VI. ATMOSPHERIC MOISTURE:

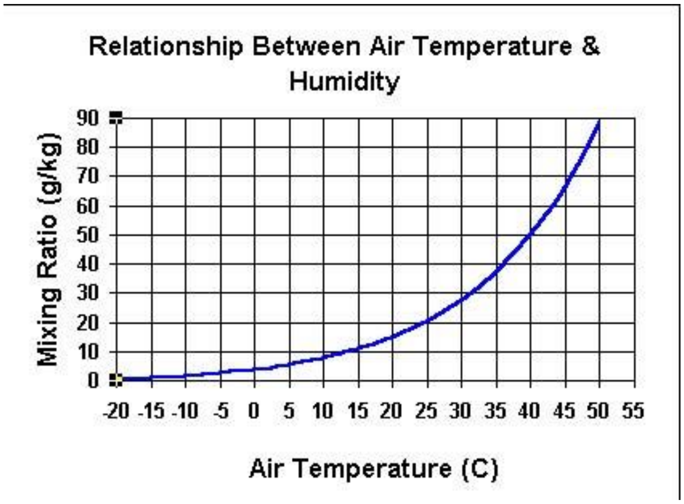
A. The ability of air to hold water vapor is a very strong function of temperature.
  1) Warm air can hold much more water vapor than cold air.
    a) That's one reason why water vapor is not well mixed through the atmosphere.
    b) Most of the vapor is located pretty close to the ground because the air further aloft is too cold to hold it.

B. A sample of air will have 2 moisture properties.
  1) **Vapor supply (VS)**:
    a. Tells us how much water vapor actually exists in the sample.
  2) **Vapor capacity (VC)**:
    a. Tells us how much water vapor air can hold at a maximum, and that's primarily a function of temperature.

C. We can express both VS and VC as mixing ratios.
  1) A **mixing ratio** is a mass of water vapor divided by a mass of dry air, excluding the vapor. (Like a recipe)
    a. Suppose a sample of air had 10 grams of water vapor per every 1 kilogram of dry air, it's vapor supply would be 10 g/Kg.
    b. Is 10 g/Kg of VS a lot or a little?
      i) Actually, it depends on what the sample's vapor capacity is.
  2) **Relative humidity**, or RH, is a ratio of vapor supply and capacity expressed as a percentage.
  3) If VS is 10g/Kg and VC is 10g/Kg, then the relative humidity is 100 %.
    a. We're at saturation and that air can hold no more water vapor.
  4) If VS is 10g/Kg and the VC is 20g/Kg, the relative humidity would only be 50%, and that air would not feel especially damp.
  5) If VS is 10g/Kg and the VC is 30g/Kg, the relative humidity would only be 33%. It might be on a warm summer day and would feel uncomfortably dry to you.

  [We should appreciate that vapor supply is a measure of absolute humidity, the actual vapor content of the air.]

D. Vapor capacity values for air at sea level: (Note the strong function of temperature)
  1) At -20°C or -4°F, air holds 0.75 g/kg.
  2) At -10°C or 14°F, air holds 2.0 g/kg.
  3) At 0°C or 32°F, air holds 4 g/kg.
  4) At 10°C or 50°F, air holds 8 g/kg.
  5) At 20°C or 68°F, air holds 15 g/kg.
  6) At 30°C or 86°F, air holds 28 g/kg.
  7) At 40°C or 104°F, air holds 50 g/kg. (Note 66X from -4°F)….It's Exponential.



8) Vapor capacity is also called "**saturation mixing ratio**" since it represents the mixing ratio or vapor supply that would be present in air if it were saturated.

9) At **saturation**, air is holding all the water vapor it can.

10) The vapor capacity numbers clearly show that it doesn't take much water vapor to saturate cold air.
    - a. It's easy to make clouds or fogs out of cold air, but it also means it's very hard to get much precipitation out of very cold air.
        - i) It may be saturated, but the vapor supply values are so small that precipitation has to be small.
    - b. The vapor capacity of hot air is enormous, and it's very hard to saturate.

