Lecture Ch. 8

- Cloud Classification
  - Descriptive approach to clouds
- Drop Growth and Precipitation Processes
  - Microphysical characterization of clouds
- Complex (i.e. Real) Clouds
  - Examples

Curry and Webster, Ch. 8
Read Ch. 12 next.

Figure 8.1 View of the Earth from satellite.

Clouds on Earth

Stratosphere: occurs because of an abundance of ozone, which absorbs strongly in the ultraviolet wavelengths of the solar spectrum.

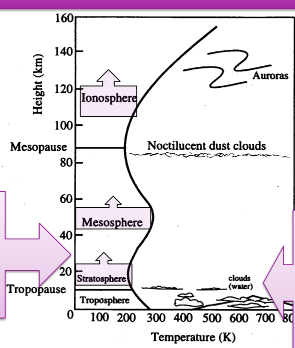
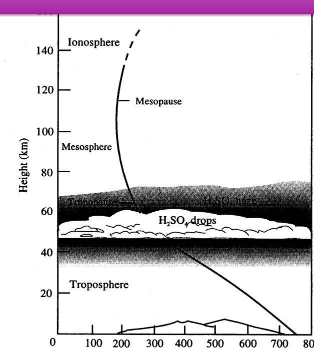


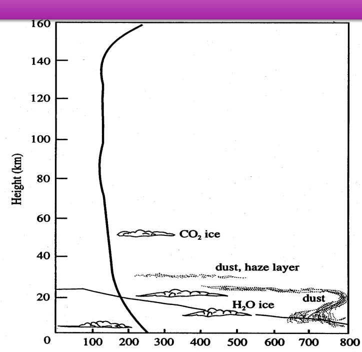
Figure 14.1 Vertical structure and features of Earth's atmosphere

Troposphere: If transparent to solar radiation, then the planetary surface is heated and turbulent fluxes transport heat vertically. If the atmosphere absorbs strongly in the infrared it can also change the vertical temperature profile.

Clouds on Venus



Clouds on Mars



Cloud Classification

Clouds are also distinguished by the heights above ground level at which they form:

1) high clouds whose bases are higher than 6 km in the tropics and 3 km in the polar regions (prefix: *cirro*);
2) middle clouds whose bases lie between 2 and 8 km in the tropics and 2 and 4 km in the polar regions (prefix: *alto*);
3) low clouds whose bases lie below 2 km;
4) clouds of vertical development.

The prefix *nimbo* or the suffix *nimbus* indicates the presence of rain.
... the cloud classification is based on ten main cloud

10 main cloud types

1. Cirrus (Ci)
2. Cirrocumulus (Cc)
3. Cirrostratus (Cs)

All high clouds

4. Altocumulus (Ac)
5. Altostratus (As)

Middle clouds

6. Nimbostratus (Ns)

Grayish, block the sun, sometimes patchy

7. Stratocumulus (Sc)
8. Stratus (St)

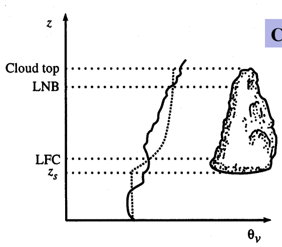
Low clouds

9. Cumulus (Cu)
10. Cumulonimbus (Cb)

Sharp outlines, rising, bright white

Cumulus Clouds

Swelling Cumulus
Active heaped-up cloud with flat bottom and growing cauliflower top. [http://www.fox8wghp.com/spacious.htm]



Cumuliform Clouds

Figure 8.21 Typical temperature profiles in a convective environment. The solid profile represents the environmental temperature; the dashed profile corresponds to the temperature within the cloud. The cloud base forms near the lifting condensation level, z_s. Near the cloud base, the temperature increases more rapidly with height in the cloud than in the surroundings, resulting in a relatively large temperature difference between the environmental temperature and the cloud interior temperature. A cloud that reaches the level of free convection (LFC) will accelerate upwards until it reaches the level of neutral buoyancy (LNB), where the environmental temperature is equal to the interior cloud temperature.

