## Forming clouds

- Clouds form when the air becomes supersaturated with respect to water (or ice)
- Size of cloud droplets is usually <10microns
- Precipitation (raindrops, ice crystals) are larger (> 1000 microns- 1 millimeter)
- Usually occurs due to adiabatic cooling produced by ascent
- Can also occur due to
  - Radiational cooling (e.g., radiation fogs)
  - Sensible cooling (e.g., advection fogs)
  - Mixing (e.g., contrails)
  - Other processes that cool or moisten parcels
- The formation of a cloud droplet is called *nucleation*

## Dalton's law of partial pressures

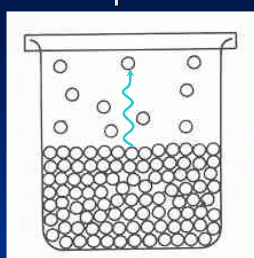
- The total pressure exerted by a mixture of gases equals the sum of the partial pressure of the gases

$$p = p_{O_2} + p_{N_2} + e$$

$$e = p_{H_2O}\ (vapor\_pressure)$$

- *Partial pressure* – pressure a gas would exert if it alone occupied the volume the entire mixture occupies
- Meteorologists differentiate between "dry" gas partial pressure and water vapor partial pressure (vapor pressure) $p = p_d + e$ $e \ll p, p_d$

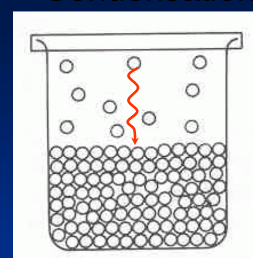
## Evaporation



Bohren (1987)

- Water molecules moving from liquid to vapor phase
- Accompanied by latent cooling (heat removed)
- *Always* occurring

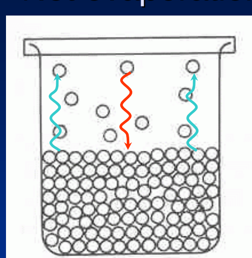
## Condensation



Bohren (1987)

- Water molecules moving from vapor to liquid phase
- Accompanied by latent heating (heat released)
- *Always* occurring

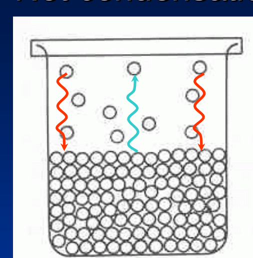
## Net evaporation



Bohren (1987)

- What we commonly refer to as evaporation is when the rate of evaporation exceeds the rate of condensation

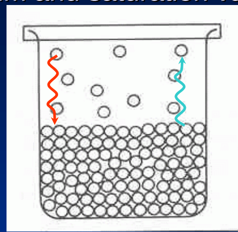
## Net condensation



Bohren (1987)

- What we commonly refer to as condensation is when the rate of condensation exceeds the rate of evaporation

## Equilibrium and saturation vapor pressure

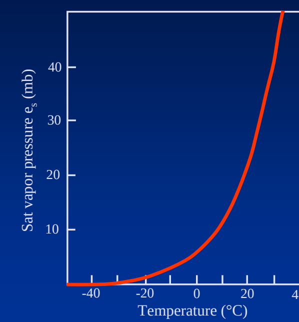


Bohren (1987)

- *Equilibrium vapor pressure* – evaporation and condensation are occurring, but are in equilibrium
- *Saturation vapor pressure* – equilibrium vapor pressure for a plane surface of pure water
- For solutions and cloud droplets, equilibrium vapor pressure does not necessarily equal the saturation vapor pressure

## Saturation vapor pressure

- Varies strongly with temperature




Wallace and Hobbs (1977)

## Mixing ratio

- Measure of the amount of water vapor in the air
- Ratio of mass of water vapor to the mass of dry air in a volume of air

$$w \equiv m_v / m_d$$

- Units g/kg
- Typical values
  - Midlatitude winter = 1-5 g/kg
  - Midlatitude summer = 5-15 g/kg
  - Tropics = 15-20 g/kg
- Doesn't change (conserved) following parcel motion if there is no net condensation/evaporation