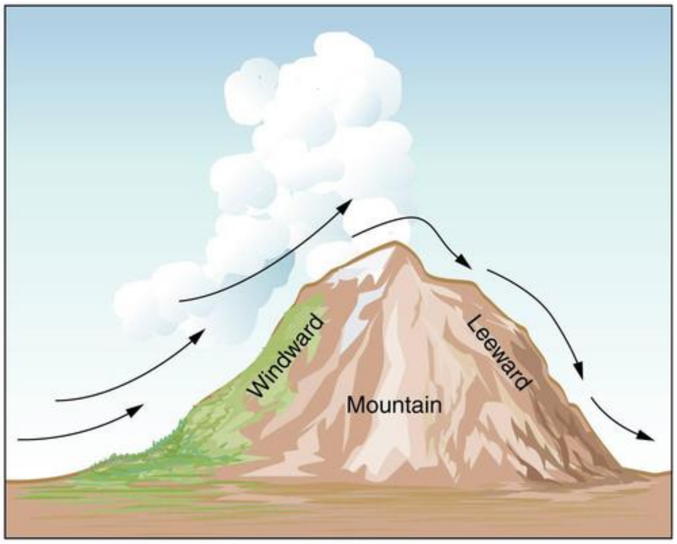
11) **Mixing ratio** tells us what fraction of air water vapor represents.
    - a. A vapor supply of 10 g/kg means air is 10 parts water vapor for every 1000 parts dry air, so the water vapor content is actually just a little bit under 1%.

E. Examples:

1. A foggy winter day in Minnesota vs. a hot dry summer day in Death Valley.
    - a. In Minnesota, our temperature might be -10°C or 14°F. The vapor capacity is 2 g/kg and is saturated. So the vapor supple is 2 g/kg also.
    - b. In Death Valley, suppose the temperature is 40°C, or 104°F, so that's probably a little before lunchtime. The vapor capacity of that air is 40 g/kg, and if the relative humidity is 5%, that's oppressively dry.
    - c. This means the vapor supply is 2.5 g/kg, more moisture in Death Valley than in Minnesota. [Humans are poor judges of absolute humidity]
2. Santa Ana winds originating over in Nevada might have a temperature of 50°F, so that's a vapor capacity of 8 g/kg. [Remember, these winds start over the cold dry desert during the winter]. Let's say the relative humidity is 100%. [That's an exaggeration, but that would mean the vapor supply is 8 g/kg as well.]

    a. Now let's move that air downslope 2 miles into Los Angeles. [Remember that these winds become hot because they travel downslope and experience compression warming].
        i) We call this the "dry adiabatic process," involving temperature change due to volume contraction, rather than heat exchange.
        ii) A sample of descending dry air will heat up at a rapid rate, 10°C per km, or 30°F per mile.
    b. The Santa Ana winds air temperature increases by 60°F, becoming 110°F.
    c. Its new vapor capacity is more than 50 g/kg, but the vapor supply is still only 8 g/kg.
    d. So instead of being saturated as we started out, the relative humidity is now under 16%.
    e. We had a drop of relative humidity from a very moist 100% to bone-dry 16%, just by moving the air downslope. In fact, relative humidity down to 5% is not uncommon when the winds are howling. The dry air is thirsty and it steals moisture from wherever it finds it, like vegetation, which is one reason why low relative humidity is so conducive to fire.
    f. Therefore, as moist air move downslope, its vapor supply may not change, but its vapor capacity increases dramatically, due to the compression warming and exponential relationship between vapor capacity and temperature.
3. Let's go back to a foggy winter day in Minnesota.
    a. The temperature was 14°F, relative humidity at 100%, vapor supply and capacity at 2 g/kg.
    b. Let's bring this air indoors and heat it up to a reasonable room temperature of 68°F, or 20°C, but without changing its vapor supply.
    c. Its vapor supply is still 2 g/kg, but the heated air's new vapor capacity is 15 g/kg, so our new relative humidity is 2 divided by 15 or 13%, shockingly low, literally.
    d. When the RH gets down to values below 20%, static electric shocks become a common problem. Under higher humidity conditions, objects become coated with a very thin layer of surface water, even when the RH is way below 100%. Water isn't just a good conductor of heat---it conducts electricity very well, as as a result, the charge cannot hold and it cannot build up.
    e. If I heat air in a furnace, that's an example of a diabatic process, temperature change by heat exchange, so diabatic is the opposite of adiabatic. The source of the temperature change doesn't matter. If you increase the temperature a little, the RH decreases a lot.
    f. Note that the examples so far show that the RH is inversely related to temperature.

4. Suppose air starts at a foot of a 2-mile tall mountain on a hot and relatively dry day.
    a. Let's say the temperature is 110°F, 42°C. The vapor capacity of that air is more than 50 g/kg, and let's say the vapor supply is only 8 g/kg, so the relative humidity is under 16%.
    b. Now we force that air to ascend to a mountaintop 2 miles high.



