- When the plant is at an **early stage of development** it is small and has a small leaf area, therefore the *actual evapotranspiration* is low compared to the *maximum demand of the atmosphere*.
- When the plant is **fully matured** it may be much taller and rougher, so evapotranspiration may be higher even under the same weather conditions.
- During **senescence**, dead leaves don't transpire therefore the rate of evapotranspiration will fall.



- The **wider the leaf area**, the *greater the rate of transpiration* because wide leaves tend to have more stomata.
- **Stomatal transpiration is higher in most plants, even in the early stages of the tall plants.** But in *tall plants* the surface area of woody part is more than the leaf surfaces.

3. Geographical factors

- ET is also dependent upon an area's geography, latitude and climate.
- Regions on the globe with the most solar radiation experience more evapotranspiration.
- ET rates are also highest in areas with a hot and dry climate.
- ET is less in higher latitudes.

4. Soil factors

- ET depend upon the water table depth, soil moisture, and capillary character.
- When the soil is lacking moisture, plants begin to transpire less water in an effort to survive, this in turn decreases ET.



Soil chemistry: The chemical makeup of the soil is also a major factor affecting ET rates.

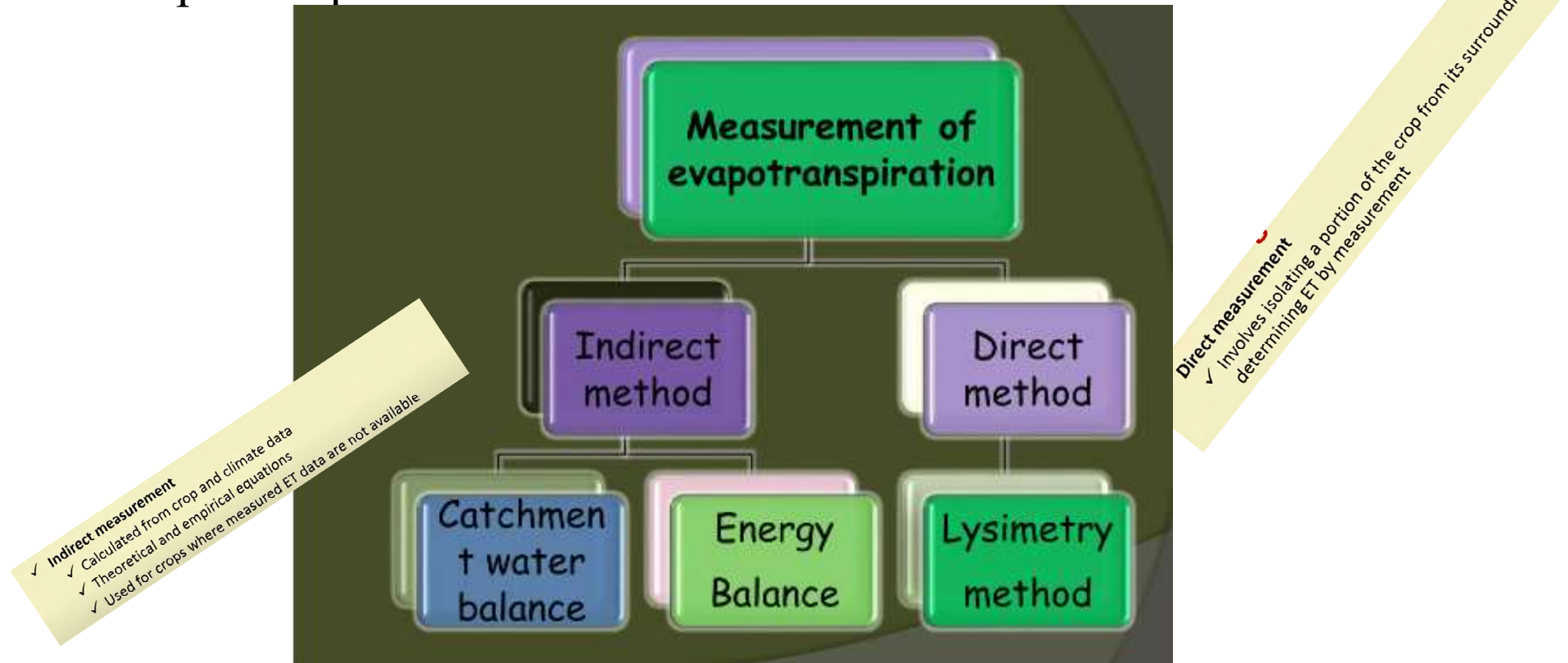
- At the molecular level, most clays will have a chemical affinity (attraction) for water.
- Clay's chemical affinity for water results from a planar geometry and the charge distribution at the molecular level.
- The chemical affinity for water is much less for sands and silts.
- The chemical interaction between the clay and the water impedes both evaporation and plant transpiration.

Soil salinity: Another factor that affects plant transpiration is the *salt content of the soil*.

- The primary driving force of the movement of water from the roots to the leaves is **osmosis**.
- Osmosis **is** the diffusion or movement of water that is driven by a salt concentration gradient.
- *Increasing soil salinity will decrease plant transpiration* because the *salt concentration gradient* will diminish thus affecting the overall ET.

5.2.2. Measures of Evapotranspiration

- Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in *lysimeters* are required to determine evapotranspiration.
- It is the *most commonly used method* of measuring actual evapotranspiration based on *water balance* methods.



Direct methods

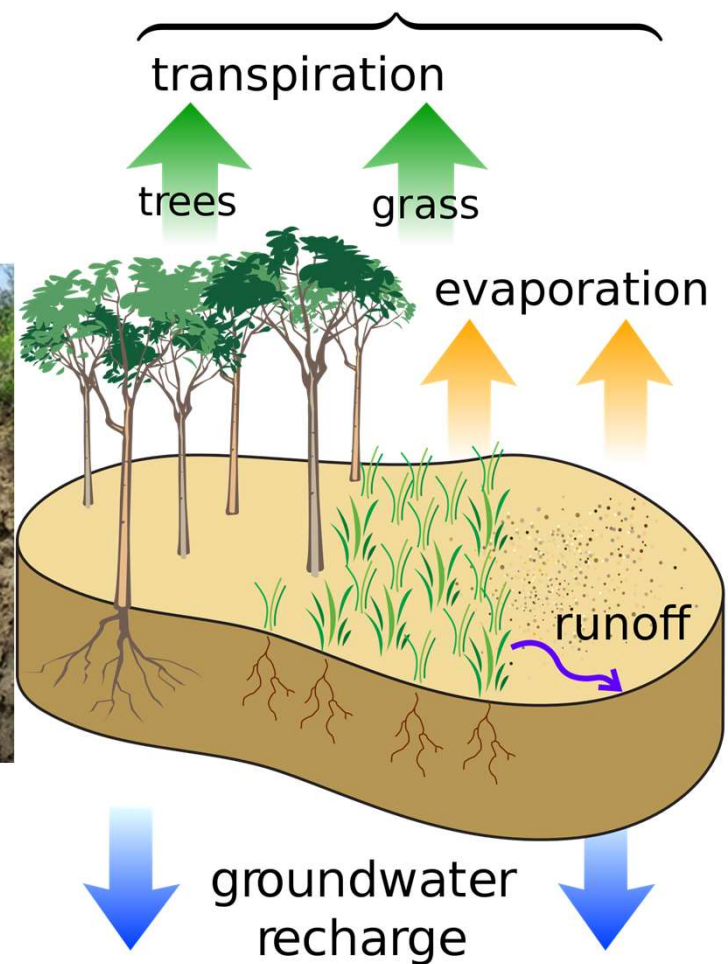
- A **lysimeter** is a measuring device that can be used to measure the actual evapotranspiration which is released by plants, usually crops or trees.

By recording the *amount of precipitation (or manually irrigated) that an area receives* and the *amount lost through the soil*, the amount of water lost to evapotranspiration can be calculated.



Figure 5. A wick lysimeter.

evapotranspiration =
transpiration + evaporation



Field Measurement (Field water balance)

$$ET_{\Delta T} = SM_1 - SM_2 + IR + R_e + U - D - SR,$$

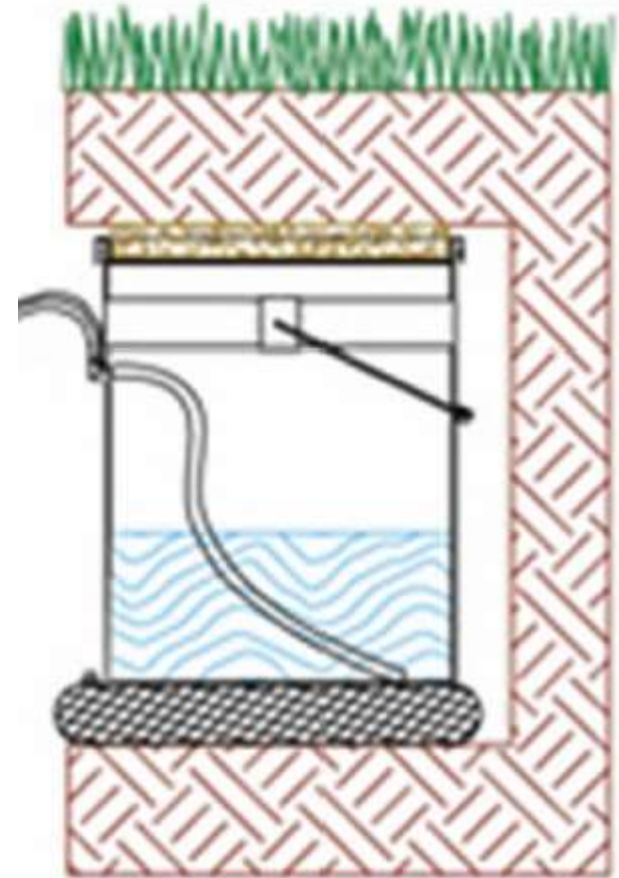
$$SM_t = \sum_{i=1}^n (V_{wi} \times \rho_{si} \times z_i) \times 100,$$

Lysimeter

- It is a device used to measure the amount of actual ET which is released by plants.
- There are two types,
 - Weighing type
 - Non weighing type
- Based on the scale, the amount of water evapotranspired in the system can be determined in terms of change in mass.

A **weighing lysimeter** provides a direct measure of the amount of water used in **evapotranspiration** by isolating and continuously monitoring a vegetated area in a field.

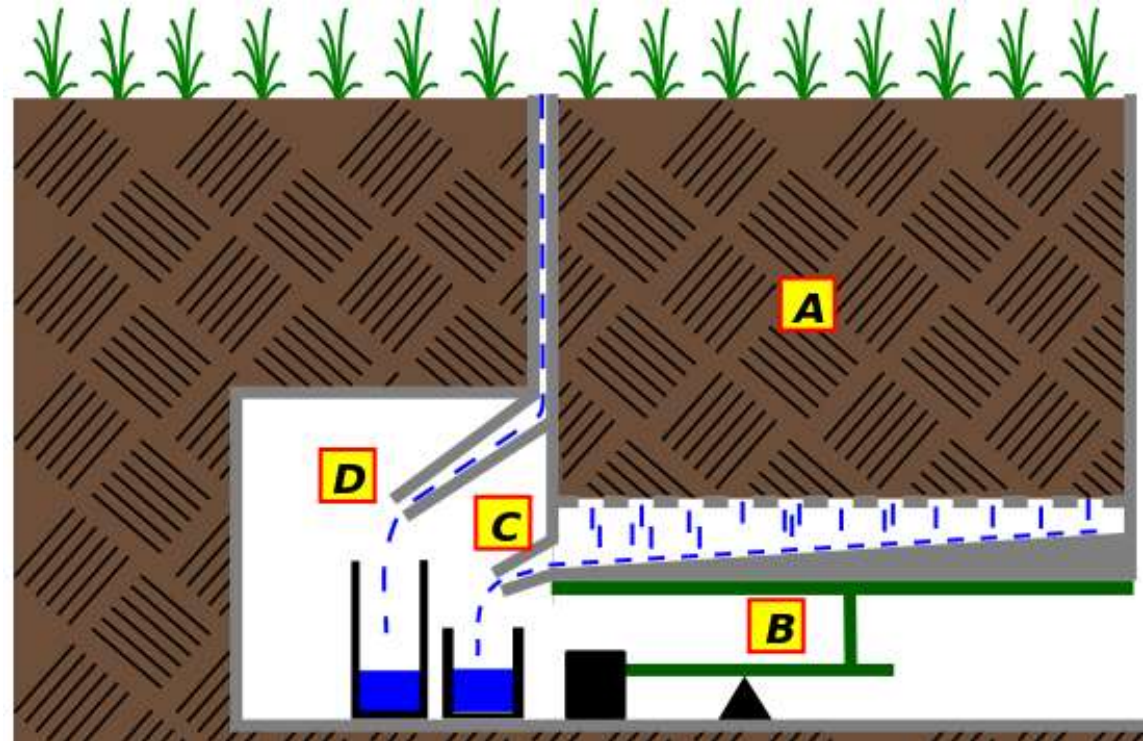
- With the weighing lysimeter, an intact soil column is excavated with a **specialized auger**.
- This column is encased in a concrete enclosure and placed back into the ground.
- **Beneath the column** is a **weighing balance** which, depending on the model, can measure the several-tonne soil column to milligram precision.



How a lysimeter works

- *Weighing lysimeters* are one of the very best ways of measuring the **actual evapotranspiration** from a small area of land because they use **mass balance** (i.e., changing weight) to give us the combined total plant transpiration, soil evaporation, and interception losses over time.

- In non weighing type of lysimeter, a water drain system is used to estimate the drainage water.
- So that ET can be determined by deducting the drainage water from the total water input.



Weighing lysimeter schematic.

- A is the soil monolith,
- B is the load cell (weighing mechanism),
- C is the deep drainage being collected, and
- D is a measurement of surface runoff being collected.

Indirect Method

- Direct and in situ measurement of evapotranspiration (ET), such as the eddy covariance (EC) method, is often expensive and complicated, especially over tall canopies.
- In view of soil water balance, depletion of soil moisture can be attributed to canopy ET when horizontal soil moisture movement is negligible and percolation ceases.
- Evapotranspiration can be estimated by creating an equation of the water balance.

