Tuesday AM, Explain: Water, Clouds, Latent Heat

TUESDAY: air & water & clouds

Water, Phase Changes, Clouds

- How can freezing make something warmer?
- 'warm air can hold more water' – why?
- How do clouds form?

The (extraordinary) properties of Water

- Physical States (Water Vapor, Liquid Water, Water Ice):
  - only substance that occurs naturally in all of its three phases on the earth's surface
- Heat Capacity:
  - highest of all common liquids and solids
- Surface Tension:
  - highest of all common liquids
- Latent Heat of Fusion (melting):
  - highest of all common substances
- Virtually incompressible as a liquid

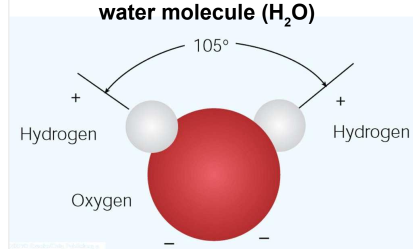
More (extraordinary) properties of Water

- At +4°C water when warmed OR cooled will expand! → solid phase has lower density than liquid at +4°C!
- Radiative Properties:
  - transparent to visible wavelengths
  - virtually opaque to many infrared wavelengths
  - Large possible range of albedo:

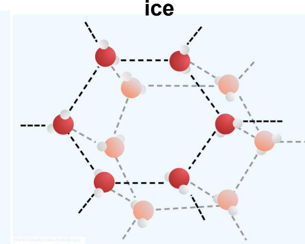
Liquid water	10% (daily average)
Ice	30 to 40%
Snow	20 to 95%
Cloud	30 to 90%

Molecular Structure of Water

water molecule (H_2O)



ice



- Water's unique molecular structure and hydrogen bonds enable all three phases to exist in earth's atmosphere
- Liquid water is associated with transient, ice with more permanent bonds between water molecules
- Energy needs to be added to overcome bonds

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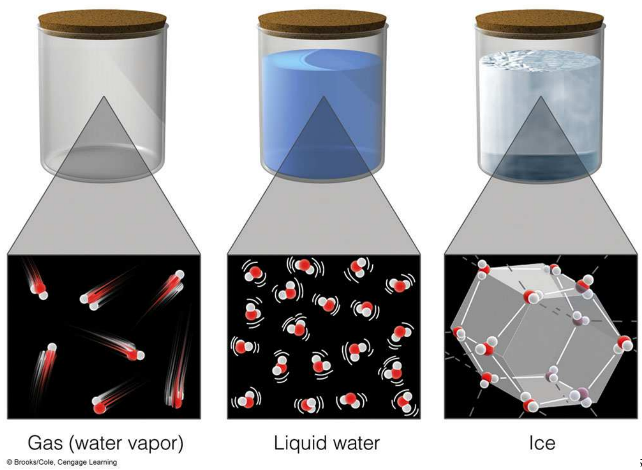

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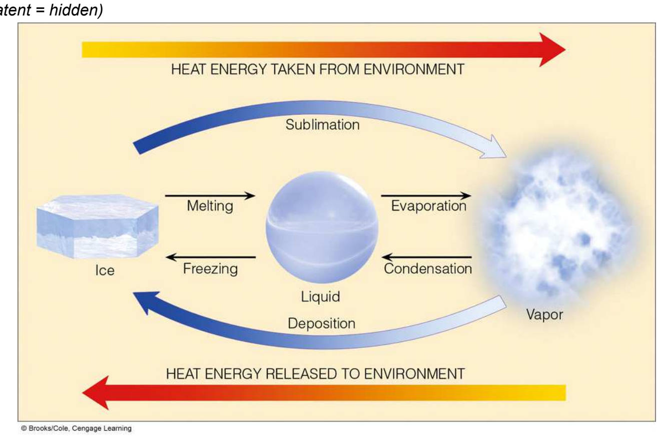
Latent heat due to water phase changes

(latent = hidden)



When water vapor condenses to form clouds, the surrounding air is heated.