Types of cumulus

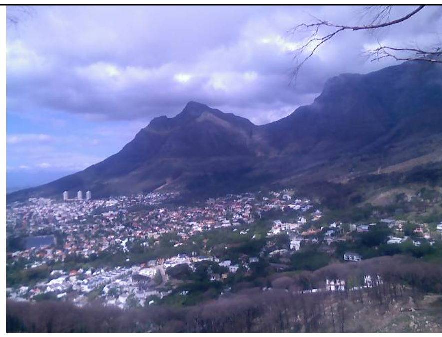
- Fair weather cumulus
  - Horizontal/vertical scale = 1 km
  - No precipitation
- Towering cumulus
  - Horizontal/vertical scale = several km
  - Frequently precipitate
- Cumulonimbus
  - Vertical extension to tropopause with anvil tops
  - Width = 10s of km
  - Heavy precip, lightning, thunder, hail
- Mesoscale convective complex
  - Aggregation of cumulonimbus (100s of km)
  - Large amount of rain
  - Can develop circulation pattern

Cumulonimbus Clouds

Cumulonimbus
Massive cloud system producing heavy showers, sometimes with hail. Most active clouds may have lightning and thunder. A few spawn tornadoes. [http://www.fox8wghp.com/spacious.htm]

Stratus Clouds

Stratus
Low lying layer of cloud (called fog if on the ground) with no structure. [http://www.fox8wghp.com/spacious.htm]



If you are in Cape Town when the Southeaster blows (usually in the summer of the southern hemisphere), you will see a layer of cloud just covering the top of Table Mountain. This is the "tablecloth".

Of course, the phenomenon is also supported by a meteorological explanation. The moisture-laden south-easter blows against Table Mountain from over the False Bay and rises. At a height of approximately 900 meters the winds reach the colder layers of air and thick clouds form. These clouds roll over the mountain and down towards the City Bowl. The characteristic tablecloth forms when the clouds reach the warmer, lower air layers and dissolve once more.

Cirrus Clouds

Cirrus

An ice crystal cloud, wispy in appearance. May produce ice crystal snow in winter or in mountains. [http://www.fox8wghp.com/spacious.htm]

Altostratus Clouds

Altostratus

Thickly layered water droplet cloud. Sun seen as through ground glass. [http://www.fox8wghp.com/spacious.htm]

Nimbostratus Clouds

Nimbostratus

Thick layered cloud - usually dark gray. Produces continuous rain or snow over large area. [http://www.fox8wghp.com/spacious.htm]

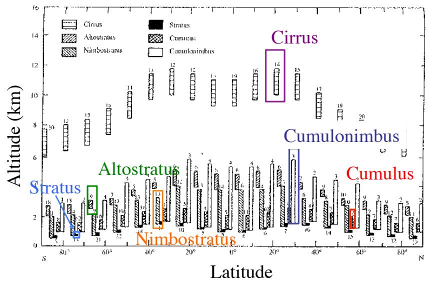
Fog

Fog is not included as a genus in this cloud classification scheme. *Fog* is composed of very small water drops (sometimes ice crystals) in suspension in the atmosphere and it reduces the visibility at the surface to less than 1 km. It will be shown in Section 8.4 that fog may be considered as a stratus cloud whose base is low enough to reach the ground.

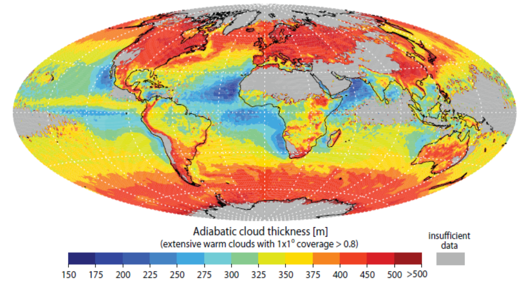
http://www.tqnyc.org/2009/00767/fog.jpg

Global Cloud Distribution

Zonally averaged climatology of cloud type



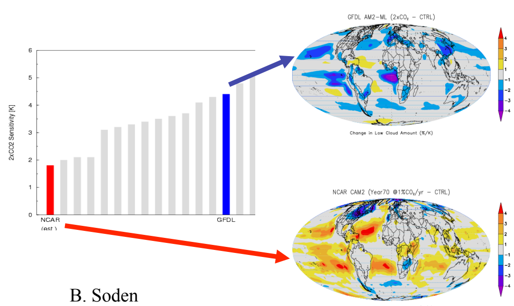
Adiabatic cloud thickness of stratiform boundary layer clouds