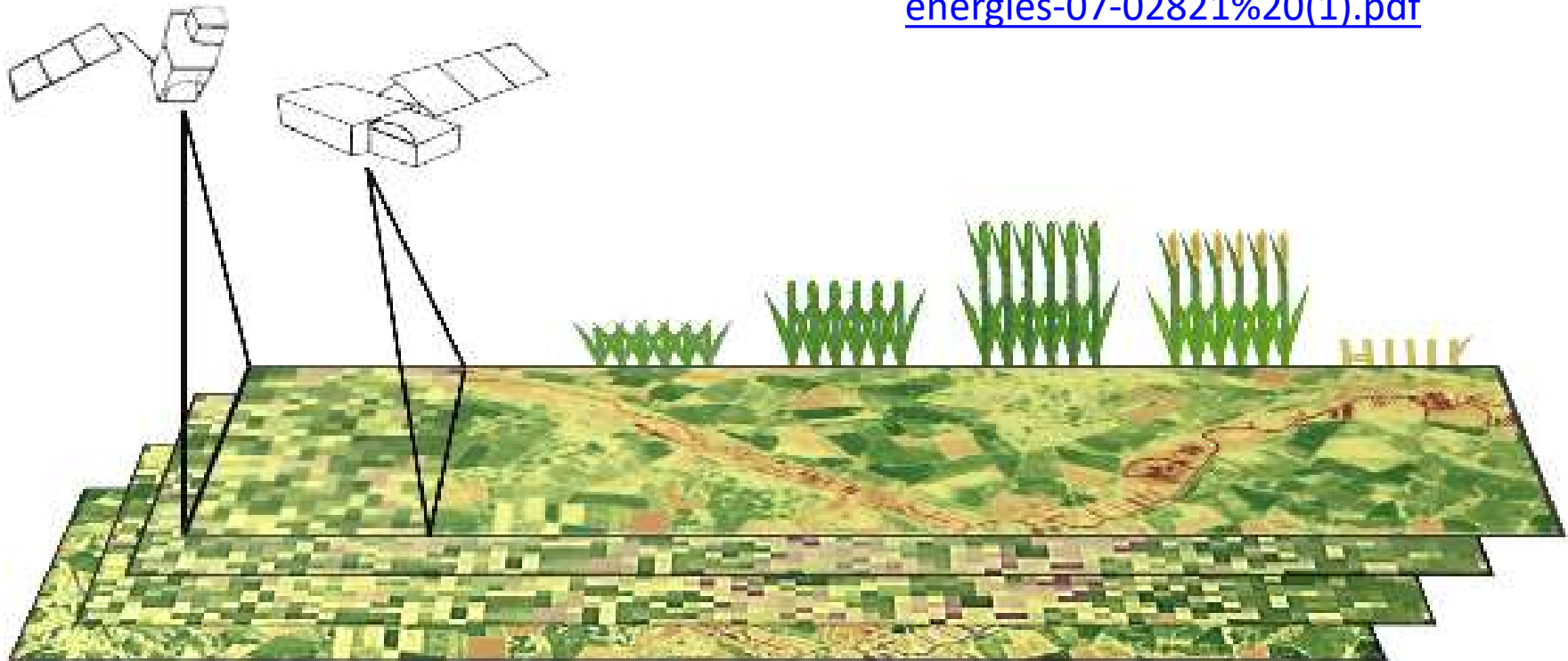
$$ET = P - \Delta S - Q - D,$$

where, ET is evapotranspiration, P is precipitation, ΔS is change in storage, Q is stream flow, and D is groundwater recharge

Evapotranspiration Estimation with Remote Sensing

- With the advent of new satellite technology, the radiative energy exchanges between Sun, Earth, and space may now be quantified accurately.
- Nevertheless, much less is known about the magnitude of the energy flows within the climate system and at the Earth's surface, which cannot be directly measured by satellites.

[energies-07-02821%20\(1\).pdf](#)



5.3. Atmospheric humidity

Humidity is a measure of the *water vapor content of the air*
or *atmospheric moisture*.

- The **amount of water vapor** in the **air depends** on the *controls of evaporation*.

5.3.1. Types of Humidity - absolute, relative and specific

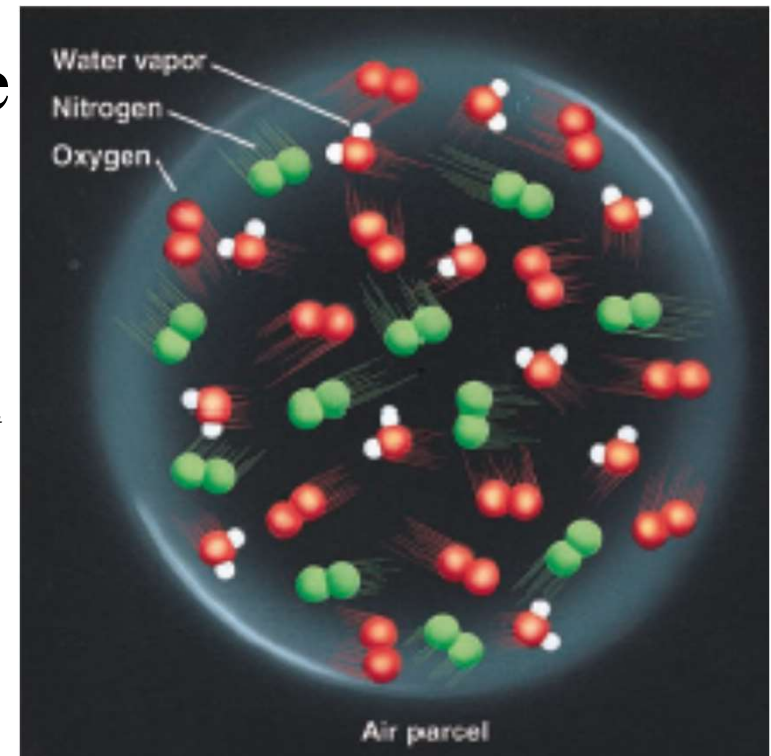
- There are several ways in which a meteorologist can express the humidity of the air.
- Each humidity measure is controlled to some degree by air temperature.

There are three main measurements of humidity: absolute, relative, and specific.

Absolute humidity is the *water content of the air*.

- Suppose we enclose a volume of air in an imaginary thin elastic container—a parcel—*about the size of a large balloon*,
- With a chemical drying agent, we can extract the water vapor from the air, weigh it, and obtain its mass.
- If we then compare the vapor's mass with the volume of air in the parcel, we will have determined the absolute humidity of the air—that is, the mass of water vapor in a given volume of air, which can be expressed as

$$AH = \frac{\text{mass of water vapor}}{\text{volume of air}}$$



The water vapor content (humidity) inside this air parcel can be expressed in a number of ways. (from Metrology Today)

- When a volume of air fluctuates, the absolute humidity changes—even though the *air's vapor content has remained constant*.
- *For this reason, absolute humidity is not commonly used in atmospheric studies.*
- Humidity, however, can be expressed in ways that are *not influenced by changes in air volume*.

Specific humidity is the *ratio* of the *mass* of *water vapor in a parcel* to the *mass of all the air (including water vapour)* in the parcel. Thus,

$$SH = \frac{\text{mass of water vapor}}{\text{total mass of air}}$$

- Given that *weight is not significantly influenced by temperature or atmospheric pressure*, **specific humidity** is much more useful as a measure of humidity.

Mixing Ratio; is another convenient way to express humidity by comparing the *mass of the water vapor* in the parcel to the *mass of the remaining dry air*. Thus,

$$MR = \frac{\text{mass of water vapor}}{\text{mass of dry air}}$$

- Because the atmosphere is made up of so little moisture by volume, the mixing ratio is virtually the same as the *specific humidity*.

Both specific humidity and mixing ratio are expressed as **grams of water vapor** per **kilogram of air** (g/kg).

- The *specific humidity* and *mixing ratio* of an air parcel remain constant as long as *water vapor is not added to or removed from the parcel*.
- This happens because the total number of molecules (and, hence, the mass of the parcel) remains constant, even as the parcel expands or contract.

Relative humidity is the most common way of describing atmospheric moisture, it is also, unfortunately, the most misunderstood.

- The concept of relative humidity may at first seem confusing because it *does not indicate the actual amount of water vapor in the air*.
- Instead, it tells us *how close the air is to being saturated*.
- The **relative humidity** (RH) is the **ratio** of the amount of water vapor actually in the air to the maximum amount of water vapor required for saturation at that particular temperature (and pressure).

- It is the ratio of the air's water vapor content to its capacity; thus,
$$RH = \frac{\text{water vapour content}}{\text{water vapour capacity}}$$

- We can think of the **actual vapor pressure** as a measure of the air's actual water vapor content, and the saturation **vapor pressure*** as a measure of the air's total capacity for water vapor. Hence, the relative humidity can be expressed as

$$RH = \frac{\text{actual vapor pressure}}{\text{saturation vapor pressure}} * 100\%$$

- Relative humidity is given as a **percent**. Air with a **50% relative humidity** actually contains *one-half the amount of water vapor required for saturation*.
- Air with a 100% relative humidity is said to be saturated because it is filled to capacity with water vapor.
- Air with a relative *humidity greater than 100%* is said to be **supersaturated**, a condition that does not tend to occur often or last long.

5.3.2. Factors of atmospheric humidity

■ Humidity depends on water vaporization and condensation, which, in turn, mainly depends on temperature.

Amount of water vapor: if you increase the amount of water in the air (by adding it due to evaporation), Relative humidity will go up.

Temperature: since warm air *can hold more water [i.e. capacity]* than cold air, if you lower the temperature, the relative humidity will go up even if you don't add more water.

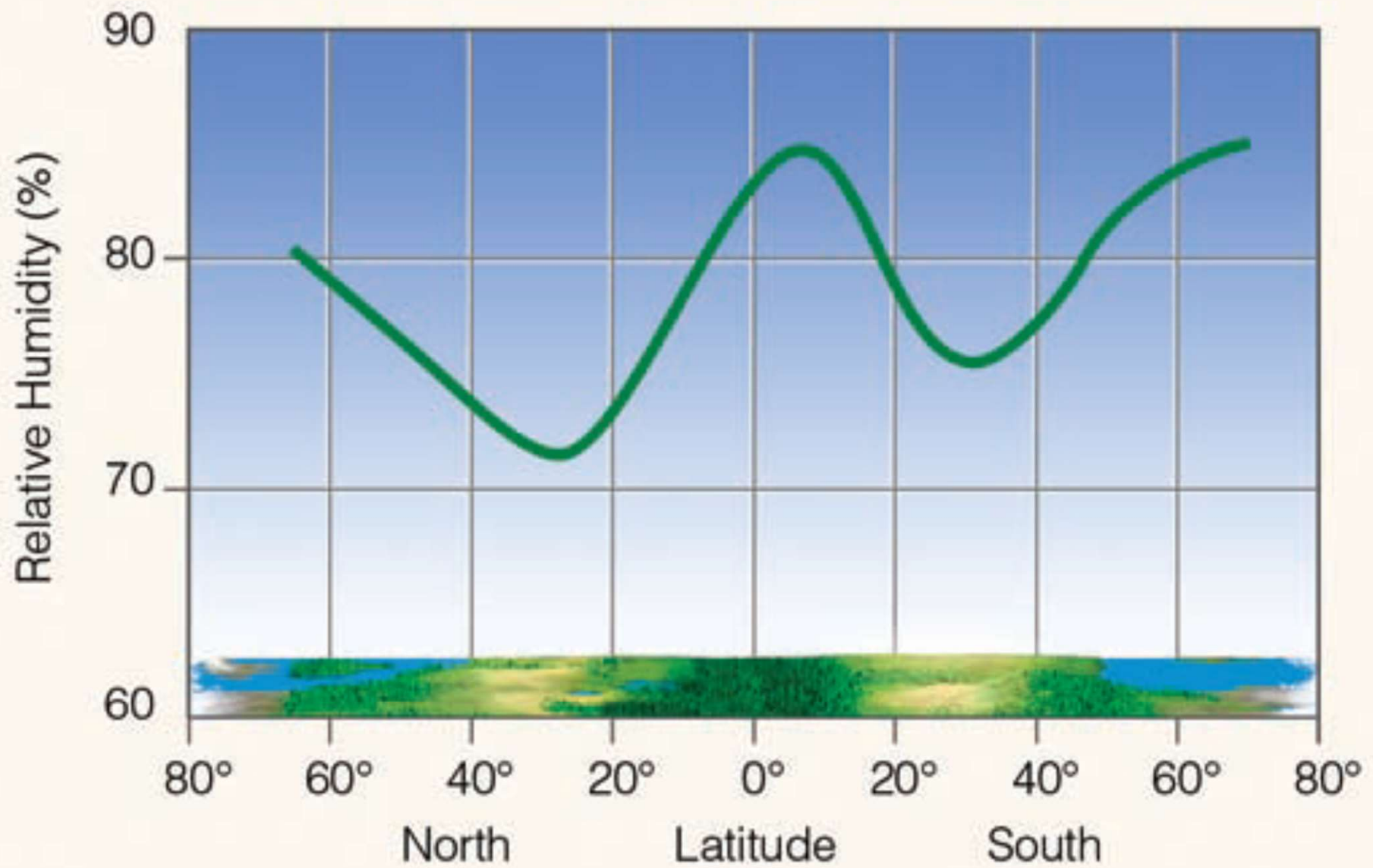
- The same amount of water vapor results in higher relative humidity in cool air than in warm air.

5.3.3. Temporal and spatial variation of humidity

- Seasonal humidity variations depend on *two factors: seasonal changes in **temperature**, and seasonal changes in **atmospheric circulation**.*
- In **temperate climates**, the warmer air in summer has a higher **saturation vapor pressure** than the **cooler winter air**.
- Average **summer** and **winter** relative humidity values tend not to differ much, but the specific humidity tends to be much larger in summer. In monsoon climates, relative and specific humidity tend to increase dramatically during the monsoon season, when onshore winds carry moisture-laden air from the ocean to land areas.

➤ The average relative humidity varies from the equator to the poles.