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Latent Heat due to Water Phase Changes

- Energy is required to break bonds between molecules of H_2O in solid ice
- Adding energy to ice causes molecules to vibrate faster in the crystal structure
- Adding enough molecular energy overcomes crystal bonds, releasing the molecules as liquid
- When water freezes into ice, this “hidden” (latent) energy is released as sensible heat
- Even more energy is released when water vapor (gas) condenses to form liquid water!

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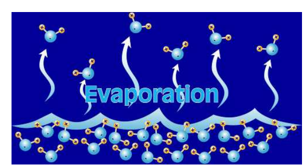
Evaporation vs Condensation

- **Evaporation cools:** (heat) energy is needed to break up bonds between molecules (similar for sublimation)
- **Condensation warms:** (heat) energy / internal energy from freely moving molecules is released as molecules bond with each other (similar for deposition)



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Sublimation: evaporation of ice directly to water vapor

- Take one gram of ice at zero degrees Celcius
- Energy required to change the phase of one gram of ice to water vapor:
  - Add 80 calories to melt ice
  - Add 100 calories to heat up to 100 C
  - Add 540 calories to evaporate the liquid
- Total energy ADDED for sublimation of 1 gram of ice:
  - **80 + 100 + 540 = 720 calories!**

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Deposition: convert water vapor directly to ice

- Take one gram of water vapor at 100 degrees C
  - Release 540 calories to condense
  - Release 100 calories to cool down to 0 C
  - Release 80 calories to freeze water
- Total energy RELEASED for deposition of 1 gram of ice:
  - **80 + 100 + 540 = 720 calories!**

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Water Vapor Pressure

- Molecules in an air parcel all contribute to pressure
- Each subset of molecules (e.g. N_2, O_2, H_2O) exerts a partial pressure
- The vapor pressure, e, is the (partial) pressure exerted by water vapor molecules in the air
  - similar to atmospheric pressure, but due only to the water vapor molecules
  - often expressed in millibar (mb): 2-30 mb common at the surface (compare to total surface pressure of 1000 mb)

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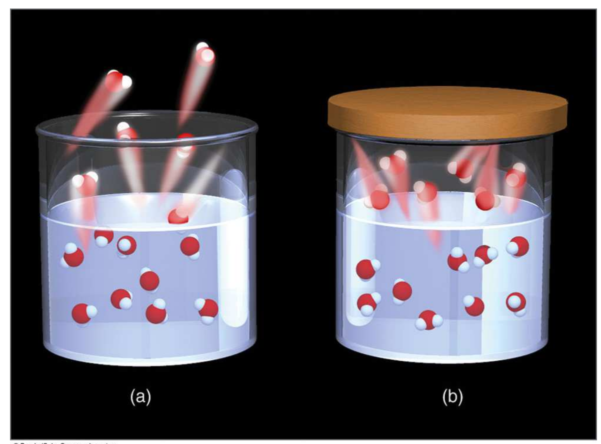
Saturation Vapor Pressure (1)



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Tuesday AM, Explain: Water, Clouds, Latent Heat

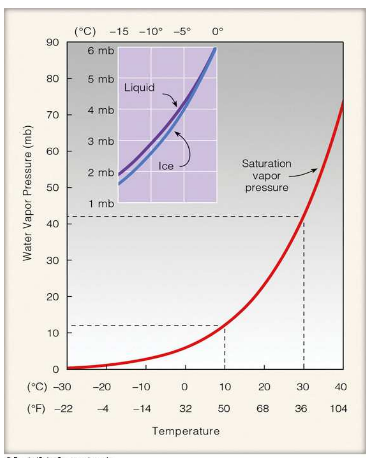
Saturation Vapor Pressure (2)

- Water molecules over a surface of water will jump back and forth from vapor to liquid form
- If you put a lid on and close the container to the outside air, an equilibrium will eventually be reached where as many molecules evaporate from the liquid than condense on the liquid → saturation
- At this equilibrium the water vapor pressure becomes the saturation vapor pressure, which gives a measure of the water vapor content of the saturated air

Saturation Vapor Pressure (3)

- At higher temperature, molecules are more energetic and more can escape from water to air. The saturation vapor pressure is consequently higher for higher temperatures (hence the expression, sometimes used, "warmer air can hold more water")
- The saturation vapor pressure over a surface of water is a strong function of temperature.
- Saturation vapor pressure varies as a function of solute in the water, including salt: the saturation vapor pressure over the salty ocean is lower than over pure water. This also affects cloud formation.