(c) Orographic (barrier)

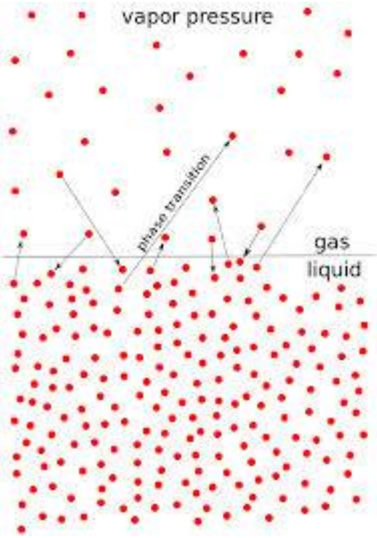
    c. It cools 60°F on the way up, all the way down to 50°F, or 10°C.
    d. Its vapor capacity has decreased from a formerly enormous value down to a humble 8 g/kg. That's the same as the vapor supply, so our relative humidity is now 100%.
    e. We started very hot and relatively very dry, and with just a little bit of lifting, we've brought this air to saturation through expansion cooling.
    f. Any further lifting would cool the air more, causing the vapor capacity to become small than its vapor supply.
    g. Now, with a vapor excess in that air, that air parcel that started off brutally dry, has now become a cloud. A cloud has been born.
    h. Therefore, we can increase relative humidity by lowering the air temperature, and with enough cooling, we can potentially raise the relative humidity all the way to 100%.
    i. So as long as the air has a little bit of moisture, even just a smidgeon of moisture, we can lift that air to saturation, it we can have the means to lift it.

F. Why does vapor capacity increase with temperature? Why does warm air hold more water vapor than cold air?
    1) The 3 phases of any substance are vapor, solid, and liquid. For simplicity let's just consider vapor and liquid at temperatures above freezing.

a. Water substances are always moving between these two phases, always going back and forth.
   i) Vapor molecules are becoming liquid. They’re **condensing**.
   ii) Liquid drops are becoming vapor. They’re **evaporating**.

b. The microscopic activity of a water molecule is a function of it’s temperature, and increases quickly with it’s temperature as well.
   i) Water molecules are always in collision.
   ii) The lower the temperature is, the less likely 2 vapor molecules can avoid bonding upon collision, so the drops that they form are more likely to be long lived.
   iii) The higher the temperature, the more likely that a water molecule can escape from it’s liquid prison and become vapor, so there will be very few surviving drops.

2) Consider water vapor molecules in the vicinity of a plain surface of liquid water, like a lake or pond.
   a. These vapor molecules are exerting a pressure, force per unit area on the liquid water surface, and we call this “vapor pressure”.
      i) It’s a small part of the total atmospheric pressure exerted on the liquid because vapor represents only a very small part of the air’s mass.
      ii) But if we increase the number of vapor molecules in the air, if we increase it’s amount, we would increase the vapor pressure.
      iii) The vapor pressure is a function of the vapor mass.

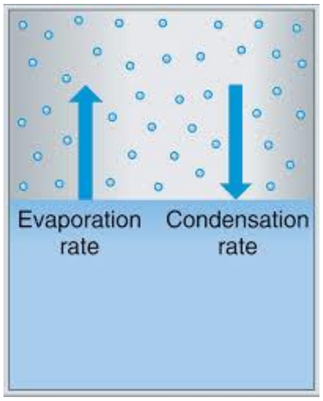


   b. Temperature is measuring the microscopic energy and vibration of translation of water molecules the air and in the liquids.
      i) The vapor molecules in motion may chance to collide with the liquid water surface. If and when they do, there’s always a chance they’ll

become incorporated into the liquid water prison. [They will have condensed].

ii) Meanwhile, water molecules in the liquid water prison seek to escape, to break the surly bonds with their neighbors and return to the atmosphere as vapor. If and when they succeed, they will have evaporated.

iii) When the rates of condensation and evaporation are the same, the vapor liquid system is in equilibrium. This equilibrium is called "**saturation**".



iv) At saturation, there's just enough vapor molecules around to replace the water that escapes from the liquid. This vapor mass exerts a pressure, and the pressure is called the "**saturation vapor pressure**".

v) "Subsaturation" happens if there are too few vapor molecules around to replace those that manage to escape from the liquid water prison. [the liquid water surface is losing more vapor molecules than it's gaining, so it is evaporating.

vi) The shortage of vapor mass also means that the vapor pressure is smaller than it needs to be. This means that the actual vapor pressure is less than the saturation vapor pressure.

vii) Actual vapor pressure represents supply. Saturation vapor pressure represents demand, need, or capacity, and indeed, for purposes, actual **vapor pressure is the vapor supply**, and **saturation vapor pressure is the vapor capacity**.