- High relative humidities are normally found in the tropics and near the poles, where there is little separation between air temperature and dew point.
- The average relative humidity is **low** near latitude 30° —a latitude where we find the deserts of the world-girdling the globe.
- Of course, not all locations near 30°N are deserts. Take, for example, humid New Orleans, Louisiana. During July, the air in New Orleans with an average dew-point temperature of 22°C contains a great deal of water vapor—nearly 50 percent more than does the air along the southern California coast.



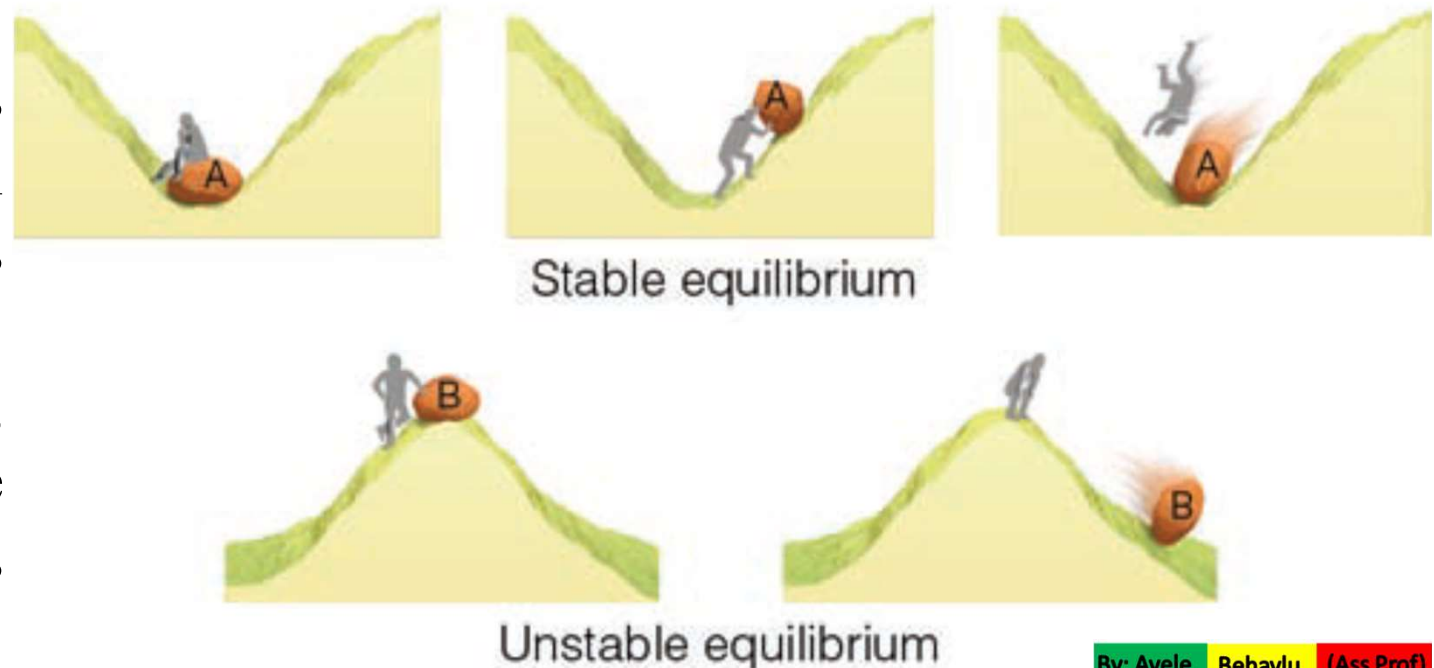
5.3.4. Atmospheric Equilibrium: Stability and instability

Atmospheric stability

- Most clouds form as air rises and cools. Why does air rise on some occasions and not on others? And why do the size and shape of clouds vary so much when the air does rise? Let's see how knowing about the air's stability will help us to answer these questions.
- When we speak of **atmospheric stability**, we are referring to a **condition of equilibrium**.

- For example, **rock A** resting in the depression in *stable* equilibrium. If the rock is pushed up along either side of the hill and then let go of, it will quickly return to its original position.
- On the other hand, **rock B**, resting on the top of the hill, is in a state of *unstable* equilibrium, as a slight push will set it moving away from its original position.

When rock A is disturbed, it will return to its original position; rock B, however, will accelerate away from its original position.



- Applying these concepts to the atmosphere, we can see that air is in **stable equilibrium** when, after being lifted or lowered, it tends to return to its original position—it **resists upward and downward** air motions.
- Air that is in **unstable equilibrium** will when given a little push, **move farther away from its original position**—it **favours upward and downward** motion.

- To explore the behaviour of rising and sinking air, we must first *put some air in an imaginary thin elastic wrap*. This small volume of air is referred to as a **parcel of air**.*
- Although the air parcel can expand and contract freely, it does not break apart, but remains as a single unit. At the same time, neither external air nor heat can mix with the air inside the parcel. The space occupied by the air molecules within the parcel defines the air density. The average speed of the molecules is directly related to the air temperature, and the molecules colliding against the parcel walls determine the air pressure inside.

- At Earth's surface, the parcel has the same temperature and pressure as the air surrounding it. Suppose we lift the air parcel up into the atmosphere.
- We know that air pressure decreases with height. Consequently, the air pressure **surrounding the parcel lowers**. The lower pressure outside allows the air molecules inside to push the parcel walls outward, expanding the parcel. Because there is no other energy source, the air molecules inside must use some of their own energy to expand the parcel. This shows up as slower average molecular speeds, which result in a lower parcel temperature. If the parcel is lowered to the surface, it returns to a region where the surrounding air pressure is higher.
- The higher pressure squeezes (compresses) the parcel back into its original (smaller) volume.
- This squeezing increases the average speed of the air molecules and the parcel temperature rises.
- Hence, *a rising parcel of air expands and cools, while a sinking parcel is compressed and warms.*

- If a parcel of air expands and cools, or compresses and warms, and there is no interchange of heat with its surroundings, this situation is called an **adiabatic process**.
- As long as the air in the parcel is **unsaturated** (*the relative humidity is less than 100 percent*), the rate of adiabatic cooling or warming remains constant.
- This rate of heating or cooling is about 10°C for every 1000 m of change in elevation. Because this rate applies only to unsaturated air, it is called the **dry adiabatic rate**.

- As the **rising air cools**, its **relative humidity increases** as the **air temperature** approaches the **dew-point temperature**.
- If the rising air cools to its **dew-point temperature**, the relative humidity becomes 100 percent.
- Further lifting results in **condensation**; a cloud forms, and latent heat is released inside the rising air parcel.
- 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 called the **moist adiabatic rate**.

- If a saturated parcel containing water droplets were to sink, it would compress and warm at the moist adiabatic rate because evaporation of the liquid droplets would offset the rate of compressional warming.
- Hence, the rate at which rising or sinking saturated air changes temperature—the moist adiabatic rate—is less than the dry adiabatic rate.

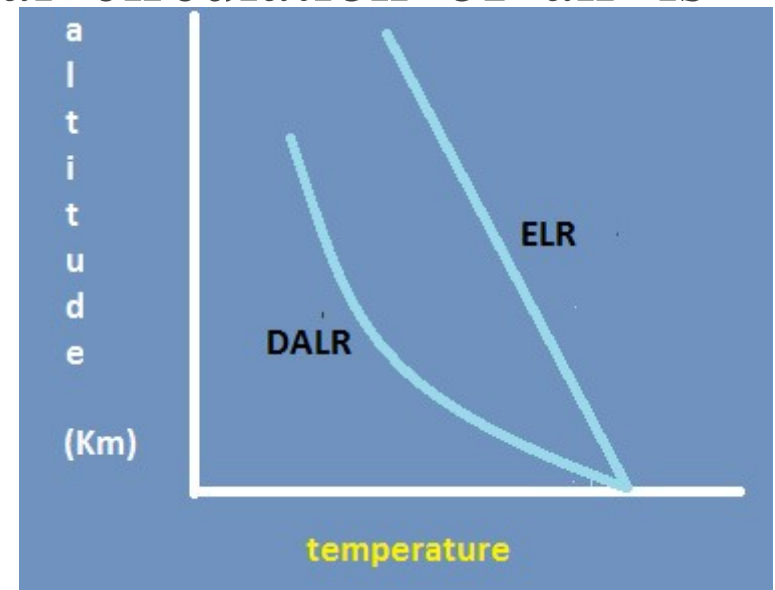
Determining Stability

- We determine the stability of the air by comparing the temperature of a rising parcel to that of its surroundings.
- If the rising air is colder than its environment, it will be denser (heavier) and tend to sink back to its original level. In this case, the air is *stable* because it *resists upward movement*.
- If the rising air is warmer and, therefore, less dense (lighter) than the surrounding air, it will continue to rise until it reaches the same temperature as its environment. This is an example of *unstable* air.
- To figure out the air's stability, we need to measure the temperature both of the rising air and of its environment at various levels above Earth.

Stable equilibrium: after a small displacement the body returns to its original equilibrium position.

A Stable Atmosphere

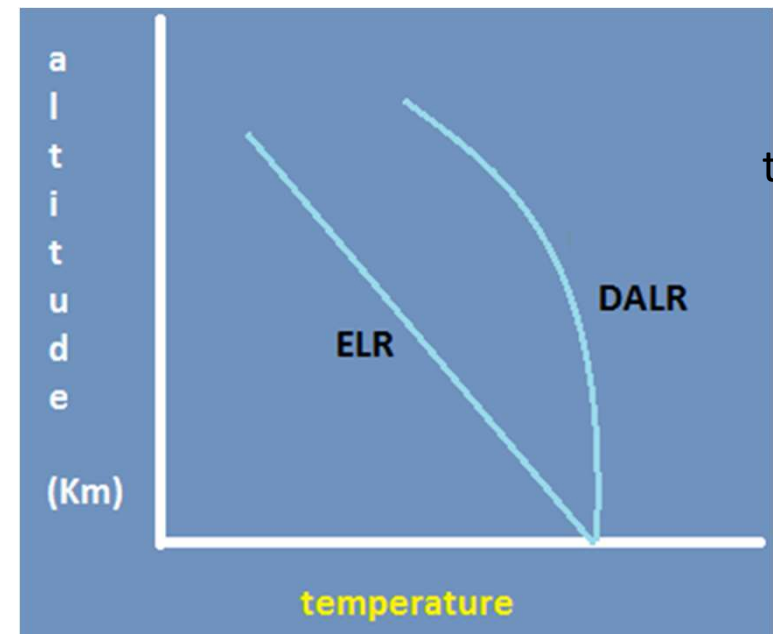
- When the *dry adiabatic lapse rate* of an ascending dry air is higher than the *normal lapse rate* and if it is not saturated and *does not attain dew point* it becomes *colder than surrounding air* at a certain height with the result it becomes *heavier* and *descends*.
- This process causes the **stability of atmospheric circulation** due to which vertical circulation of air is *resisted*.



Unstable equilibrium: after a small displacement the body does not return to the original equilibrium position and moves to a new equilibrium position.

Unstable Atmosphere

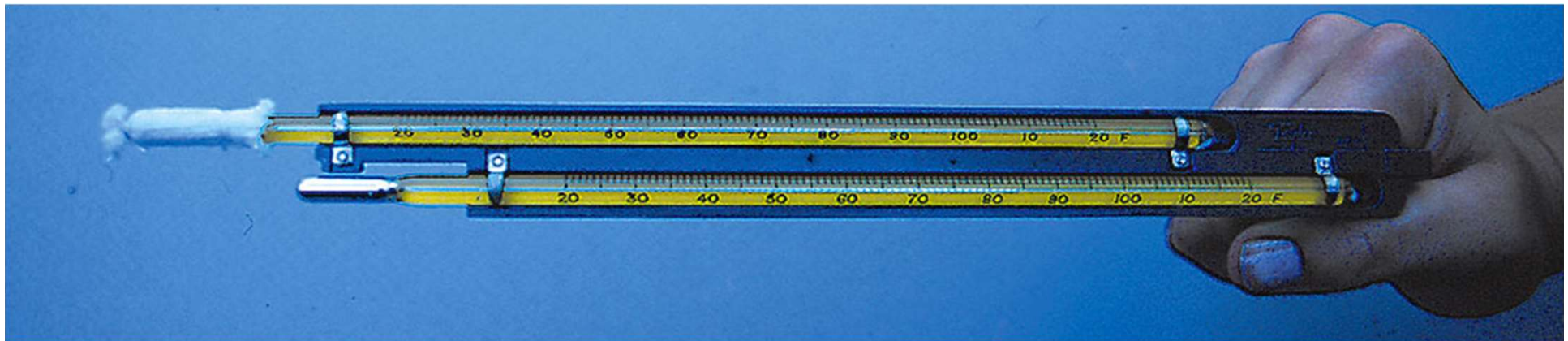
- When the *normal lapse rate* is greater than the *dry adiabatic lapse rate* of ascending parcel of air the rising air continues to rise upward and expand and thus becomes **unstable** and is in *unstable equilibrium*.
- In other words, *atmospheric instability* is caused when the *rate of cooling of rising air* (*dry adiabatic lapse rate*) is *lower* than the *normal lapse rate*.



5.3.5. Measures of humidity

A. *Sling psychrometer*

- The sling psychrometer consists of a dry and wet-bulb thermometer. The term bulb refers to that portion of the glass tube where the mercury is stored. The dry and wet bulbs are exactly alike in construction.
- The only difference is that the wet bulb has a piece of muslin cloth or wick wrapped around its bulb and which is dipped in the water shortly before the psychrometer is read.



- This is how it is done. The weather observer first wets the cloth cladding the wet-bulb, whirls the psychrometer a few times, then reads the wet-bulb. He reads the dry-bulb last. Normally, the wet-bulb's reading will be lower than the dry-bulb's.
- The dry-bulb reading is the air temperature.
- The difference between the dry and the wet-bulb readings will give, with the aid of a psychrometric table, the dew point temperature and the relative humidity.