Saturation Vapor Pressure (4)



- As temperature goes up, saturation vapor pressure goes up strongly
- Saturation vapor pressure: contribution due to water vapor to total air pressure; gives an indication of the maximum amount of water vapor that can exist in the air at equilibrium
- This curve is the basis for the so-called "water vapor feedback" as is often discussed with global climate change

Saturation Vapor Pressure (5)

- Winds are able to ventilate the surface drawing water vapor away, hence increasing the rate of evaporation from the water surface.
- In nature the two dominant factors controlling evaporation are 1) the degree of sub-saturation of the air above the water surface, and 2) the wind speed.

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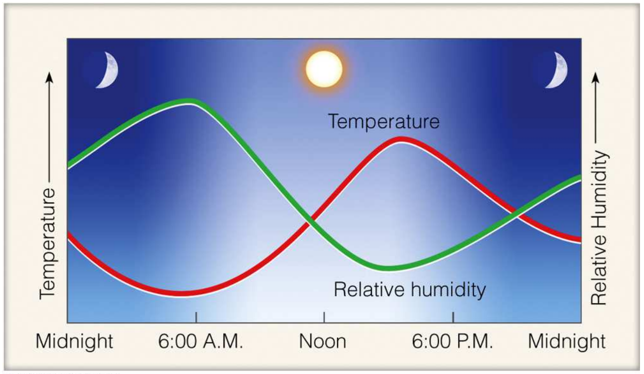
How do we express the amount of water vapor in an air parcel?

- Absolute humidity
  - mass of water vapor in a given volume of air (g/m^3)
  - *changes when air parcel volume changes*
- Specific humidity (*most widely used in atmospheric science*)
  - mass of water vapor per mass of air (g/kg)
- Mixing ratio
  - mass of water vapor per mass of dry air (g/kg)
- specific humidity & mixing ratio do not change as long as no phase change takes place, i.e. as long as no water vapor is added/removed to/from the air parcel
- Dew point temperature

Relative Humidity (RH)

- RH = water vapor content / water vapor capacity
- Relative Humidity is the ratio of actual (water) vapor pressure (e) to the saturation vapor pressure (e_s):
  - (in percent) 100 * e / e_s
  - range: 0–100%, but ... > 100% does exist
  - air with RH > 100% is said to be supersaturated
  - air with RH < 100% is said to be subsaturated
- RH can be changed by:
  - changes in water vapor content, e
  - changes in temperature, which alters e_s

RH might change during the day, even though the actual water vapor content remains the same



- At 6 am, saturation vapor pressure is close to actual water vapor content (vapor pressure).
- At 3 pm, actual water vapor content hasn't changed, but the saturation vapor pressure has risen. Therefore, relative humidity is lower.

Dewpoint Temperatures

How to find the dewpoint:

- Decrease air temperature without changing it's water vapor content
- When you have lowered the temperature enough to reach saturation, you have reached the dewpoint temperature
- Relative humidity is 100% by definition at the dewpoint
- Dewpoint is a measure of the water vapor content of the air
- It is not a measure of the air's temperature!

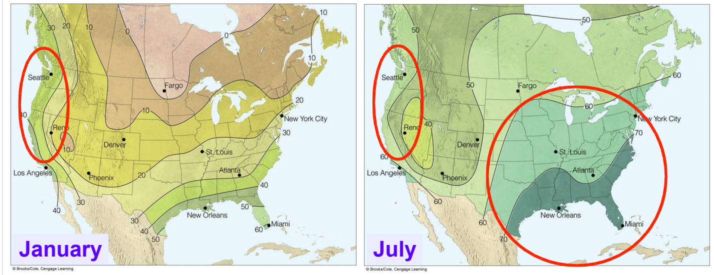
Dew

On cloudless, calm nights, temperature of the surface and near surface air can drop to the dewpoint temperature.