## Saturation mixing ratio

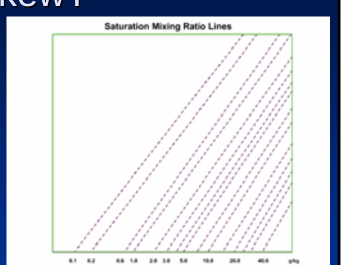
- The ratio of the mass ($m_{vs}$) of water vapor in a given volume of air that is saturated with respect to a plane surface of pure water to the mass ($m_d$) of dry air

$$w_s = \frac{m_{vs}}{m_d}$$

- Depends strongly on temperature, not on actual water content in air

## SkewT

- Saturation mixing ratio lines represent constant values of water vapor capacity.
- They are labeled at the bottom of the diagram for a range of 0.1 to 40.0 grams per kilogram; i.e., in parts of water vapor per 1000 parts of dry air.
- Depending on which temperature is used, then the actual or satuation mixing ratio can be determined
  - T -> $w_s$
  - $T_d$ -> w




## Relative humidity, dewpoint, supersaturation

- *Relative humidity* (with respect to water) - the ratio (%) of the actual mixing ratio to the saturation mixing ratio at the same temperature and pressure

$$RH \equiv 100 \frac{w}{w_s}$$

- *Dewpoint* - the temperature to which air must be cooled at constant pressure for it to become saturated with respect to a plane surface of pure water
- *Supersaturation* = RH-100; volume of air may contain more water vapor than would be expected over a plane surface of pure water

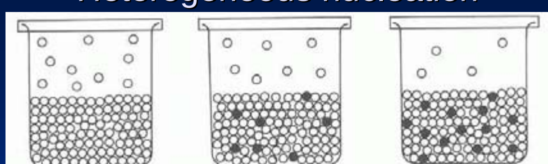
## Homogeneous nucleation

- *Homogeneous nucleation*: Formation of a *pure* water droplet by condensation without the aid of a particle suspended in the air
- Hard to do
  - Growth of a cloud droplet represents a battle between
  - Work required to create more droplet surface area and energy provided to the system by condensation

## Heterogeneous nucleation

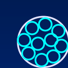
- How do clouds form?
  - They get help: Heterogeneous nucleation
- *Heterogeneous nucleation*: Formation of a cloud droplet on an atmospheric aerosol
- Atmospheric aerosols that are soluble in water dissolve when water begins to condense on them
- The solution lowers the equilibrium vapor pressure & creates more favorable conditions for droplet growth

## Heterogeneous nucleation

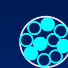


- In a solution, there are fewer water molecules on the water surface available for evaporation
- Evaporation rate is lower than for pure water
- Equil. saturation vapor pressure is *lower* than for pure water

## Heterogeneous nucleation



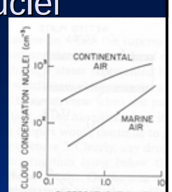
Small pure water droplet
Surface is all water molecules
Largest possible evaporation rate
Maximum equilibrium vapor pressure



Small solution droplet
Surface has fewer water molecules
Less evaporation
Smaller equilibrium vapor pressure

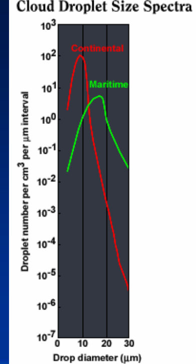
## Cloud condensation nuclei

- *Cloud condensation nuclei (CCN)* – Aerosol which serve as nuclei for water vapor condensation
- The larger and more soluble the aerosol, the lower the supersaturation needed for activation
- There is an order of magnitude more CCN in continental air than maritime air




Wallace and Hobbs (1977)

**Cloud Droplet Size Spectra**

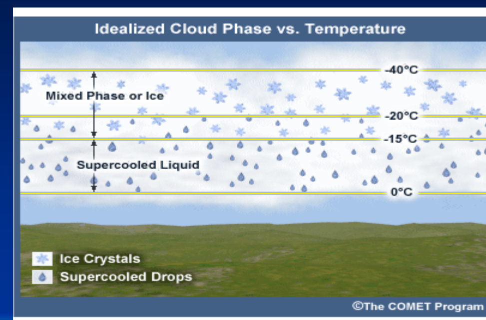



- Maritime clouds feature
  - Larger cloud droplets
  - Lower cloud droplet number concentrations
- Continental clouds feature
  - Smaller cloud droplets
  - Higher cloud droplet concentrations