*(Dew point is the temperature at which the water vapor will condense
Relative humidity is the ratio of the amount of water vapor actually
present in the air to the maximum amount of water vapor the air can
hold at a given temperature).*

B. Hygrometer

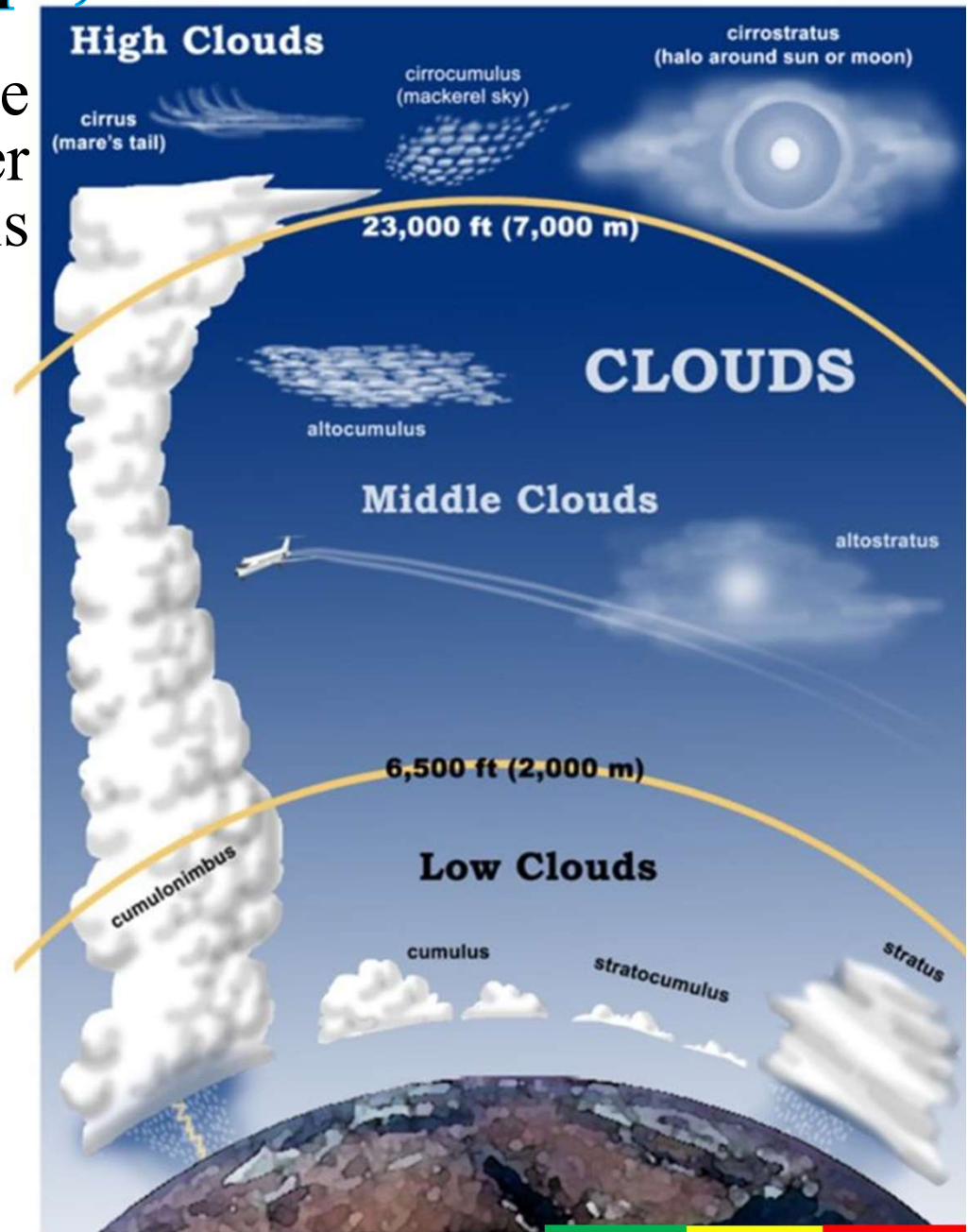
- The other instrument used to measure humidity is the Hygrometer. The hygrometer is *less accurate than the psychrometer*. It uses human hair from which the oil has been removed by using ether.
- The hair becomes longer as the relative humidity of the air increases. This change can be made to move an indicator needle which moves over a scale, the graduations of which reads from 0% to 100%.

C. Hygrothermograph

- The hygrothermograph records both relative humidity and temperature on graph paper in the same manner as the thermograph and barograph do.

5.4. Cloud formation, type, and characteristics

- A cloud is a visible aggregate of tiny water droplets or ice crystals suspended in the air.
- Clouds are *aesthetically appealing* and *add excitement to the atmosphere*.
- Without them, there would be **no** rain or snow, thunder or lightning, rainbows or halos.
- How monotonous it would be if there were only a clear blue sky to look at.



- Some are found only at **high elevations**, whereas others *nearly touch the ground* (or are classified as fog if they do touch the ground).
- Clouds can be *thick* or *thin*, *big* or *little*—they exist in a seemingly *endless variety* of *forms*.
- To impose order on this variety, we divide clouds into *10 basic types*.
- With a careful and practiced eye, you can become reasonably proficient in correctly identifying them.

Classification of Clouds

- Although ancient astronomers named the major stellar constellations about 2000 years ago, clouds were *not formally identified* and classified *until the early 19th c.*
- The French naturalist Jean-Baptiste Lamarck (1744–1829) proposed the first system for classifying clouds in **1802**; however, his work *did not receive wide acclaim.*
- One year later, Luke Howard, an English naturalist, developed a cloud classification system that *found general acceptance.*

- In essence, Howard's innovative system employed Latin words to describe clouds as they appear to a ground observer.
- He named a sheetlike cloud *stratus* (Latin for “*layer*”); a puffy cloud *cumulus* (“*heap*”); a wispy cloud *cirrus* (“*curl* of *hair*”); and a rain cloud *nimbus* (“*violent rain*”).
- In Howard's system, these were the four *basic cloud forms*.
- Other clouds could be described by combining the basic types.
- For example, *nimbostratus* is a *rain cloud* that shows layering, whereas *cumulonimbus* is a *rain cloud* having pronounced vertical development.

- In 1887, Ralph Abercromby and Hugo Hildebrands son expanded Howard's original system and published a classification system that, with *only slight modification*, is *still in use today*.
- *Ten* principal cloud forms are divided into *four primary cloud groups*.
- Each group is identified by the *height of the cloud's base above the surface*: *high clouds*, *middle clouds*, and *low clouds*.
- The *fourth group* contains *clouds showing more vertical* than *horizontal development*.
- Within each group, cloud types are identified by their appearance.

HIGH CLOUDS	LOW CLOUDS
Cirrus (Ci)	Stratus (St)
Cirrostratus (Cs)	Stratocumulus (Sc)
Cirrocumulus (Cc)	Nimbostratus (Ns)
MIDDLE CLOUDS	CLOUDS WITH VERTICAL DEVELOPMENT
Altostratus (As)	Cumulus (Cu)
Alto cumulus (Ac)	Cumulonimbus (Cb)

- The approximate base height of each cloud group is given in Table below.
- Note that the altitude separating the high and middle cloud groups overlaps and varies with latitude.
- Large temperature changes cause most of this latitudinal variation.

Approximate Height of Cloud Bases Above the Surface for Various Locations			
CLOUD GROUP	TROPICAL REGION	MID-LATITUDE REGION	POLAR REGION
High (Ci, Cs, Cc)	20,000 to 60,000 ft <u>(6000 to 18,000 m)</u>	16,000 to 43,000 ft <u>(5000 to 13,000 m)</u>	10,000 to 26,000 ft <u>(3000 to 8000 m)</u>
Middle (As, Ac)	6500 to 26,000 ft <u>(2000 to 8000 m)</u>	6500 to 23,000 ft <u>(2000 to 7000 m)</u>	6500 to 13,000 ft <u>(2000 to 4000 m)</u>
Low (St, Sc, Ns)	surface to 6500 ft <u>(0 to 2000 m)</u>	surface to 6500 ft <u>(0 to 2000 m)</u>	surface to 6500 ft <u>(0 to 2000 m)</u>

1. High Clouds

- High clouds are **cirro-form clouds** composed mostly of ice.
- These clouds include
 - **cirrus,**
 - **cirrostratus** and
 - **cirrocumulus.**

Cirrus clouds appear as wispy thin veils or detached filaments composed mostly of ice.

- Strong winds aloft often create fibrous ice trails which tend to curl at their ends.
- Cirrus clouds with *hooked filaments* are sometimes called "*mare's tails*".
- Cirrus clouds are associated with an approaching *warm front*.

Cirrostratus is a transparent, whitish veil of cloud that usually covers much of the sky.

- Sometimes cirrostratus clouds are so transparent that you can barely see them.
- They often create a halo around the sun or moon.
- Cirrostratus clouds thicken and grade into altostratus clouds with the approach of a warm front.

Cirrocumulus are clouds that appear as white patches made up of *very small cells or ripples*.

The globules of clouds are arranged in a regular pattern and are commonly called "*mackerel sky*" for their similarity to the scales of a fish.



2. Middle Clouds

- Clouds found in the middle levels of the troposphere have the prefix *ALTO* attached to their name.
- Two clouds are described here:
altocumulus and **altostratus**.

Alto cumulus (Ac) clouds are middle clouds that are composed mostly of droplets and are rarely more than 1 km thick.

- They appear as gray, puffy masses, sometimes rolled out in parallel waves or bands.
- Usually, one part of each cloud element is darker than another, which helps to distinguish it from the higher cirrocumulus.
- Also, the individual puffs of the alto cumulus appear larger than those of the cirrocumulus.
- A layer of alto cumulus can sometimes be confused with altostratus; in case of doubt, clouds are called alto cumulus if there are rounded masses or rolls present.
- Alto cumulus clouds that look like “little castles” (castellanus) in the sky indicate the presence of rising air at cloud level. The appearance of these clouds on a warm, humid summer morning often portends thunderstorms by late afternoon.



Altostratus (As) are gray or blue-gray clouds composed of ice crystals and water droplets. Altostratus clouds often cover the entire sky across an area that extends over many hundreds of square kilometers. In the thinner section of the cloud, the sun (or the moon) may be *dimly visible* as a round disk, as if the sun were shining through ground glass. This appearance is sometimes referred to as a “watery sun”. Thick cirrostratus clouds are occasionally confused with thin altostratus clouds. The gray color, height, and dimness of the sun are good clues to identifying an altostratus.



The fact that halos occur only with cirriform clouds also helps one to distinguish them. Another way to separate the two is to look at the ground for shadows.

- If there are none, it is a good bet that the cloud is altostratus because cirrostratus are usually transparent enough to produce them. Alto-stratus clouds often form ahead of mid-latitude cyclonic storms having widespread and relatively continuous precipitation. If precipitation falls from altostratus, the cloud base usually lowers, and the precipitation is steady and not showery as found with cumuliform clouds. If the precipitation reaches the ground, the cloud is then classified as *nimbostratus*.

3. Low Clouds

➤ **Low Clouds** are almost always composed of water droplets, although in cold weather they may contain ice particles.

Nimbostratus (Ns) are *dark-gray*, “wet”-looking *cloud layers* associated with more or less *continuously falling rain or snow*.

- The intensity of this precipitation is usually light or moderate—it is never of the heavy, showery variety unless well-developed cumulus clouds are embedded within the **nimbostratus cloud**.



- Precipitation often makes the base of the nimbostratus cloud impossible to identify clearly. The distance from the cloud's base to its top can be over 3 km.
- Nimbostratus is easily confused with altostratus.
- Thin nimbostratus is a usually darker gray than thick altostratus, and you normally cannot see the sun or the moon through a layer of nimbostratus.
- *Visibility below a nimbostratus* cloud deck is usually *quite poor* because *rain will evaporate* and *mix with the air in this region*.
- If this air becomes saturated, a lower layer of clouds or fog can form beneath the original cloud base.
- Because these lower clouds drift rapidly with the wind, they form irregular shreds with a ragged appearance that are called *stratus fractus*, or *scud*.

Stratocumulus (Sc) are low, lumpy clouds that appear in rows, in patches, or as rounded masses with blue sky visible between individual cloud elements



WU1

- Often they appear near sunset as the spreading remains of a much larger cumulus cloud.
- Occasionally, the sun will shine through the cloud breaks, producing bands of light (called *crepuscular rays*) that appear to reach down to the ground.
- The colour of **stratocumulus** ranges from *light to dark gray*.
- It differs from the altocumulus in that it has a **lower base** and *larger individual cloud elements*.

Stratus (St) is a *uniform grayish cloud* that often covers the entire sky.

➤ It resembles a fog that does not reach the ground.

➤ Actually, when a thick fog “lifts,” the resulting cloud is a deck of low stratus.

➤ Normally, no precipitation falls from stratus, but sometimes it is accompanied by a light mist or drizzle.

➤ This cloud commonly occurs over Pacific and Atlantic coal waters in summer.



- A thick layer of stratus might be confused with nimbostratus, but the distinction between them can be made by observing the low base of the stratus cloud and remembering that light-to-moderate precipitation occurs with nimbostratus.
- Moreover, the stratus often has a more uniform base than does nimbostratus.
- Also, a deck of stratus may be confused with a layer of altostratus.
- However, if you remember that stratus are lower and darker gray and that the sun normally appears “watery” through altostratus, the distinction can be made.

4. Clouds with Vertical Development

- Familiar to almost everyone, the *puffy* **cumulus** (Cu) cloud takes on a variety of shapes, but most often it looks like a *piece of floating cotton* with sharp outlines and a flat base.



- The base appears white to light gray, and, on a humid day, may be only 1000 m above the ground and a kilometer or so wide.

