Ingredients needed for clouds formation

Water vapor
Cooling: cools air to reach saturation for condensation to occur
Cloud condensation nuclei (CCN)

1. Water in the atmosphere

1) Three states of water
   a) Liquid (droplets): some broken bonds
   b) Solid (ice crystals): Almost no bonds
   c) Gas (vapor): All bonds are broken. Vapor is invisible!
   Note: clouds are made of water droplets or/and ice crystals
2) Change in temperature and energy between different states
   a) Latent heat: energy required to break molecular bonds.
      Exchange of latent heat happens only when state changes.
      Note: Latent heat powers thunderstorms
   b) Evaporation: liquid water $\rightarrow$ water vapor
      e.g. sweat. Latent heat is needed, cooling
   c) Condensation: water vapor $\rightarrow$ liquid water
      e.g. formation of cloud droplets, latent heat is released, warming
      e.g. warm air contacts cold drink bottle, latent heat warms the drink
      Condensation occurs when the air parcel is <u>saturated</u>

2. Saturation, relative humidity, dew point

1) Saturation (at equilibrium)
   a) both liquid water and vapor exist
   b) evaporation and condensation are in balance
   An air parcel is saturated when:
      its vapor pressure exceeds its saturation vapor pressure;
      Or, its relative humidity becomes greater than 100%;
      Or, its temperature reaches dew point
2) Measures of humidity
   a) Relative humidity (in %)
      - It is the ratio of actual <u>vapor pressure</u> to <u>saturation vapor pressure</u>
      - Conceptually it's the ratio of <u>water vapor content</u> to <u>water vapor capacity</u>
      - It tells you how close the air is to saturation
      - It depends on both the amount of water vapor and temperature
      - RH decreases as temperature increases if water content is fixed

      <u>Vapor pressure</u>: The net force per unit area exerted by molecules of water vapor in a parcel of air.

      <u>Saturation vapor pressure</u>: the pressure exerted by water vapor when the air is saturated; depends on temperature only; increases with temperature; it does not tell you the amount of actual water vapor

e.g. For an air parcel, as temperature ↓, saturation vapor pressure ↓, RH↑
Implication: warm saturated air contains more water vapor than cold saturated air.

b) Dew point (in °C or °F)
- It the temperature to which air has to cool down to for condensation to occur
- It tells you what much water vapor molecules the air holds at present
- it depends only on the amount of actual water vapor content

3. Cloud Condensation Nuclei (CCN)

1) Water vapor condenses more easily if there are some larger particles, which can help attract water vapor → cloud condensation nuclei (CCN)
2) Sand, dust, smoke, sea salt... Enough CCN in the air
3) More CCN, thicker clouds (harder to see through)
Example: ship tracks caused by enhanced CCN
Example: Fog thickened by high CCN from pollution
Example: "cloud in the bottle" experiment(match provides particles serving as CCN)

4. Adiabatic cooling and buoyancy

Clouds form when air is cooled to saturation. In many cases, the cooling occurs as the air rises.

1) Why does rising air cool?
   a) atmospheric pressure decreases with height
   b) air parcel expands as it is lifted until the pressure inside the parcel becomes the same as the outside pressure again
   c) air molecules move slower
   d) temperature of the air parcel (proportional to the speed of the molecules) drops
2) <u>Adiabatic</u> means no heat is added or removed from rising air parcel
3) Example: Fair-weather cumulus
   a) Clouds form as the air is lifted (due to solar heating) and cools
   b) Puffy but flat bottom, condensation start to occur at the same elevation
   c) Height of the cloud base shows us the distance low-level air must be lifted to cool to its dew point.
   d) Air motion below clouds
      Rising air: Heating of the ground by the sun, surface air gets warmed
      Warmer → less dense →positive buoyancy →rising
      Sinking air: colder →more dense →negative buoyancy →sinking
      No clouds in descending air
4) Buoyancy & Density
   Less dense than surrounding →positive buoyant (e.g. hot air balloon)
   Denser than surrounding →negative buoyant (e.g. steel duck)
5) Density & Temperature (why warm air is less dense and rise?)

Gas law: $P = \rho R T$. [P is pressure, ρ is density, T is temperature, R is a constant]

Pressure is proportional to density x temperature

When pressure of an air parcel matches that of the surrounding air, the air parcel is:

warmer than the surrounding → less dense →positive buoyant →rising

colder than the surrounding →more dense →negative buoyant →sinking

Sum up: A story for a rising air parcel

An air parcel rises when it is lighter than the surrounding air

A rising air parcel expands and cools down

The cooling from expansion alone will push the parcel back down

If the parcel contains enough moisture, the latent heat from condensation counteracts the cooling

5. Cloud shapes and stability

The shape of clouds dependents on the atmospheric stability

1) How does temperature changes with height?

   Lapse rate is the rate at which temperature drops with height. Three types:

   Environmental (or background) lapse rate: how fast the background air temperature drops with height (varies depending on where you are)

   Dry adiabatic lapse rate: how fast temperature drops in an air parcel as it is adiabatically raised up without condensation (always 10°C /km)

   Moist adiabatic lapse rate: how fast temperature drops in a saturated air parcel as it is adiabatically raised up (varies depending on the amount of water vapor, less than 10 °C /km because of latent heat release) [NO fixed value for moist adiabatic lapse rate. It is a function of temperature]

2) How to assess atmospheric stability?