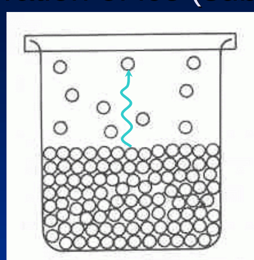
COMET

## Microphysics of cold clouds

- *Cold cloud* – a cloud that extends above the 0°C level
- Water does not necessarily freeze at 0°C
- *Supercooled cloud droplets* – Cloud drops that exist at temperatures below 0°C
- *Mixed cloud* – A cloud consisting of both ice particles and supercooled cloud droplets
- *Glaciated cloud* – A cloud consisting entirely of ice



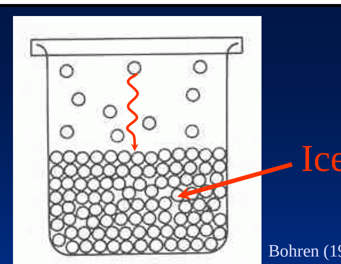

## Evaporation of ice (sublimation)



Bohren (1987)

- *Sublimation* occurs when water molecules move directly from ice to vapor phase (no liquid phase)
- Accompanied by latent cooling (heat removed)
- *Always* occurring

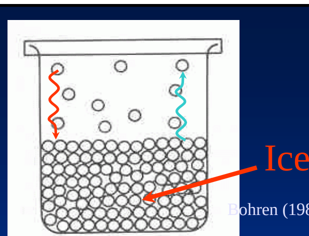
## Vapor deposition




Bohren (1987)

- Water molecules move directly from vapor to ice phase
- Accompanied by latent heating
- *Always* occurring
- Also called deposition

## Equilibrium and saturation vapor pressure for ice

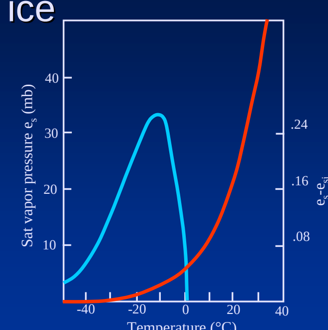



Bohren (1987)

- *Equilibrium vapor pressure for ice* – sublimation and deposition are occurring, but are in equilibrium
- *Saturation vapor pressure for ice* – Equilibrium vapor pressure for a plane surface of pure ice
- For solutions and ice particles, equilibrium vapor pressure for ice does not necessarily equal the saturation vapor pressure for ice

## Saturation vapor pressure for ice

- The saturation vapor pressure for ice is ≤ that for water
  - $e_{si}=e_s$ at 0°C
  - Otherwise $e_{si}<e_s$
  - $e_s$-$e_{si}$ is largest at –10°C to –15°C




Wallace and Hobbs (1977)

## Frost Point

*Frost point* - the temperature to which air must be cooled at constant pressure for it to become saturated with respect to a plane surface of pure ice

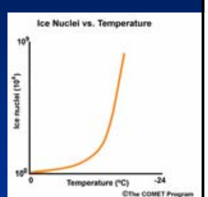
- Frost point > dewpoint (equal at 0°C)
- Reach frost point before dewpoint
- Easier to become saturated wrt ice than wrt water

## Homogeneous ice nucleation

- *Homogeneous nucleation* – freezing of a water droplet that contains no foreign particles
- Hard to do
  - Ice embryo must exceed a critical size to allow entire droplet to freeze
  - If critical size is not reached, ice embryo breaks up and cloud droplet does not freeze
  - Number and sizes of embryos increases with decreasing temperature
- Homogeneous nucleation occurs
  - ~ -36°C for droplets between 20 and 60 microns in radius
  - ~ -39°C for droplets smaller than 20 microns in radius
  - At –40°C, water is usually frozen

## Heterogeneous nucleation

- *Heterogeneous nucleation* – Freezing of a droplet that contains a foreign particle known as a freezing nucleus
- Analogous to cloud droplet formation, freezing nucleus allows water to freeze by decreasing the energy needed to move from the water to ice phase
- Allows droplets to freeze at higher temperatures than homogeneous nucleation (but not necessarily 0°C)




## Ice multiplication

- There are relatively few ice nuclei in clouds compared to the number of ice particles
- How do we get large numbers of ice particles?
  - Ice multiplication – creation of large numbers of ice particles through
    - Mechanical fracturing of ice crystals during evaporation
    - Shattering of large drops during freezing
    - Splintering of ice during riming