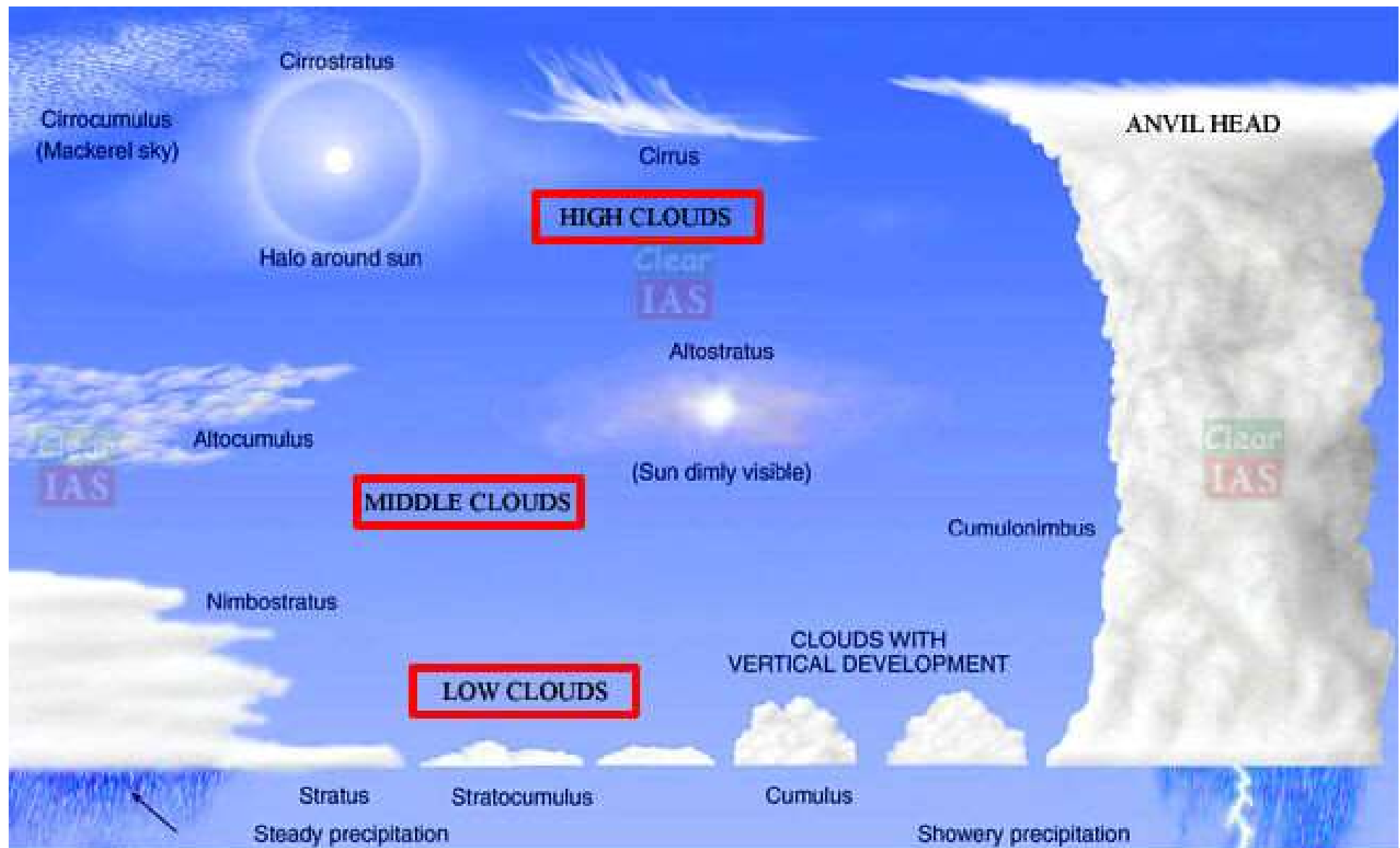
- The top of the cloud—often in the form of rounded towers—denotes the limit of rising air and is usually not very high. These clouds can be distinguished from stratocumulus by the fact that cumulus clouds are detached (usually with a great deal of blue sky between each cloud), while stratocumulus usually occur in groups or patches.
- Also, the cumulus has a *dome- or tower-shaped top* as opposed to the generally flat tops of the stratocumulus.
- Cumulus clouds that show only *slight vertical growth* are called *cumulus humilis* and are associated with *fair weather*; therefore, we call these clouds “*fair-weather cumulus*.”
- Ragged-edge cumulus clouds that are smaller than cumulus humilis and scattered across the sky are called *cumulus fractus*.

- If a *cumulus congestus continues to grow vertically*, it develops into a giant **cumulonimbus** (Cb)—a *thunderstorm cloud*.
- While its *dark base* may be *no more than 600 m* above Earth's surface, its *top* can *extend upward* to the *tropopause*, over *12,000 m*.
- Cumulonimbus clouds can occur as an isolated cloud or as part of a *line* or “*wall*” of clouds.

➤ The *tremendous amounts of energy released by the condensation* of water vapor within the *cumulonimbus* results in the development of *violent updrafts and downdrafts*, which can exceed 70 knots.



- The lower (warmer) part of the cloud is usually composed of only water droplets.
- Higher up in the cloud, water droplets and ice crystals both abound, while toward the cold top, there are only ice crystals.
- Swift winds at these higher altitudes can shape the top of the cloud into a huge flattened anvil (*cumulo-nimbus incus*).
- This great thunderhead can contain all forms of precipitation—large raindrops, snowflakes, snow pellets, and sometimes hailstones—all of which can fall to Earth in the form of heavy showers.
- *Lightning*, *thunder*, and even *tornadoes* are associated with *cumulonimbus*.



A generalized illustration of basic cloud types ***based on:***

- ***height above the surface*** and
- ***vertical development***



5.5. Condensation Process and forms

- **Condensation** is the process through which the *physical state of matter changes* from the *gaseous* phase into the *liquid* phase.
- It is the *reverse of evaporation*, where liquid water becomes a vapor.
- For example, condensation occurs when water vapour (gaseous form) in the air changes into liquid water when it comes in contact with a cooler surface.
- When the water in the air comes in contact with a cold surface, it condenses to form water droplets.

Condensation can be simply explained as:

- A change of gas into a liquid.
- include those reactions in which two molecules are joined with loss of water.
- the removal of heat from a system in such a manner that vapor is converted into liquid.

Forms of condensation

Dew

At night, as there is no incoming solar energy and the ground continues to radiate away heat, its temperature falls.

- Surfaces cool strongly at night by **radiative cooling**
- If a ***surface cools below the dew point, water condenses on the surface*** and **dew drops are formed**.
- strongest on clear, calm nights



The ***dew point*** is the temperature at which the air is saturated with water vapor

Frost

- If the temperature is below freezing, the dew point is called the *frost point*.
- If the surface temperature falls below the frost point water vapor is deposited directly as *ice crystals*.
- The resulting crystals are known as *frost*, *hoarfrost*, or *white frost*



Haze

- This is a slightly different phenomenon which is a suspension of extremely small, *dry particles* in the air, *not water droplets*.
- These particles are invisible to the naked eye, but sufficient to give the air an opalescent appearance.
- Haze is an atmospheric phenomenon where *dust, smoke*, and *dry particles* in the air obscure the sky's clarity.



Fogs

- *Fogs are clouds* in contact with the *ground*.
Several types of fogs commonly form
 - Radiation fog
 - Advection fog
 - Upslope fog
 - Evaporation (mixing) fog



Clouds

- If the air temperature cools below the dew point ($RH > 100\%$), water vapor will tend to condense and form cloud/fog drops.
- Drop formation occurs on particles known as *cloud condensation nuclei* (CCN)
- The most effective CCN are water-soluble.
- *Without particles clouds* would *not* form in the atmosphere
 - RH of several hundred percent required for pure water drop formation
- Clouds result when air becomes saturated away from the ground

• Condensation nuclei are **tiny particles in the air on which water vapor condenses** and they are the key to making clouds, fog, haze, rain, and other forms of precipitation. Condensation nuclei come in many forms.

5.6. Precipitation and its types

- Precipitation is the *release of water from the atmosphere to reach the surface of the earth.*
- The term ‘precipitation’ covers *all forms of water being released by the atmosphere*, including *snow, hail, sleet, and rainfall.*
- It is the major input of water to a river catchment area and as such needs careful assessment in any hydrological study.

5.6.1. Processes of precipitation formation

(Bergeron-Findeisen theory, collision and coalescence)

- The *Collision Coalescence* and the *Bergeron Findeisen* theory tries to explain *how water droplets* when formed in the cloud *actually fall to the ground* as *rainfall*.

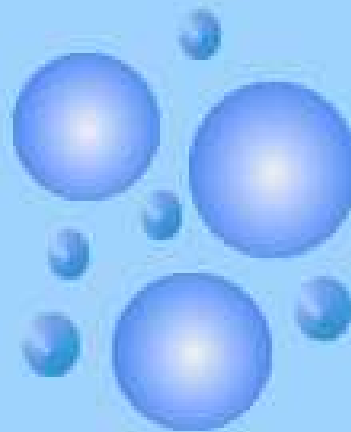
- For rain to fall down, 3 things are needed:
 1. Uplift mechanism which lifts air parcels.
 2. Condensation nuclei where water vapour accumulates to form tiny droplets ... and
 3. the Collision coalescence or Bergeron Findeisen process actually makes the droplets fall as rain.

Collision Coalescence

- This theory explains that *water droplets (big and small)* in a cloud *collide against each other* caused by *convictional currents* in the cloud.
- The initial small droplets are not dropped but kept suspended in the cloud until they are *large enough to be dropped*.
- As other large water droplets (that are still suspended in the cloud) collide with *small water droplets*, they coalesce (*join*) causing them to *become bigger*.
- Eventually, they *get larger* that they are *unable to be suspended any longer in the cloud* and hence they *fall down*.
- Upon falling, the large droplets are **ripped apart** by convictional currents and *air friction* which disintegrates them into new droplets which fall as *rainfall*.
- *Collision Coalescence* mostly applies to *warm convictional clouds* in *tropical areas*.



small and large droplets collide and coalesce



droplets become bigger



droplets split into rain

<https://youtu.be/piYqc6k0wmc>

Bergeron Findeisen Theory

- The *ice-crystal process* is also known as the *Bergeron process* after the Swedish meteorologist *Tor Bergeron*, who proposed that essentially *all raindrops begin as ice crystals*.
 - This process occurs when *supercooled water* and *ice crystals* exist together.
 - *Supercooled water surfaces* have a *high vapour pressure* (pressure generated by water vapour on a water body or air than *ice surfaces*).
 - *Water vapour* around *ice crystals* have *no time to condense* and thus goes straight for *deposition* (*solid*).
- **Bergeron) process** of rain formation is extremely important in **middle** and **high latitudes**, where clouds extend upward into regions where the air temperature is below freezing. Such clouds are called **cold clouds**.

https://youtu.be/aPNufbf_n_p0

- Water vapor moves from high vapor pressure (supercooled water) and is deposited in the ice crystals where they freeze and merge with other ice crystals.
- The *ice crystals* become *heavy* and therefore *fall*, whereupon falling experience *warm temperatures* and *melt* as *rainfall*.
- This process mainly occurs in *towering cumulonimbus clouds* where ice crystals are mainly located around the *anvil* (*uppermost part of cumulonimbus clouds*) because of very low temperatures and in temperate and mid-latitude regions where *temperatures are low*.
- However, this theory *fails to apply to tropical areas* where rain can form in low-level clouds *without ice crystals*.

5.6.2. Forms of Precipitation

- While falling, raindrops and snowflakes can be altered by atmospheric conditions encountered beneath the cloud and transformed into other forms of precipitation that can profoundly influence our environment.



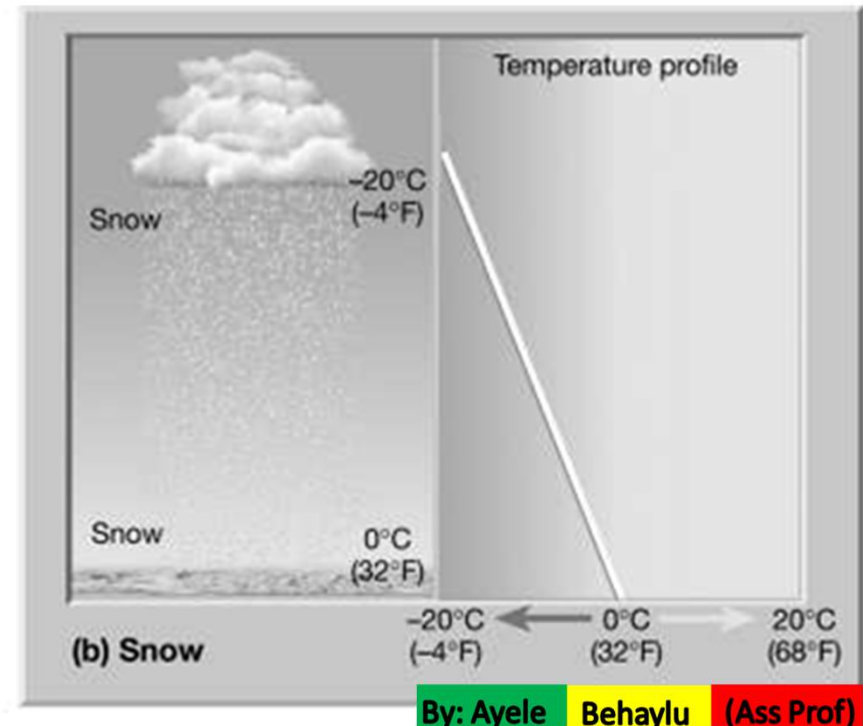
- Most people consider **rain** to be any falling drop of liquid water.
- To the meteorologist, however, that ***falling drop must have a diameter equal to, or greater than, 0.5 mm*** to be considered **rain**.