MODIS cloud LWP, and cloud temperature, used to determine adiabatic h

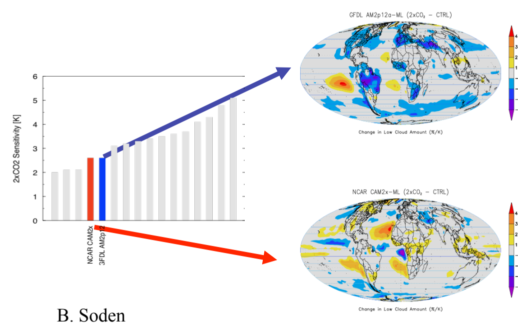
PBL Clouds are thin!

GFDL AM2p5 vs NCAR CAM2



B. Soden

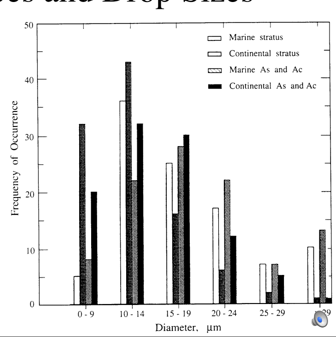
GFDL AM2p12a vs NCAR CAM2x



B. Soden

Cloud Types and Drop Sizes

- Frequency distributions of the mean cloud droplet size for various cloud types



What Determines Drop Size?

Nucleation/Activation + Condensation

- Köhler curve
  - Particle dry size
  - Particle soluble components
- Condensational growth from water
  - Latent heating
  - Available water

0.05 µm ➔ 10 µm

Condensation + Collision/Coalescence

- Condensational growth from additional water
  - More cooling
  - More water vapor
- Collision of droplets and their coalescence
  - Distribution of big/small drops

50 µm ➔ 100 µm ➔ 1+ mm

Taller and longer-lived clouds get bigger drops

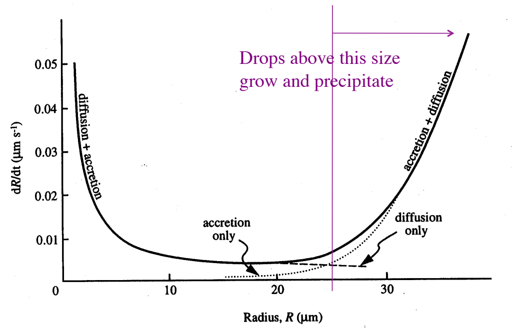


Figure 8.6 Drop growth rate by condensation and accretion. The dashed line represents growth by diffusion only, and the dotted line represents growth by accretion only, while the solid curve represents the combined growth rate. Condensational growth rate decreases with increasing radius, while accretional growth rate increases with increasing radius.

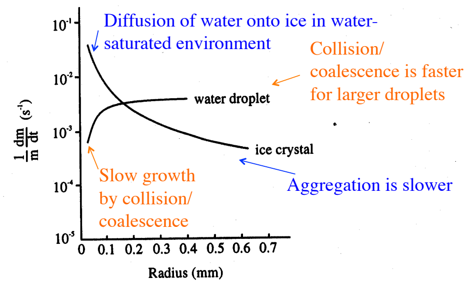


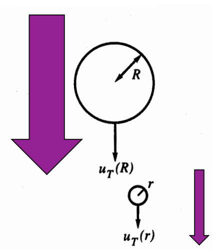
Figure 8.8 Growth rates for ice crystals and water drop. Initially, the ice growth rate exceeds the water drop growth rate. However, once the water drop grows to a sufficient size, its collection efficiency is no longer small, and its growth rate increases rapidly. (From Rogers, 1976.)

Drop Growth and Size

- Bigger particles (~25 micron) grow faster

Since collection efficiency increases with the radius of the collecting drop, and the terminal velocity increases with radius, rate of growth by collection proceeds more and more rapidly as drop size increases. Figure 8.6 compares the condensational

Larger drops are faster so they collide with the smaller drops in their way.