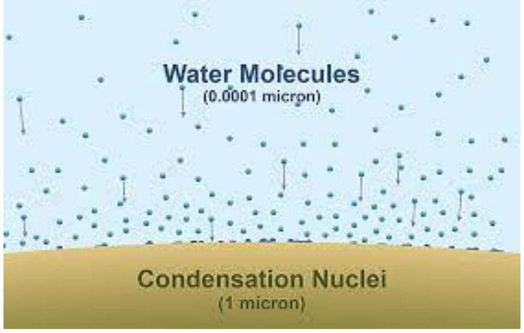
viii) Vapor supply and vapor capacity are moisture concepts expressed as mass or quantity.

ix) As the temperature gets higher, more vapor molecules would be needed to be present in order to balance the escapees. That balance is saturation, and the saturation vapor pressure and vapor capacity increase with temperature.

        - x) Since the microscopic energy increases quickly with temperature, so does saturation vapor pressure and vapor capacity. They're exponential functions.
        - xi) So in a nutshell, the ability of air to hold water vapor is really the ability of vapor to avoid condensing. It's the ability of water vapor to succeed in evaporating.

G. How does the condensation process start?

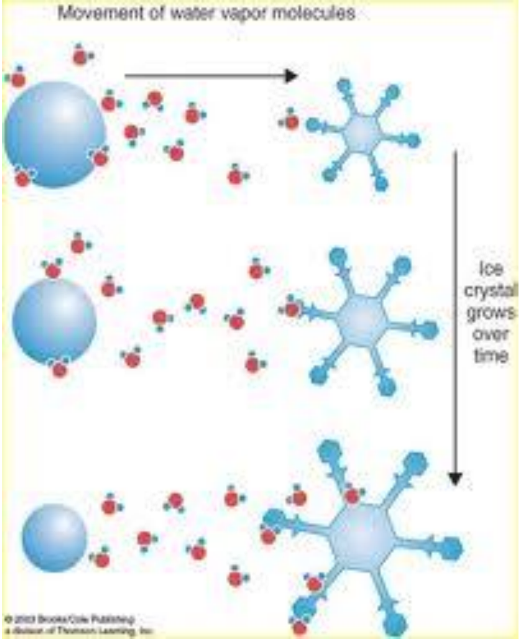
1) It turns out that vapor molecules require a surface to condense on.
    a. Large existing liquid water surfaces definitely work, but you don't find those everywhere.
    b. Other useful surfaces are bridges, your skin, blades of grass, and car windshields. But what about in the middle of the air?
2) There's grit suspended in the air, grit like sand particles, dust, soot, salt crystals, even in what we call clean air, and all of these surfaces in midair can serve to support cloud droplet formation when the conditions are ripe, and we call them "**condensation nuclei**".
    a. Some surfaces make very good hosts for condensing water molecules, and we call them "**hygroscopic nuclei**".
    b. Particles formed by sulfuric and nitric acid pollutants, soot particles, and other things like that help make haze in polluted cities because they attract water that might not otherwise condense, they are hygroscopic nuclei.
    c. Salt is a great hygroscopic nuclei.



        - i) Indeed, water vapor will start condensing on salt particles at a relative humidity as low as 75%. [This is why salt shaker salt clumps up]

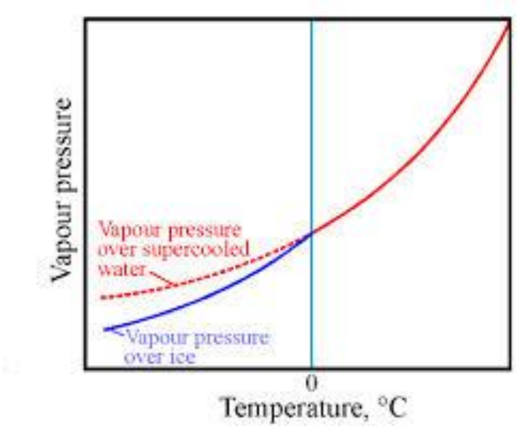
3) Condensation particles start off as small cloud droplets, and these small particles fall only very, very slowly, relative to still air.
    a. But collisions amongst these droplets can result in larger, faster-falling drops, and larger drops falling through a group of smaller particles may grow by accreting these droplets. They coalesce.
    b. This is the collision coalescence or warm rain process. Warm rain means it does not involve ice.