2. Snow

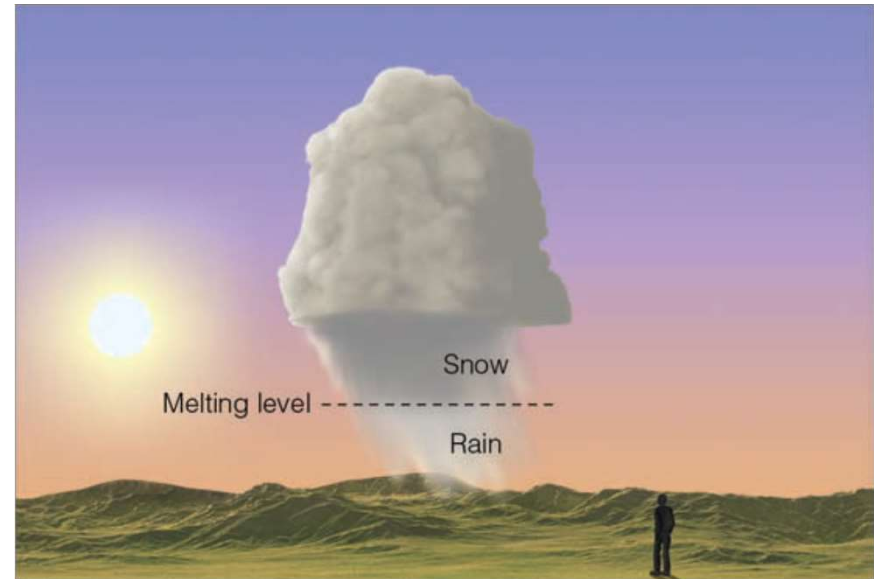


- The cloud and all of the air beneath the cloud must be *below freezing*.
- However, in *winter*, the freezing level is much lower, and falling snowflakes have a better chance of survival.
- Snowflakes can generally fall about 300 m below the freezing level before completely melting

- Much of the precipitation reaching the ground actually begins as snow.
- In *summer*, the freezing level is usually above 3600 m, and the *snowflakes* falling from a cloud *melt* before reaching the ground.

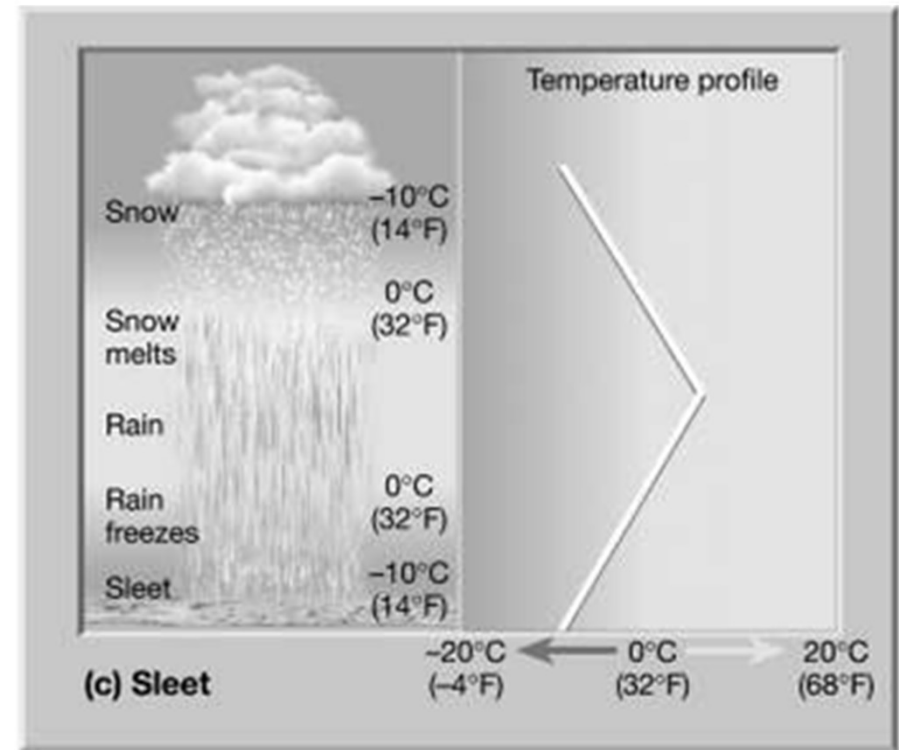


- Occasionally, you can spot the melting level when you look in the direction of the sun if it is near the horizon.



- Because ***snow scatters incoming sunlight better than rain***, the darker region beneath the cloud contains falling snow, while the lighter region is falling rain.
- The melting zone, then, is the transition between the light and dark areas

3. Sleet



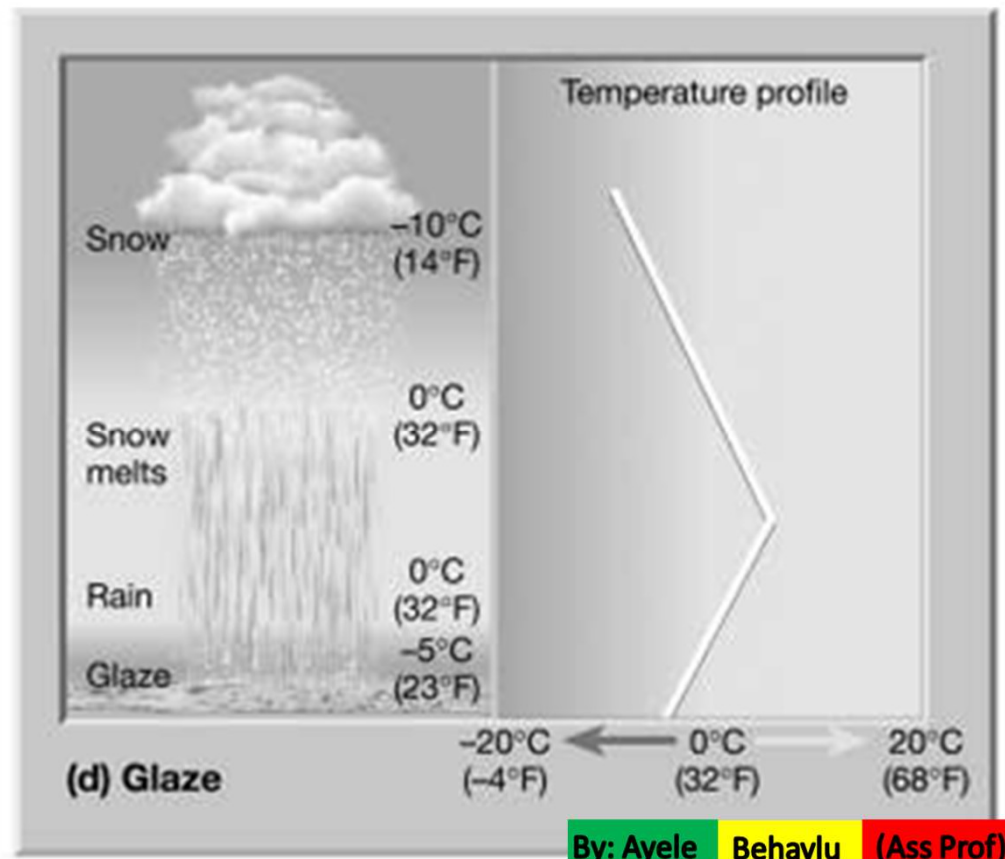
- Sleet (Ice Pellets) are frozen raindrops that strike the earth's surface.
- The snow falls through a layer that is a little above freezing and the **snow partially melts**.
- If the snow completely melts it will be more likely to reach the earth's surface as supercooled water instead of sleet.

- If the snow partially melts there will still be ice within the falling drop for water to freeze on when the drop falls into a subfreezing layer.
- The lowest layer of the troposphere will be below freezing in a sleet situation and deep enough to freeze drops completely.
- The lower boundary layer can be above freezing and sleet occur if the sleet does not have time to melt before reaching the surface

4. Glaze

- Rain that hits below-freezing surface to form a glaze.
- The surface must be at or below freezing while the air above the surface must be *warmer than freezing*

•



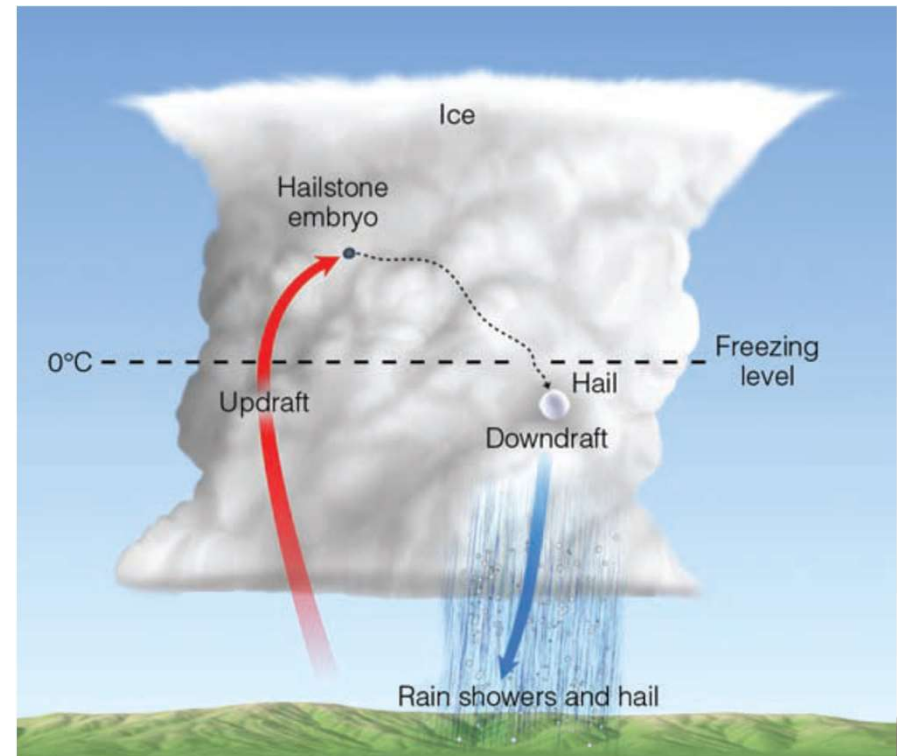
5. Hail

- Hail is dense precipitation ice that is at least 5 millimeters in diameter.
- It forms due to ice crystals and supercooled water that freeze or stick to the embryo hailstone.



- Soft hail is whiter and less dense since it has air bubbles.
- Soft hail occurs when hail grows at a temperature below freezing by ice crystals and small supercooled water and cloud droplets merging onto the hail.

- Hard hail occurs when liquid water drops freeze on the outer edges of the hailstone after the outer edge is above freezing.
- The freezing of supercooled water releases latent heat and this can result in the outer edge of the hailstone warming above freezing. Then the water refreezes creating solid ice.
- Hail will commonly have soft ice and hard ice layers when it is sliced open. Hailstones are *pieces of ice*, either transparent or partially opaque, *ranging in size from* that of *small peas* *to* that of *golf balls* or *larger*



6. Drizzle



❑ Fine, uniform drops of water with diameters smaller than 0.5 mm are called **drizzle**.

- Their size generally ranges 0.2-0.5mm and their terminal velocities are between 70 and 200 cm per second.
- Drizzle falls mostly from the low-stratus cloud and it is frequently accompanied by fog and poor visibility.

NB: Authors of the book entitled “**METROLOGY TODAY**” (Ahrens & Henson) represent drizzle as a diameter about one-third of the width of the letter ‘o’ in the print version of their stated book.

7. Dew

- Dew is the *smallest water drops formed during condensation* on the earth surface, most frequently on the grass during the warm period of a year.



- Dew arises mostly with clear and calm weather in the evening hour and at night when there is no fog.
- Fog develops when soil and vegetation cool at temperatures typical of the dew point.
- Dew can produce a large amount of precipitation

8. Frost

- Is a feathery deposit of ice formed on the ground or on the surface of exposed objects by dew or water vapour that has frozen.



9. Fog

- It restricts visibility to 1000 m or less.
- Dense fog restricts to 100 m or less.
- Fog consists of suspended tiny water droplets (could also be suspended ice crystals).
- *Fog* is a *cloud* on the ground.



10. Mist

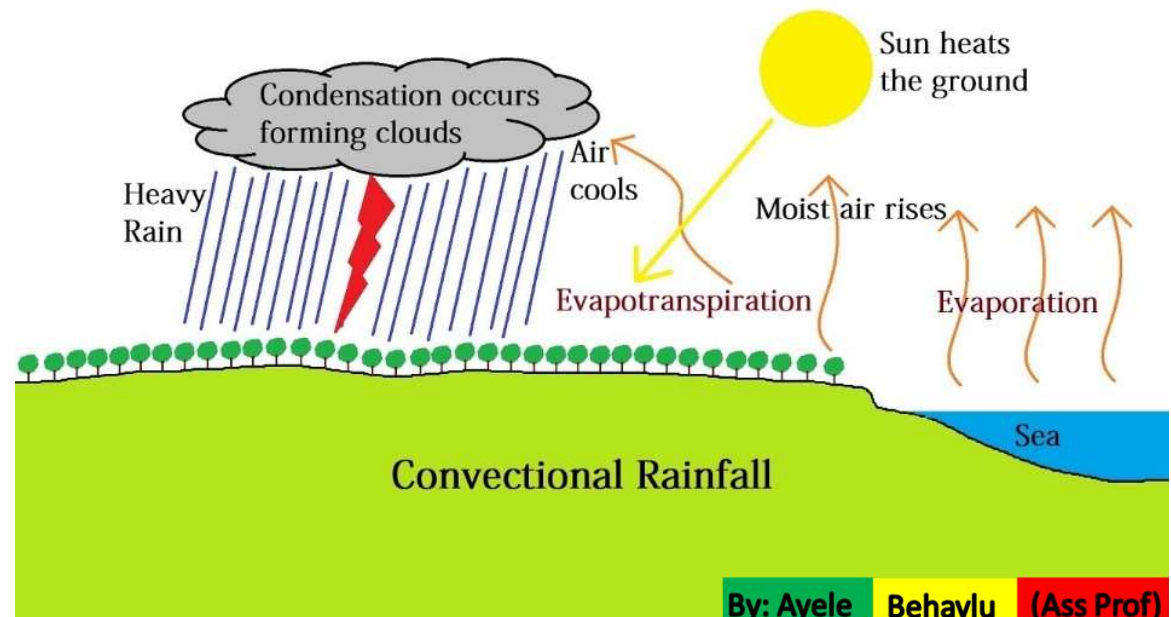
- A *very thin fog* at the surface of the earth by condensation of atmospheric vapour.