This corresponds to RH = 100% → condensation.

Hence the term *dew*point.

Dewpoint Temperatures



- West coast U.S. has higher water vapor content and dewpoint in summer than in winter, but highest humidity in winter when it's "always" raining
- Greatest dewpoints occur in eastern U.S. during summer, sometimes approaching 85 F!

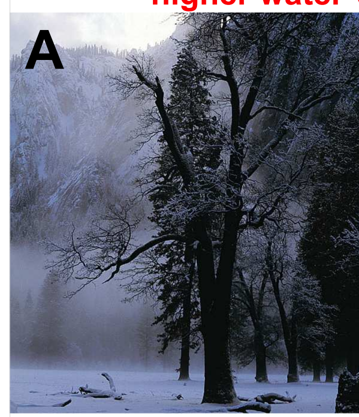
Frost

On cloudless, calm nights, temperature of the surface and near surface air can drop to the dewpoint temperature.

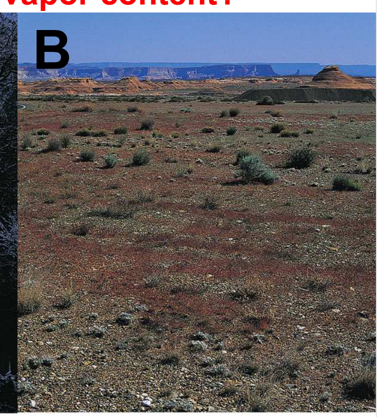
If this temperature is below freezing, frost forms.

The dewpoint in this case is called "*frost*point".

Which environment has the higher water vapor content?



(a) POLAR AIR: Air temperature –2°C (28°F)
Dew point –2°C (28°F)
Relative humidity 100 percent



(b) DESERT AIR: Air temperature 35°C (95°F)
Dew point 10°C (50°F)
Relative humidity 21 percent

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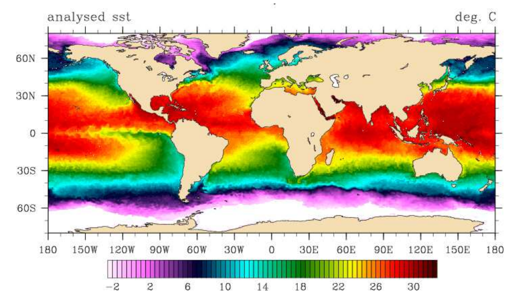
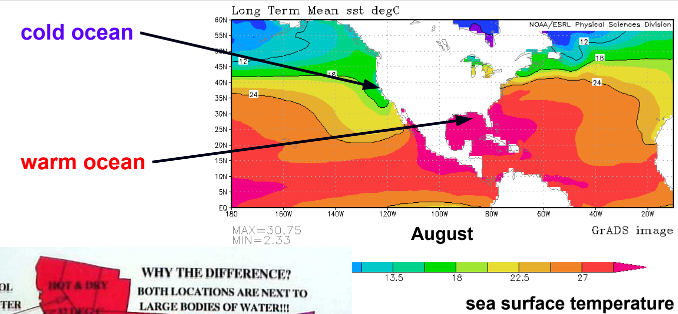
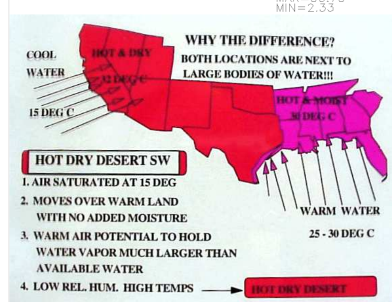
Why is the southwest coast of the U.S. hot and dry while the gulf coast is hot and moist?

- Both are adjacent to large bodies of water
- Both experience onshore wind flow on a regular basis
- Why does one have a desert-like climate and the other ample moisture and rainfall?