Whether or not the two particles stick is determined by the collection efficiency

Figure 8.4 Collision geometry for a collector drop of radius R falling with speed $u_T(R)$ through a population of smaller drops of radius r, falling with a speed $u_T(r)$.

Collection Efficiency E is the probability that a collision AND coalescence event will occur.

10% collide (w/ drops outside this population)

10% collide (w/ drops outside this population)

Stochastic collection model: based on probability

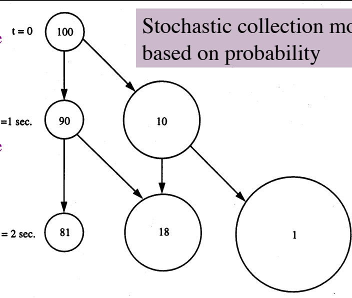
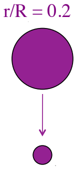
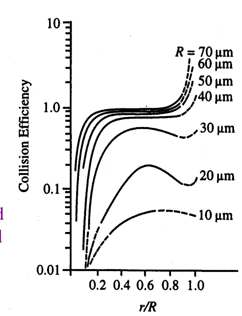


Figure 8.7 Illustration of stochastic collection model. At $t = 0$, a population of 100 drops all have the same initial radius. If 10% of the drops undergo collision and coalescence, then after one second, 10 of the drops will have grown larger, while 90 of the drops remain at the initial size. In the next second, if 10% of the drops in each category undergo collision, then one of the larger drops will undergo a second collision, while nine of the larger drops retain their size. Of the 90 that did *not* collide in the first second, nine will collide in the next second, while 81 will not. Thus in two seconds, there will be 81 drops that have not collided at all, 18 drops that have collided once, and one statistically favored drop that will have collided twice. (After Berry, 1967.)

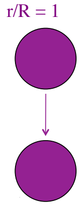
r/R = 0.2



Flow field around large particle will move smaller particle, lower E



r/R = 1



Inertia of collected drop increases, higher E

Figure 8.5 Collision efficiencies for collector drops of radius R and drops of radius r. (From Klett and Davis, 1973.)

tween a cloud particle and the earth is balanced by the frictional force of the particle as it falls through the air, the speed at which the particle is falling is called the *terminal velocity*. For a small spherical liquid drop,[1] we may approximate the terminal velocity, u_T, as

Small, spherical drop $u_T = k_1 r^2$ (8.1a)

with $k_1 = 1.19 \times 10^6$ cm^{-1} s^{-1}. This quadratic dependence of fall speed on size for drops with $r < 30$ μm is called *Stokes' law*. Stokes' law does not hold for larger particles, since the shape of larger drops is deformed as they fall and the frictional force becomes more complex. Experiments with falling drops have provided the following approximations for larger drops to be

Larger, spherical drop $u_T = k_2 r$ (8.1b)

with $k_2 = 8 \times 10^3$ s^{-1}. This equation is valid for particles in the size range 40 μm $< r <$ 0.6 mm. For the largest category of particles, 0.6 mm $< r <$ 2 mm, we have

Largest, spherical drop $u_T = k_3 r^{1/2}$ (8.1c)

where $k_3 = 2.01 \times 10^3 (\rho_0/\rho_a)^{1/2}$ cm$^{1/2}$ s^{-1} and ρ_0 is a reference density of 1.2 kg m^{-3}.

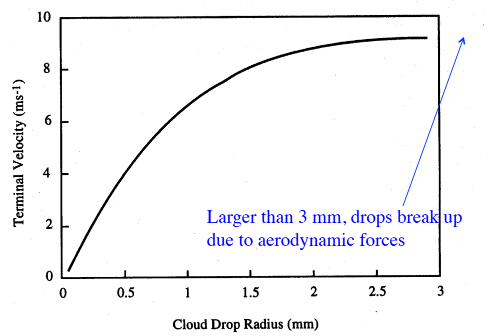


Figure 8.2 Terminal velocity of cloud drops as a function of drop radius. (Data from Gunn and Kinzer, 1949.)