5.6.3. Precipitation types

A. Convective Precipitation (Thermal Convection)

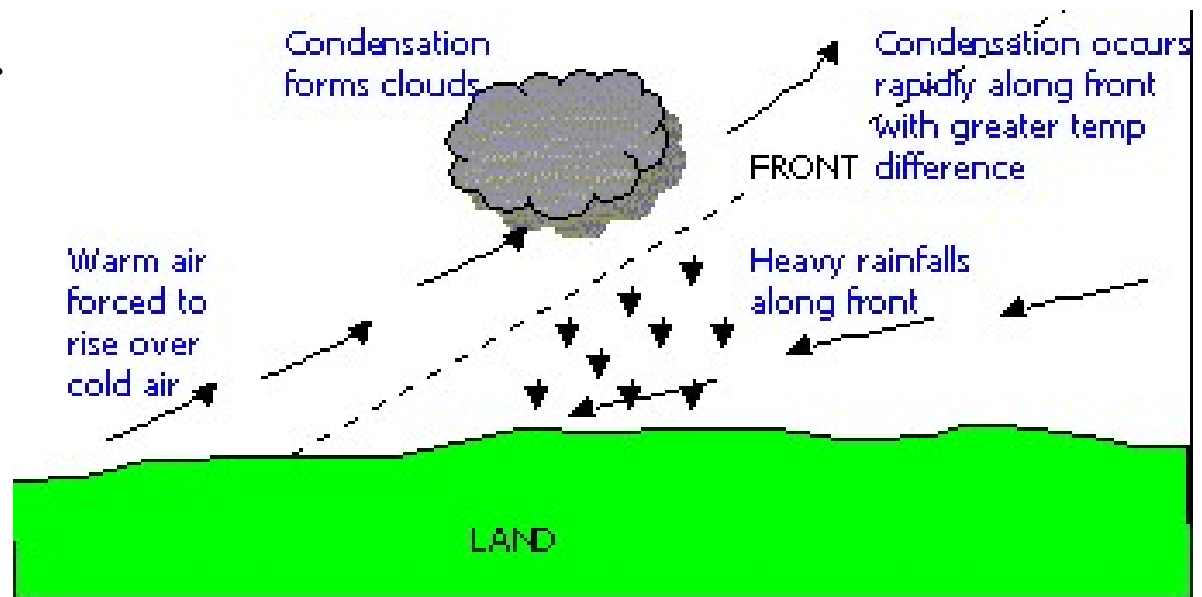
- This type of precipitation is in the form of local whirling **thunderstorms** and is typical of the **tropics**.
- The air close to the warm earth gets heated and rises due to its *low density*, *cools adiabatically* to form a *cauliflower-shaped* cloud, which finally bursts into a thunderstorm.
- When accompanied by destructive winds, they are called ‘tornados’.



B. Frontal Precipitation (Conflict Between Two Air Masses)

- When two air masses due to contrasting temperatures and densities clash with each other, condensation and precipitation occur at the surface of contact.
- This surface of contact is called a ‘front’ or ‘*frontal surface*’.

➤ If a *cold air mass drives out* a *warm air mass* it is called a ‘*cold front*’ and if a *warm air mass replaces* the retreating cold air mass, it is called a ‘*warm front*’.



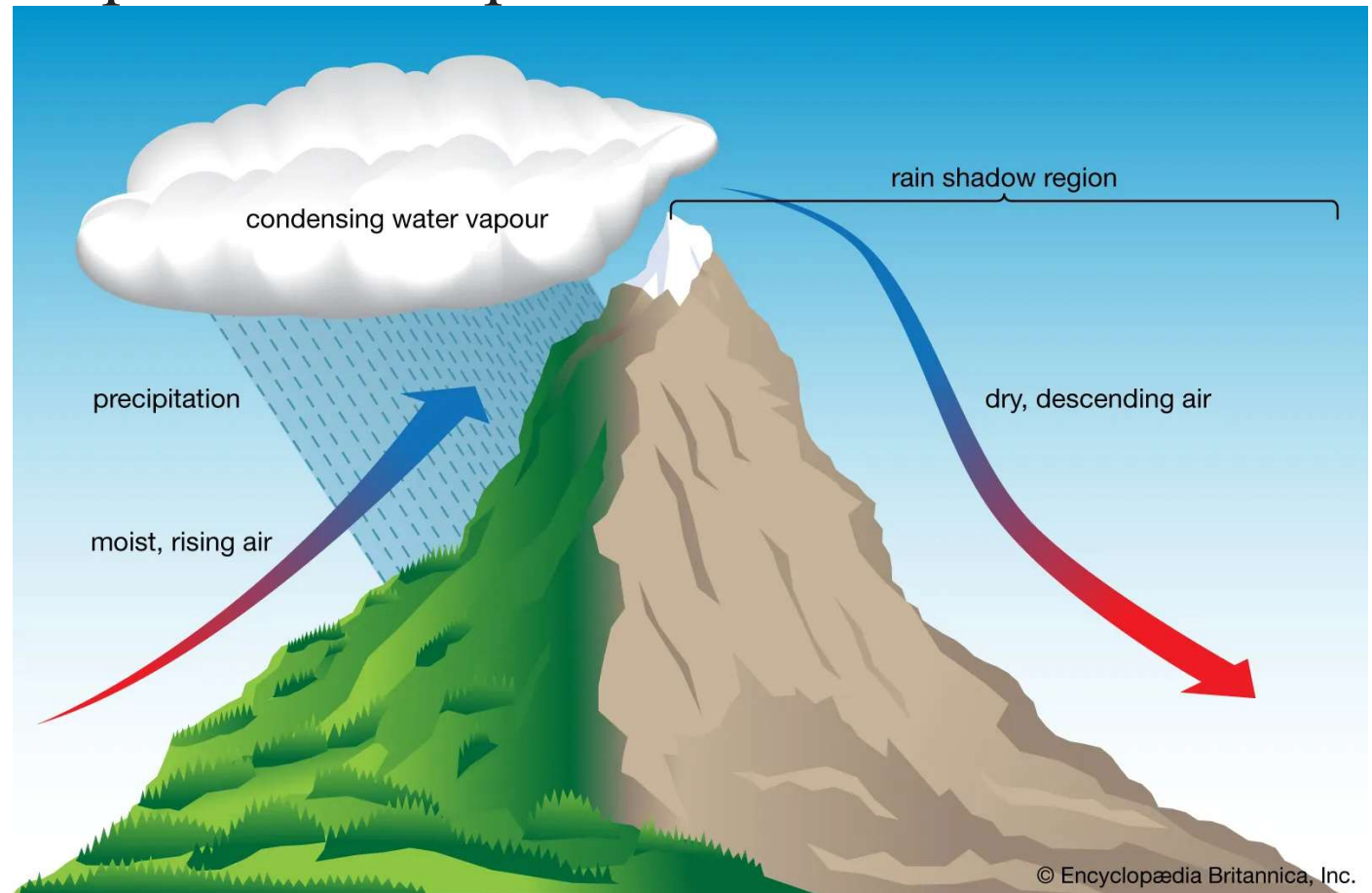
- On the other hand, if the two air masses are drawn simultaneously towards a *low-pressure area*, the front developed is stationary and is called a '*stationary front*'.
- Cold front causes *intense precipitation* on comparatively small areas, while the precipitation due to a *warm front* is *less intense* but is *spread over a comparatively larger area*.
- Cold fronts move faster than warm fronts and usually overtake them, the frontal surfaces of cold and warm air sliding against each other.
- This phenomenon is called '*occlusion*' and the resulting frontal surface is called an '*occluded front*'.



C. Orographic Lifting (Orographic Precipitation)

- In orographic lifting, the air is forced to rise up over the windward side of a mountainous topographic barrier.
- As a weather system moves up a mountain, air pressure changes and temperatures drop with altitude.

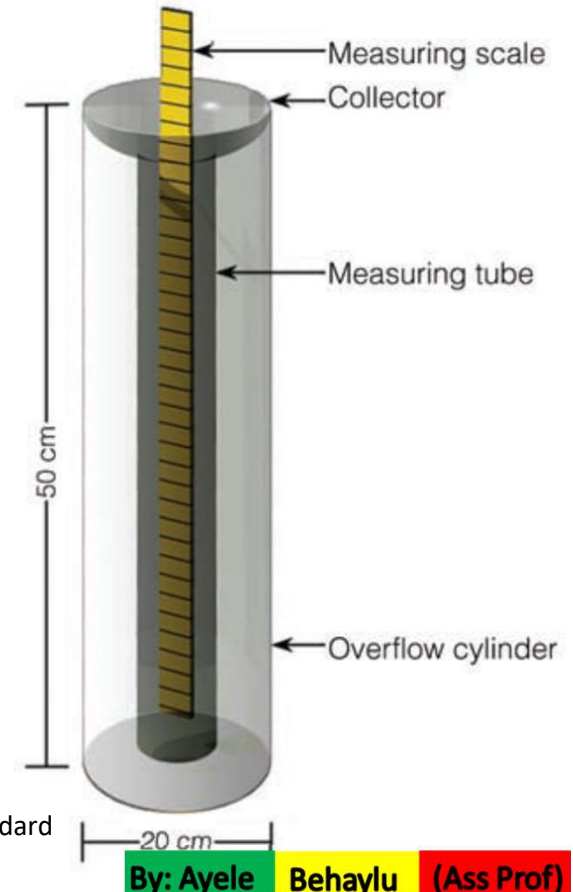
- Clouds and precipitation occur when air parcels cool due to lifting and dew point temperature.



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5.6.4. Precipitation measurement

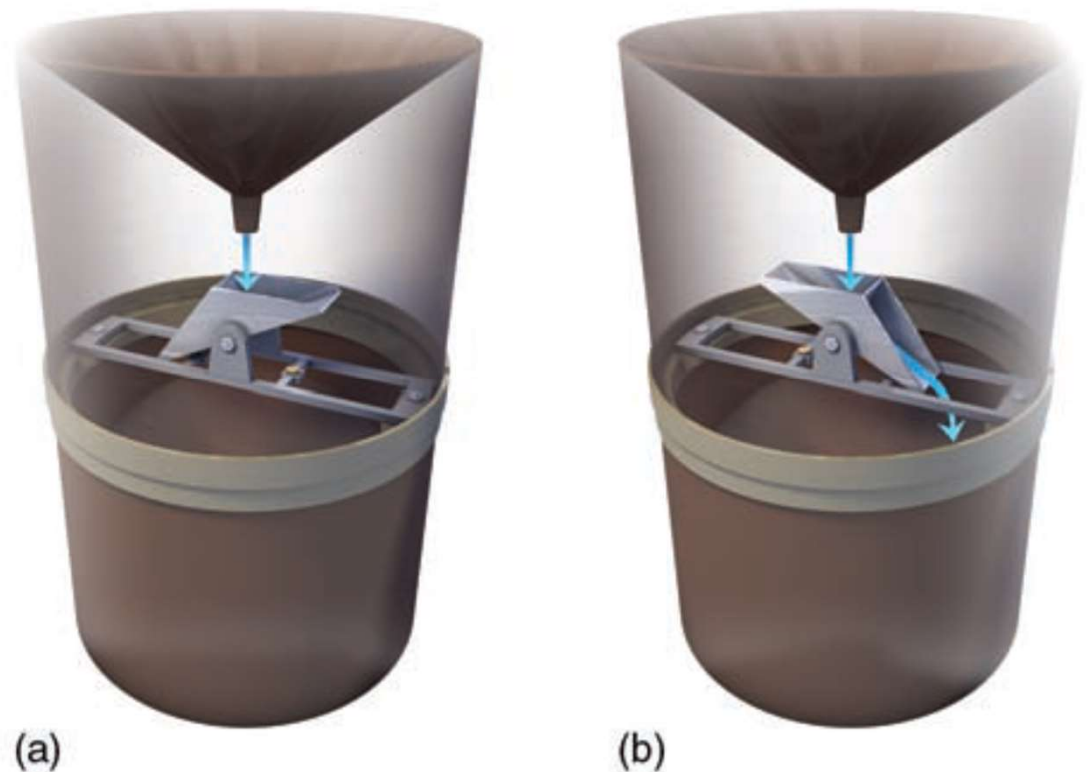
- Although rainfall is relatively straightforward to measure (other forms of precipitation are more difficult) it is notoriously difficult to measure *accurately* and, to compound the problem, is also extremely variable within a catchment area.
- Any instrument that can collect and measure rainfall is called a **rain gauge**.
- A **standard rain gauge** consists of a *funnel-shaped collector attached to a long measuring tube*.
- The cross-sectional area of the collector is 10 times that of the tube.
- Hence, rain falling into the collector is amplified tenfold in the tube, permitting measurements of great precision.



- A wooden scale, calibrated to allow for the vertical exaggeration, is inserted into the tube and withdrawn.
- The wet portion of the scale indicates the depth of water. So, 10 in. of water in the tube would be measured as 1 in. of rainfall
- This amplification permits rainfall measurements to be as precise as one-hundredth (0.01) of an inch.
- An amount of rainfall less than one-hundredth of an inch is called a **trace**.
- The measuring tube can only collect 2 in. of rain.
- Rainfall of more than this amount causes an overflow into an outer cylinder.
- Here, the excess rainfall is stored and protected from appreciable evaporation.
- When the gauge is emptied, the overflow is carefully poured into the tube and measured.

- Another instrument that measures rainfall is the **tipping bucket rain gauge**.
- This gauge has a receiving funnel leading to two small metal collectors (buckets) attached to each other and mounted on a pivot.
- The bucket beneath the funnel collects the rainwater.
- When it accumulates the equivalent of one-hundredth of an inch of rain, the weight of the water causes it to *tip and empty itself*.
- As the first bucket turns on the pivot, the second bucket immediately moves under the funnel to catch the water.
- When it fills, it also tips and empties itself, moving in the other direction on the pivot, and the original bucket moves back beneath the funnel.
- Each time a bucket tips, an electric contact is made, causing a pen to register a mark on a remote recording chart.

- Adding up the total number of marks gives the rainfall for a certain time period.
- A problem with the tipping bucket rain gauge is that during each “tip” it loses some rainfall and, therefore, under measures rainfall amounts, especially during heavy downpours.
- The tipping bucket is the rain gauge used in automated (ASOS) weather stations.