Humidity over Land reflects offshore Ocean Temperatures

Condensation & Cloud Drop Formation

- Condensation = phase transition from water vapor → liquid water phase
- Water does not easily condense without a surface present
  - Vegetation, soil, buildings provide surface for dew and frost formation
  - Particles act as sites for cloud & fog drop formation

Cloud & Fog Drop Formation

- If the air temperature cools below the dew point (RH > 100%), water vapor will tend to condense and form cloud/fog drops
- Fog is essentially a cloud that forms with its base touching the ground
- 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

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Typical Sizes:

Cloud Condensation Nuclei (CCN)

- Not all atmospheric particles are CCN
- Good CCN are hygroscopic (they “like” water)
- Many hygroscopic salt and acid particles are found in the atmosphere:
  - Natural CCN (e.g. sea salt, vegetation burning)
  - CCN from human activity (e.g. pollutants)
- The solute effect:
  - Condensation of water on soluble CCN dissolves particle
  - Solute particles at drop surface displace water molecules → reduce likelihood of water molecules escaping to vapor
  - Reduce saturation vapor pressure from value for pure water drop

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Clouds

- Clouds result when air gets saturated (RH = 100%) away from the ground (rising air expands and cools)
- Clouds can:
  - be thick or thin, large or small
  - contain water drops and/or ice crystals
  - form high or low in the troposphere
  - even form in the stratosphere (crucial for the ozone hole), and even^2 form in the mesosphere, 80 km above ground!
- Clouds impact the environment in many ways
  - Radiative balance, water cycle, pollutant processing, earth-atmosphere charge balance, ...

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Cloud Classification

- Clouds are traditionally identified by the World Meteorological Organization's International Clouds Atlas. Weather observers throughout the world use the same classification (10 principal cloud forms).
- Latin root words are the basis for the descriptive scheme:
  - Cumulus = heap or pile
  - Stratus = to flatten out or cover with a layer
  - Cirrus = curl of hair or tuft of horse hair
  - Nimbus = precipitating
  - Altum = height

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Cloud Classification

- Clouds are categorized by their height, appearance, and vertical development:
  - High Clouds → generally above 16,000 ft (~ 5 km) at middle latitudes
    - **Cirrus, Cirrostratus, Cirrocumulus**
  - Middle Clouds → 7,000 to 23,000 ft (2–7 km)
    - **Altostratus, Altocumulus**
  - Low Clouds → below 7,000 ft (2 km)
    - **Stratus, Stratocumulus, Nimbostratus**
  - Vertically developed clouds (via convection)
    - **Cumulus, Cumulonimbus**

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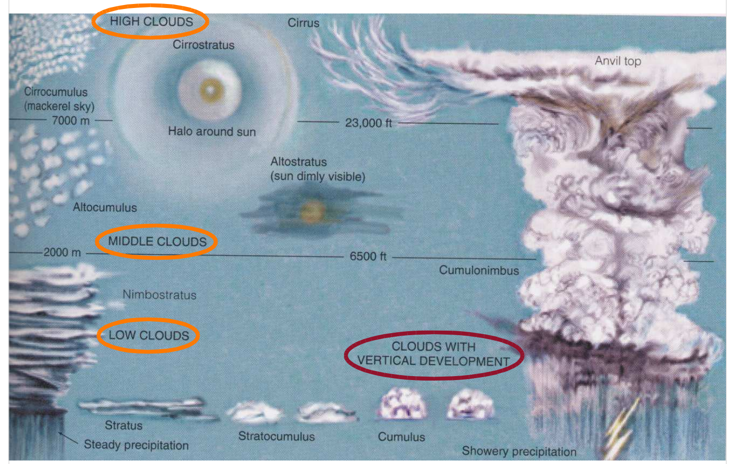
Cloud Type Summary



High Clouds

- White during the day, red/orange/yellow at sunrise and sunset, made of ice crystals
- Cirrus: thin and wispy, move west to east, indicate fair weather
- Cirrocumulus: less common than cirrus, small rounded white puffs individually or in long rows
- Cirrostratus: thin and sheet like, sun and moon clearly visible through them, Halo common, often precede precipitation

