Lecture Ch. 8b

- Precipitation Processes

Curry and Webster, Ch. 8
For Tuesday: Ch. 12

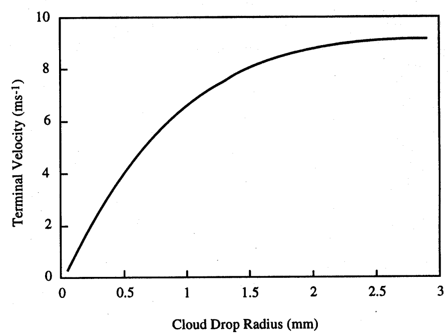

Figure 8.2 Terminal velocity of cloud drops as a function of drop radius. (Data from Gunn and Kinzer, 1949.)

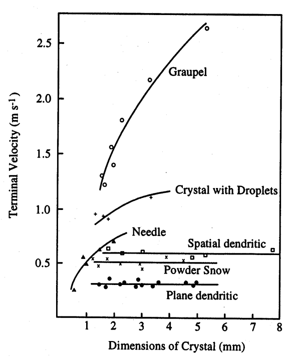

Figure 8.3 Observed terminal velocities of ice particles as a function of crystal type and size. (From Fletcher, 1962.)

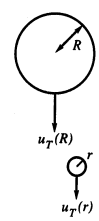

Figure 8.4 Collision geometry for a collector drop of radius R falling with speed $u_T(R)$ through a population of smaller drops of radius r, falling with a speed $u_T(r)$.

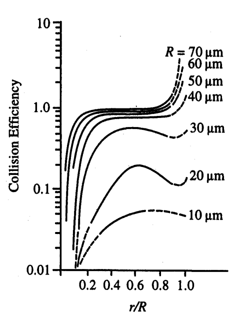

Figure 8.5 Collision efficiencies for collector drops of radius R and drops of radius r. (From Klett and Davis, 1973.)

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

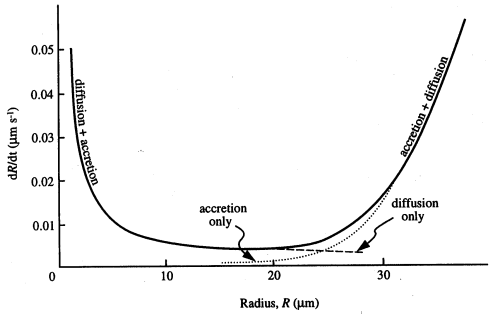

Figure 8.6 Drop growth rate by condensation and accretion. The dashed line represents growth by diffusion only, and the dotted line represents growth by accretion only, while the solid curve represents the combined growth rate. Condensational growth rate decreases with increasing radius, while accretional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

Precipitation and Drop Size

- Terminal velocity increases with drop size
- Precipitation occurs when
  - terminal velocity exceeds updraft velocity

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

- 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.

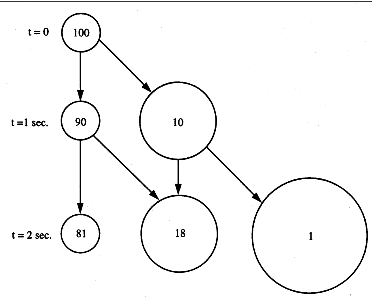

Figure 8.7 Illustration of stochastic collection model. At $t = 0$, a population of 100 drops all have the same initial radius. If 10% of the drops undergo collision and coalescence, then after one second, 10 of the drops will have grown larger, while 90 of the drops remain at the initial size. In the 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.)

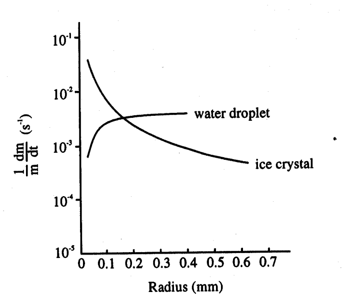

Figure 8.8 Growth rates for ice crystals and water drop. Initially, the ice growth rate exceeds the water drop growth rate. However, once the water drop grows to a sufficient size, its collection efficiency is no longer small, and its growth rate increases rapidly. (From Rogers, 1976.)

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_{a}, would be

Precipitation Efficiency

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

$$P_{ad} = \frac{\mathcal{W}_l}{\rho_l} \qquad (8.7)$$

where $\mathcal{W}_l$ here is the adiabatic liquid water path. Taking the time derivative of (8.7) and incorporating (8.5) and (8.6) gives

$$\dot{P}_{ad} = \frac{\rho_a}{\rho_l}\int_{z_b}^{z_t} \frac{dw_l}{dt}\,dz = \frac{\rho_a}{\rho_l}\int_{z_b}^{z_t} \frac{c_p}{L_{lv}}\left(\Gamma_d - \Gamma_s\right)u_z\,dz$$

where $\dot{P}_{ad}$ is therefore the *adiabatic precipitation rate* in units m s^{-1}. A *precipitation efficiency* can then be defined as the ratio of the actual precipitation rate to the adiabatic precipitation rate. Even in cumulonimbus, precipitation efficiency typically does not exceed 0.3.