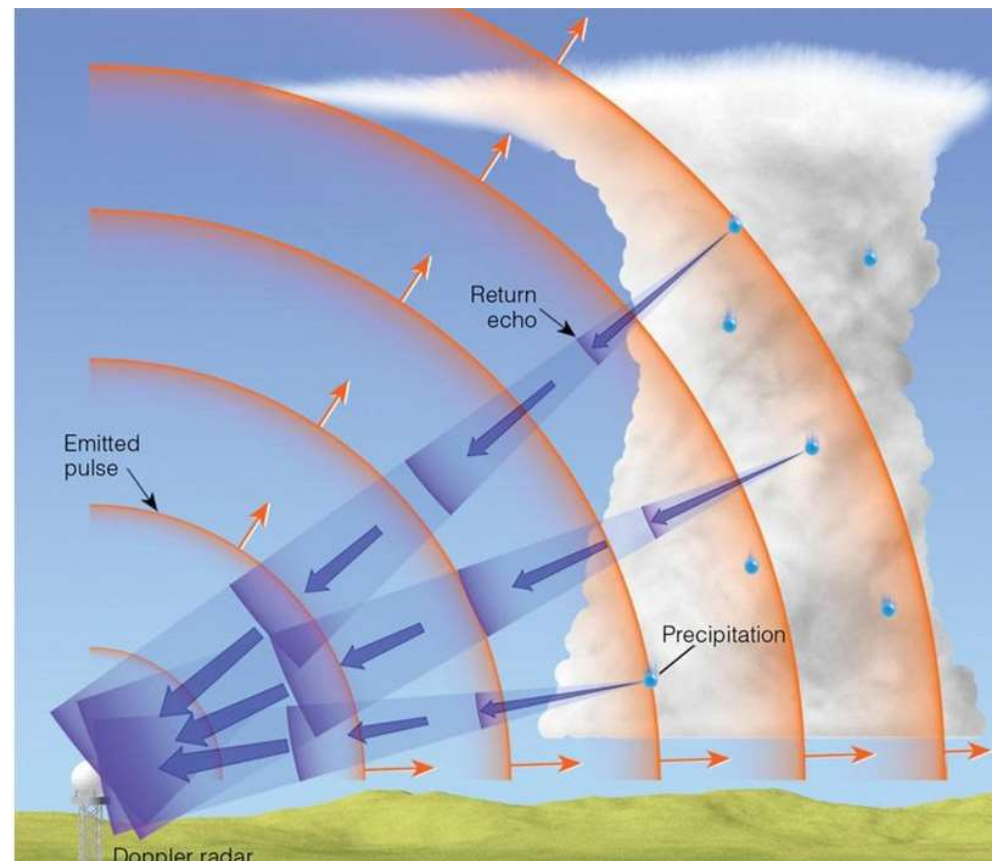


The tipping bucket rain gauge. (a) Each time one of the two buckets mounted on a pivot fills with one-hundredth of an inch of rain, it tips (b), sending an electric signal to the remote recorder

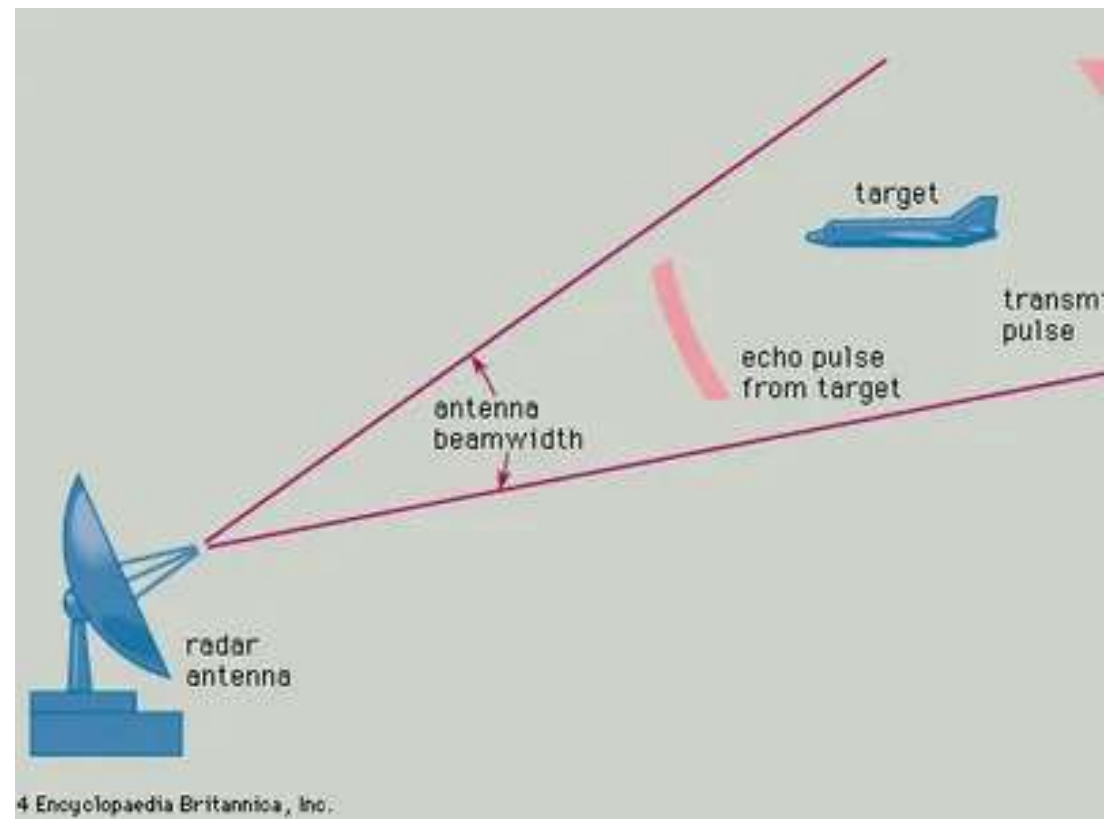
Doppler Radar

- **Radar** (*radio detection and ranging*) has become an essential tool for atmospheric scientists because it gathers information about storms and precipitation in otherwise inaccessible regions.

Atmospheric scientists use radar to examine the inside of a cloud in much the same way that physicians use X-rays to examine the inside of a human body.



- Essentially, the radar unit consists of a transmitter that sends out short, powerful microwave pulses.
 - When this energy encounters a foreign object—called a *target*—a fraction of the energy is scattered back toward the *transmitter* and is detected by a *receiver*.
- The returning signal is amplified and displayed on a screen, producing an image, or *echo*, from the target.
 - The elapsed time between *transmission* and *reception* indicates the *target's distance*.

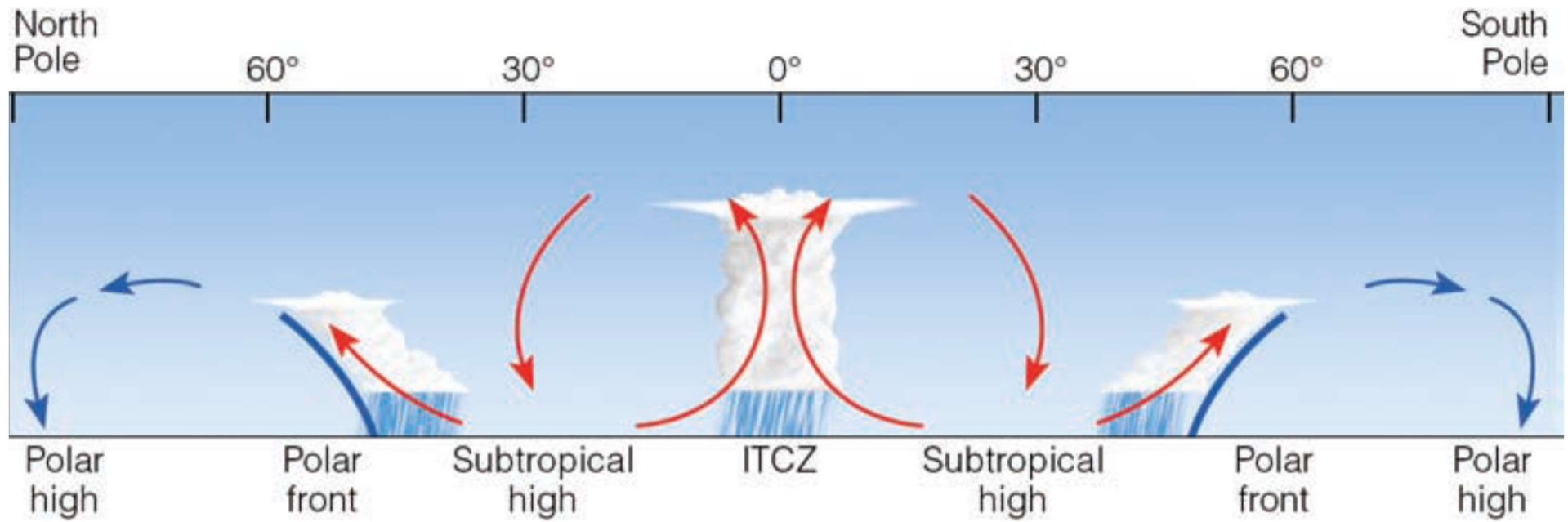


5.6.5. Global distribution of precipitation

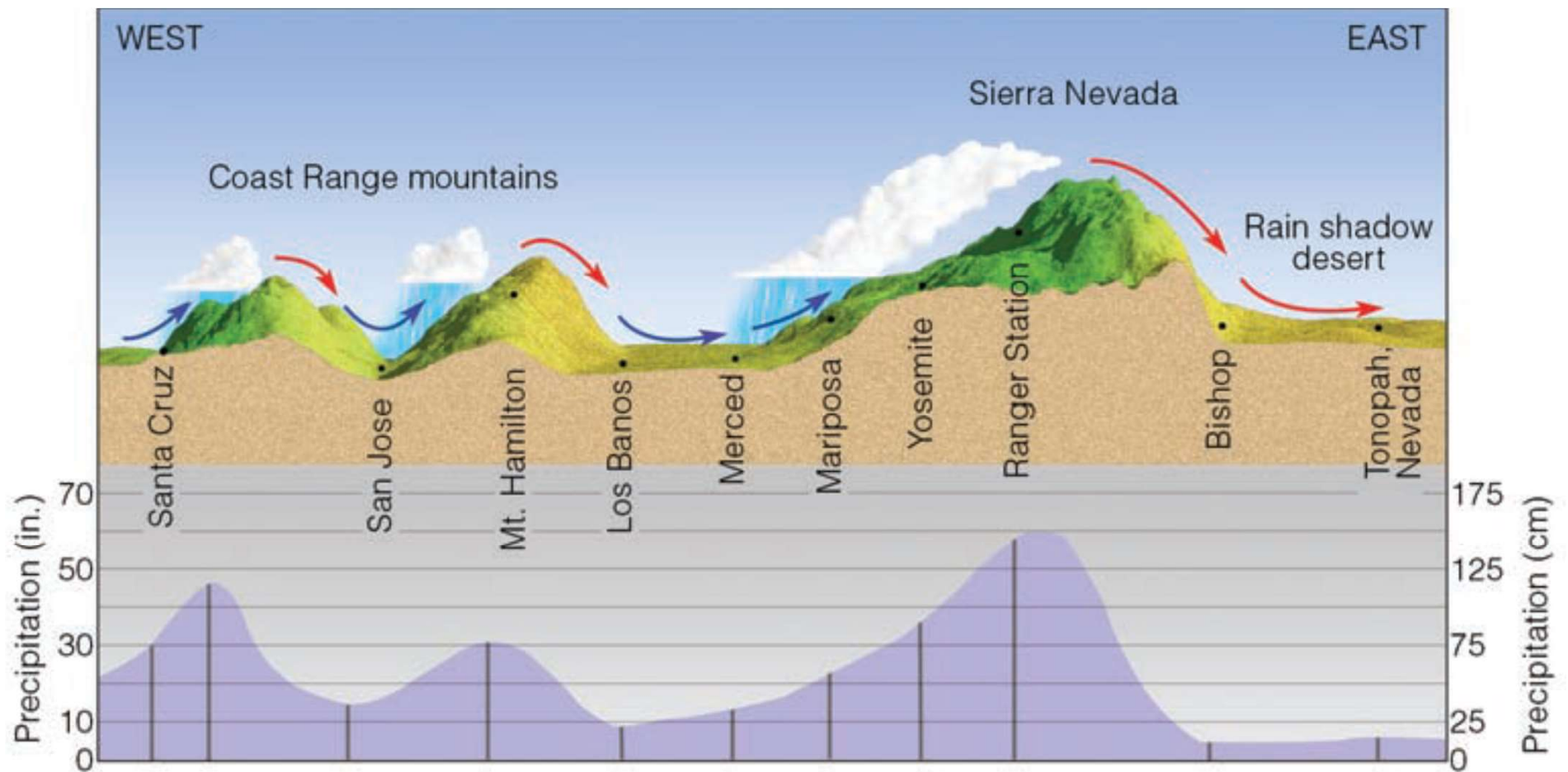
- As it is known, *moisture availability* from *precipitation* is *unequally distributed across the Earth*.
- The geographic pattern of precipitation is explained by examining the *spatial distribution of air masses, water availability through evaporation*, and *uplift mechanisms*.
- One of the most important climate elements is the influence of the *global pressure systems*.

- Precipitation near the equator is high due in part to the influence of the *ITCZ*.
- Here, convection and low pressure dominate and provide lift for the air throughout much of the year.
- At about *30° north and south* latitudes precipitation *decreases* due to the presence of subtropical high-pressure systems.
- The sinking air of the subtropical highs produces a “*dry belt*” around the globe (although we will see that not all locations at this latitude have dry climates).
- The Sahara Desert of North Africa and the Mojave Desert of southwestern North America lie within this belt.
- *Subsiding air* from *high pressure* *suppresses uplift* which *inhibits* the formation of precipitation.

- Precipitation **increases** in the *mid-latitudes* where vastly *contrasting air masses collide* along weather *fronts* to *cause precipitation*.
- As one *approaches the poles*, *precipitation decreases* on account of the *cold temperature* and *it is associated with* a *low saturation point*.
- This is obviously a gross exaggeration of the true geographical distribution of precipitation.



- Orientation of *winds*, *mountain* systems, and *air mass* are important to play important roles in the pattern of precipitation.



- The temporal variation in global precipitation is directly linked to the seasonal changes in the heating of the Earth and its effect on the movement of global pressure systems and air masses.
- The migration of the ITCZ across the Equator keeps this region very moist.
- As one moves poleward, the precipitation becomes more variable as the drying effect of the subtropical is experienced.