4) Liquid water may not, and often does not, freeze right away.
    a. The reason is at subfreezing temperatures, tiny ice crystals try to form, but they’re fragile and often rapidly disintegrate.
        i) In fact, pure undisturbed water can resist freezing all the way down to a temperature of about -40°C, or -40°F.
        ii) At the temperature, homogeneous nucleation or spontaneous freezing occurs.
    b. But at higher temperatures, water needs a helper particle to freeze, what we call and “**ice nucleus**”, and water is much more selective with regard to ice nuclei than it is with condensation nuclei.
        i) The best ice nuclei are particles that are structured like ice, such as ice itself.



        ii) Ice nuclei are not as common as one might expect, especially in the region of the cloud between temperatures of 0°C and -15°C, or 32°F and 5°F.
        iii) Due to a lack of ice nuclei and the selectivity and slowness of the freezing process, liquid water drops can persist in subfreezing temperatures, and we call this “**supercool liquid**”. [Note that supercool liquid can freeze on contact with aircraft wings and other parts, impairing it’s flightworthiness].
    c. The Bergeron process for precipitation production is based on the fact that ice crystals will grow rapidly at the expense of supercool drops, once they manage to form.

        i) The saturation vapor pressure over ice is smaller than that over water, allowing ice to survive in conditions that would cause liquid water to disappear.



        ii) In a nut shell, ice out-competes liquid in subfreezing temperatures, but it starts with a disadvantage ---a lack of ice nuclei to kick start the process. [This is particularly true in the dead zone between 5°F and 32°F, where ice nuclei are rare].
        iii) Cloud seeding is an attempt to supply the missing ice nuclei.
    d. The first attempts at cloud seeding used dry ice, frozen carbon dioxide.
        i) Dry ice is extremely cold, -78°C, -104°F. This causes liquid to freeze spontaneously, to homogeneously nucleate.
    e. An atmospheric scientist named Bernard Vonnegut experimented with silver iodide as a cloud seeding agent.
        i) Silver iodide has a crystal structure resembling ice and thus promotes the formation of more ice.

H. Summary:
  1. Warm air can hold much more water vapor than cold air.
  2. We can express this as a vapor capacity, VC, telling us how many grams of water vapor we can get into every kilogram of air.
  3. Actual vapor content, also in grams per kilogram, is vapor supply, VS, and relative humidity is the ratio of the 2.
  4. As the temperature of vapor rises, water is more able to resist bonding with its brethren on collision.
  5. That doesn't change the fact that the vapor capacity of warm air is enormous,
      a. At 100°F air can contain 12X more vapor than air at freezing, although it usually doesn't.

6. So vapor capacity is a very strong function of temperature, and air temperature is very easy to change by adding or subtracting heat, or by compressing or expanding air.
7. For a fixed vapor content, relative humidity will rise as the temperature falls, so dew and fog are most likely to occur around sunrise, when the air is typically coolest.
    a. We can make clouds through lifting air because that causes expansion cooling.
    b. Forcing air to descend, on the other hand, is a great way to make air hot, as well as relatively very dry.
8. The air carried by the Santa Ana winds mar start our cool and even relatively moist in Nevada, but by the time it drops to sea level, it's a completely different story.
9. Both condensation and freezing processes need a nucleus, a surface to star on.
    a. Condensation nuclei are abundant.
    b. Ice nuclei are much more scarce, leading to the existence of supercool liquid in clouds, with temperatures below freezing.
    c. Liquid water is still present, owing to a lack of ice nuclei, until an airplane flies through, the mother of all ice nuclei.
    d. Cloud seeding is an attempt to augment the natural lack of these nuclei.

I. Questions:
    1. Santa Ana winds represent a fire hazard, in large part because they're dry. The air stars off in the desert, where it is not only cool, but it may be relatively moist as well. So, why do they end up hot and dry?

    2. Why does rising air lead to clouds?

    3. Once clouds form, does this change the behavior of how air changes on ascent?

    4. What is the difference between vapor capacity and vapor supply?

5. What is relative humidity and how is it calculated?

6. What has more water vapor, A foggy winter day in Utah or a hot summer day in Death Valley? Explain.

7. Why is it better to shock your friend with static electricity in the Winter-time verses the Summer-time?

8. True or false: Water vapor can condense to liquid in sub-saturated air. Why?

9. In the premier episode of the TV series “Star Trek: Voyager”, a powerful entity said he performed an experiment on a populated planet that inadvertently rendered it a desert. His experiment removed all particles from the planet’s atmosphere that permitted water vapor to condense upon them, permanently ending the possibility of rainfall on the planet. Does this scenario make sense?

10. Explain the Bergeron process for both rain and ice?