Current Research: Cloud Drops

- Additional particles also reduce droplet size
  - Slowing growth to precipitation-size droplets

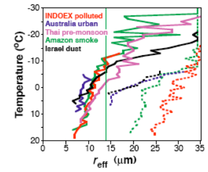

Fig. 6. Satellite-retrieved median effective radius of particles near the top of deep convective clouds at various stages of their vertical development, as a function of the cloud top temperature, which serves as a surrogate for cloud top height. The effective radius is the ratio of the integral of the third moment (r^3) of the radius, weighted with the number concentration at that radius, to its second moment (r^2). This is shown for clouds forming in polluted (solid lines) and pristine air (broken lines). The red lines denoted by "INDOEX polluted" are for data along a track that runs from South West India into the Indian Ocean. The blue lines

Ramanathan et al., 2001

SCIENCE'S COMPASS • REVIEW

REVIEW: ATMOSPHERE

Aerosols, Climate, and the Hydrological Cycle

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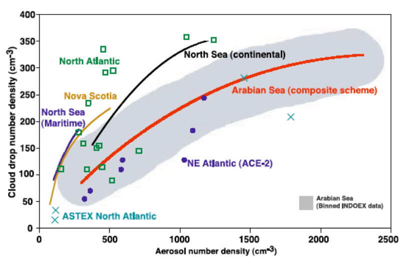

"These aerosol effects can lead to a weaker hydrological cycle, which connects directly to the availability and quality of fresh water..."

Fig. 5. Aircraft data illustrating the increase in cloud drops with aerosol number concentration. References for the data are as follows: North Sea (*28*), Nova Scotia and North Atlantic (*29*), ACE-2 (*30*), Astex (*31*), the thick red line is obtained from a composite theoretical parameterization that fits the INDOEX aircraft data for the Arabian Sea (*23*). The gray-shaded region is the INDOEX aircraft data for the Arabian Sea (*32*).

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SIO 217A Final Exam Fall 2005
Curry and Webster, Ch. 1-8, 12

1. Answer **both** part (a) and part (b).
   a) If air has a pressure of 1026.8 hPa and a mixing ratio of 0.005, calculate vapor pressure.
   b) If air has a specific humidity of 0.0196 and a temperature of 30 deg C, calculate virtual temperature.

2. Answer **all of** part (a) and part (b) and part (c). For each part, state whether you were an author or a reviewer or neither for the relevant *ROAST* report.
   a) Do you think a significant connection has been established between "global warming" and recent changes in hurricane climatology? Why, or why not?
   b) Describe two ways of measuring stratospheric CFC concentrations.
   c) Describe how the Twomey effect can be studied observationally.

3. Curry and Webster state, "Because of the nonlinearity of the Clausius-Clapeyron equation, adiabatic isobaric mixing results in an increase in relative humidity." Explain what they mean by this statement. Draw a suitable diagram and describe the process being considered, showing why the statement is true. Give an example of an observable phenomenon in the atmosphere that illustrates this statement.

4. Using a diagram with temperature on the horizontal axis and pressure or altitude on the vertical axis, describe the processes involved in the development of a typical cumulus cloud. In your discussion, include the relevance of the lapse rate, the stability of the atmosphere, phase changes of water, and other factors important to cumuliform convection.

5. Draw the Kiehl-Trenberth (1997) diagram of the estimated annual mean global energy balance for the Earth. You are **not** expected to recall the numerical values, but try to include as many of the important fluxes of energy and processes as you can remember (incoming solar radiation, outgoing longwave radiation, etc.). Now imagine that it is the year 2100, and humanity has continued to add to the concentrations of carbon dioxide, etc., by using fossil fuels as its primary energy supply throughout the 21st century. What do you think will be the main changes in this diagram between 1997 and 2000? Explain your reasoning.

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6. Consider a planet that is identical to Earth in all respects except for its albedo. State and simplify the equations needed to determine the equivalent black-body emission temperature of this planet if α_p=0. State all assumptions and approximations. Do you expect that this planet will be hotter than the Earth or colder? Discuss the reasons.

7. Calculate the maximum efficiency of work done by heat transferred from the sun to the earth. State all assumptions and approximations. Is this process reversible? Why or why not?

8. Determine how large drops must be beyond the critical radius before Raoult effects are negligibly small relative to the Kelvin effect. Use a rough sketch of a Köhler curve to show where this point occurs.

9. Define the following terms in 10 words or less; an equation, graph, or sketch may be added if appropriate:
   a. Dew-point depression
   b. Aerosol indirect effect
   c. Meridional heat transfer
   d. Virtual potential temperature
   e. Lifting condensation level
   f. Gibbs phase rule
   g. Reversible

10. Sketch the pressure-temperature phase diagram for water. On the graph, label
   3. all phases and their transitions,
   4. the triple point,
   5. the temperature and pressure at which water boils at sea level,
   6. the location of supercooled water,
   7. the location of supersaturated water vapor.