Ice crystals

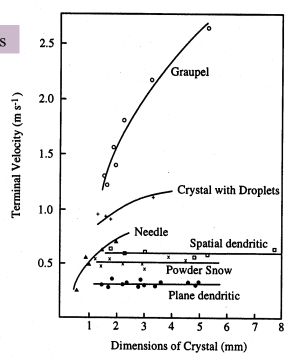


Figure 8.3 Observed terminal velocities of ice particles as a function of crystal type and size. (From Fletcher, 1962.)

What is the difference between "rain" and "drizzle"?

Isn't it just that you say "po-tay-to"
I say "po-tah-to"?
No! It's far more scientific than that!

Precipitation and Drop Size

- Terminal velocity increases with drop size
- Precipitation occurs when
  - terminal velocity exceeds updraft velocity
    - "Drizzle" occurs in stratus where 50 µm drops fall faster than 0.1-1 m/s updrafts
    - "Rain" occurs in cumulus (inter alia) when 1 mm drops fall faster than 1-10 m/s updrafts

with units mass of liquid water per mass of dry air. For a particle to reach a size large enough to precipitate out of the cloud, its terminal velocity u_T must exceed the updraft velocity within the cloud.

Precipitation and Cloud Type

- Likelihood of precipitation depends on
  - Condensed water (water and temperature)
  - Updraft velocity (dynamics)
  - Temperature (cold or warm processes)
  - Drop size (aerosol effects)

Not all clouds form precipitation-size particles. Precipitation formation is favored in clouds with a large condensed water content (typically arising from adiabatic cooling) and broad drop spectra. The dynamics of cloud motions therefore play an important role in determining whether or not a cloud precipitates. Cumuliform clouds are favored for precipitation development, because of strong updraft velocities that produce a substantial amount of condensed water. Low-level stratiform clouds rarely produce more than drizzle, since they rarely have a large amount of condensed water or the cold temperatures needed to initiate ice crystal processes.

Precipitation Processes

- Warm clouds
  - liquid water droplets only
- Cold clouds
  - ice particles
- Collision/coalescence (accretional growth)
  - Water drop + water drop
  - Ice crystal + water drop
  - Ice crystal + ice crystal

Decoupling of Stratocumulus-Topped Boundary Layer

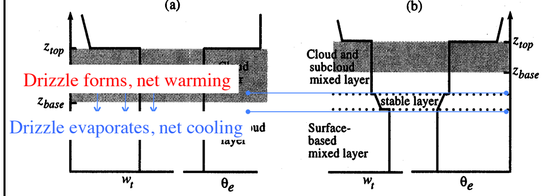
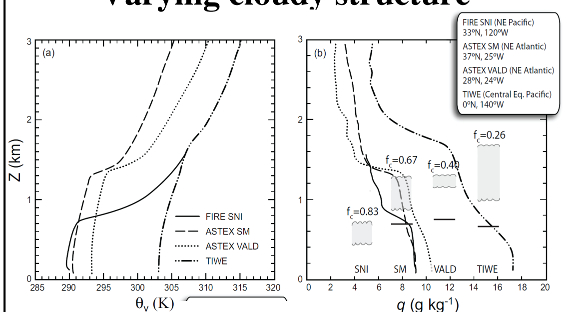


Figure 8.20 Idealized boundary-layer profiles of total water content and equivalent potential temperature. In (b), the cloud and subcloud layers are decoupled from the surface mixed layer by a stable intermediate layer. Decoupling may occur for a number of reasons, including the fallout of drizzle from the upper cloud layer, and its subsequent evaporation in the subcloud layer; a decrease in surface buoyancy fluxes; solar heating; and entrainment of warmer, drier air. (After Turton and Nicholls, 1987.)

Observations: Varying cloudy structure



R. Wood, 11/17/10

Liquid Water Path

which gives the rate of condensation at level z. The *liquid water path*, $\mathcal{W}_l$, is defined as the vertical integral of the liquid water mixing ratio:

$$\mathcal{W}_l = \int_{z_b}^{z_t} \rho_a w_l \, dz \qquad (8.6)$$

with units kg m^{-2}. If all of the adiabatic liquid water were to fall out of the cloud, the depth of the adiabatic precipitation, P_{ad}, would be