   Compare the temperature of air parcel to the temperature of environment.

   a) Environmental lapse rate varies depending on where you are
   b) The temperature of a dry air parcel (without condensation) changes always following dry adiabatic lapse rate (10 °C/km)
   c) The temperature of a saturated air parcel (with condensation) changes always following moist adiabatic lapse rate

   Three cases:

   Stable

   If environmental lapse rate < dry adiabatic lapse rate

   When the parcel is pushed up a bit, it becomes slightly colder than its surroundings, so it sinks back down (and oscillates about its original position).

   Example: stratosphere; stratus form clouds in stable air

   Example: Thunderstorms stop rising when reaches the stratosphere(why?)

   Unstable:

   If environmental lapse rate > dry adiabatic lapse rate

When the parcel is pushed up a bit, it becomes slightly warmer than its surroundings and continues to rise. Then it becomes even warmer than its surroundings and rising even faster.

Example: cumulus clouds in unstable air

Conditional Unstable:

It means stable for dry air with small vertical displacement, but unstable for saturated/humid air with large vertical movement

Moist adiabatic lapse rate < environmental lapse rate < dry adiabatic lapse rate

Example: Thunderstorms

6. Thunderstorms

1) Ingredients
   a) A suitable lapse rate: conditionally unstable beginning 1 or 2 km above the surface and continuing through a deep layer.
   b) Adequate low-level moisture
      i.e. high RH and high dew point
   c) Trigger that lifts the low-level air (overcome CIN)
      e.g. surface heating; lifting at a front; lifting air over mountains

   Note: (a) and (b) determines CAPE and CIN
   - CAPE: the total energy that can be released by an air parcel
   - CIN: The cap that allows lots of CAPE to build up until conditions are ripe for a thunderstorm.
2) Kinds of thunderstorms
   a) Single cell ("air mass") – generates lightning, rain, downburst
   b) Multi-cell - seldom makes tornadoes
   c) Supercell - long-lived, often severe, associated with most strong tornadoes
   - Type of thunderstorm is determined by CAPE and the low-level wind shear

   Note: in Midterm 1, we will only focus on single cell
3) Single cell life cycle
   a) Towering cumulus stage
      Updraft: rising air cools to saturation, cumulus forms, upward growth
   b) Mature stage
      i. Both updrafts and downdrafts
      ii. Lightning, rain and thunder
      iii. What produced downdrafts?
         - Aerodynamic drag from falling precipitation (minor)
         - The entrainment of dry air through the sides of the cloud (re-evaporation of clouds cools the air in downdraft)
         - Evaporation of precipitation also cools downdrafts
      iv. Entrainment
         - Entrainment is the mixing of unsaturated air at the edge of the cloud
         - We have ignored this in our previous arguments about hypothetical "air parcels".

    - Cloud droplets evaporates during the entrainment, therefore the mixture cools and has less liquid water

  c) Dissipating stage
    - No updrafts any more. Because the warm moist air supply has been cut off by the spreading cold pool.
    - Rain, thunder and lightning may continue for a while, but the end is near.
    - Downdrafts spreads out along the surface, which creates a cold pool under the thunderstorm.
    - The edge of the spreading cold pool is gust front. Clouds form above the gust front, because warm moist air is forced to rise over the spreading current of cold and dense air
    - Downdrafts and the spreading gust front create microburst (dangerous to aviation)

4) Hazards from single cell
  a) Lightning
  b) Microburst
  c) Flash flood: Very fast; two feet of water can carry away most automobiles

7. Lightning

1) Distribution and frequency
  a) More common over land than over ocean
  b) In US, Florida
2) Electrical charge
  a) Main charging zone (maximum negative charge) occur at temperature of -15 °C
  b) When falling graupel and hail collide with rising ice crystals, graupel and hail become negative, ice crystals become positive
  c) Positive charge (created by ice crystals) accumulates in the top of clouds
  d) Negative charge (by graupel and hail) remain lower in the clouds
3) Thunder
  a) Thunder is caused by the rapid air expansion when air is heated by a lighting stroke
  b) Sound travels much slower than light
4) Red sprites
  a) Occur way above active thunderstorms
  b) Hard to see from the ground
5) A Cloud-to-ground Lightning Event
   Stepped Leader Initiation & Descends Below Cloud Base (showing charges)
   Streamers extend upward from high points on the surface.
   Return stroke caries the main discharge.
   Dart Leader flows down from above along the path of the previous discharge.
6) Lightning Safety
  a) Direct strike (do NOT stay in an open filed)
  b) Side Flash (do NOT shelter under a tall tree)
  c) Ground current (do NOT lie flat on the ground)

d) Conduction (do NOT use cabled electronics and do NOT touch wires or metal)
e) Streamer

8. Raindrops

1) Size and shape of raindrops
   a) 0.5 – 8(?) mm, much bigger than cloud droplets
   b) Spherical or flatten (due to aerodynamic drag)
   c) Large raindrops tend to break up
2) Example: virga
   a) virga is rain but does not reach the ground, because it evaporates while falling through dry air before reaching the ground.
   b) It is more common when the air below cloud has low RH
3) How do raindrops grow?
   a) Condensation (simple, but quite slow)
   b) Collision and coalescence (with other raindrops)
      - Collision: Large droplets may collide with smaller droplets
      - Coalescence: when collisions result in a merger

   Where do the first large drops come from?
      - They start large because the form on large CCN.
      - Turbulent air motions cause similar sized droplets to collide and coalesce into a few larger droplets.

   c) Ice crystal process [not in mid-term1]

Note This document is a short summary of the lectures and does not cover reading material. Midterm 1 covers: Homework 1-3, Lectures until April 24, Reading weeks 1-4