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Cirrus Display at Dawn

Cirrocumulus

at sunset

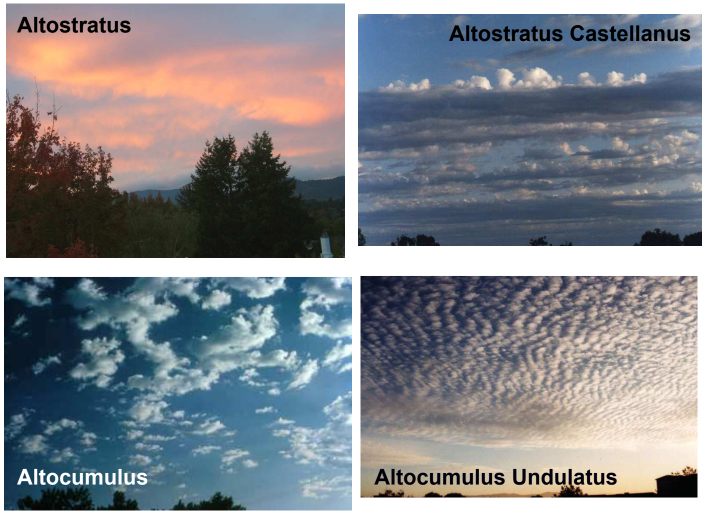
Cirrostratus (with Halo)

Con*(densation)*trails

Middle Clouds

- Altocumulus:
  - less than 1 km thick
  - mostly water drops
  - gray, puffy
  - differences from cirrocumulus: larger puffs, more dark/light contrast

- Altostratus:
  - gray, blue-gray
  - often covers entire sky
  - sun or moon may show through dimly (usually no shadows)



Low Clouds

- Stratus:
  - uniform, gray
  - resembles fog that does not reach the ground
  - usually no precipitation, but light mist/drizzle possible
- Stratocumulus:
  - low lumpy clouds
  - breaks (usually) between cloud elements
  - lower base and larger elements than altostratus
- Nimbostratus:
  - dark gray
  - continuous light to moderate rain or snow
  - evaporating rain below can form *stratus fractus*

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Looking down on an Eastern Atlantic Stratus Deck

Strato-cumulus

Stratus Fractus

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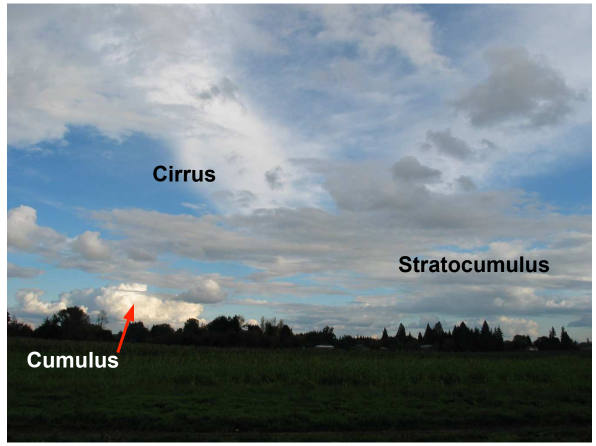
Vertically Developed Clouds

- Cumulus:
  - puffy "cotton"
  - flat base, rounded top
  - more space between cloud elements than stratocumulus
- Cumulonimbus:
  - thunderstorm cloud
  - very tall, often reaching close to tropopause
  - individual or grouped
  - large energy release from water vapor condensation

Cumulonimbus

Often the sky is fairly complex



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Unusual Clouds

- Lenticular Clouds: clouds forced by flow over topography
- Pileus: similar to lenticular clouds, but forced by flow over a thunderstorm top
- Mammatus: baglike sacks that form underneath cumulonimbus tops or underneath other clouds
- Polar Stratospheric Clouds: cirrus-like (ice) clouds that can form in the stratosphere during polar night
- Noctilucent Clouds: highest clouds on earth, ice clouds ~ 80 km above ground!

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Pileus Clouds

Mammatus Clouds

Noctilucent Clouds

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