Lecture Ch. 8a

- Review of Ch. 7 Concepts
  - Homework Ch. 7, Prob. 3
- Cloud Classification
- Precipitation Processes

Curry and Webster, Ch. 8
For Tuesday: Finish reading Ch. 8

Atmospheric Structure

- Structure of the atmosphere
  - Decreasing temperature with altitude
  - Decreasing pressure with altitude
  - Changes in water vapor with altitude
- Temperatures in meteorology
  - Potential temperature (meteorologists' entropy)
  - Virtual (potential) temperature
  - Equivalent (potential) temperature

- Describing the atmospheric structure
  - Example: Skew-T log P plot
  - Example: Tephigram

Figure 14.1 Vertical structure and features of Earth's atmosphere.

Inversions

- Inversion: A condition of strong stability characterized by a positive temperature gradient.
Subsidence Inversions

- **Subsidence Inversion**
  - Cause: adiabatic compression and warming of a large layer of earth as it sinks to lower altitude.
  - \( \frac{dT}{dP} = \frac{1}{(C_p \rho)} \), where \( C_p \) is essentially constant over \( T \).

Because of a change in \( P \) with \( z \), what can be said about \( \rho_{\text{top}} \) versus \( \rho_{\text{bottom}} \)?
Which layer is warmer, top or bottom?

Radiation Inversions

- **Radiation Inversion**
  - Cause:
    - radiation of heat by the ground at night
    - air adjacent to the surface has a \( T < \) layer at higher elevations

Water Vapor in the Atmosphere

- the Earth’s surface is the primary source of water vapor for the atmosphere
- the amount of water vapor in the atmosphere depends on:
  - the amount which enters the atmosphere through evaporation and sublimation,
  - the amount which leaves the atmosphere intermittently as rain, hail and snow
  - the amount which traverses the troposphere and the lower stratosphere
  - the amount which traverses the troposphere and the lower stratosphere
  - the amount which traverses the troposphere
- the atmosphere has very low water content
- clouds and fog form by condensation
  - cloud formation is driven by the rise of moist air due to thermally-driven updrafts, which result in simultaneous cooling and expansion, in many cases this expansion is close to adiabatic
  - fog formation and some stratus cloud formation can occur by isobaric cooling caused by surface cooling
  - air at high altitude may have a dew point \( T_d \) and a liquid condensate is formed; this process occurs when the dew point/temperature \( T_d \) is reached

Lifting Condensation Level

- Lifting condensation level varies with initial relative humidity and is a weak function of initial temperature

Seinfeld and Pandis, Fig. 15.11
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 nimbiform indicates the presence of rain.

Cumulus Clouds

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

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]

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 genre in this cloud classification scheme. Fog is composed of very small water droplets (sometimes ice crystals) in suspension in the atmosphere and its plume, the visibility at eye level, is less than 1 km. It will be shown in Box C that fog may be considered as a mixture of cloud whose base is low enough to touch the ground.

Global Cloud Distribution

• Zonally averaged climatology of cloud type

Cloud Types and Drop Sizes

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

Precipitation Processes

• Warm clouds (liquid water droplets only)
• Cold clouds (ice particles)
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
Precipitation and Drop Size

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

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. Condensation growth rate decreases with increasing radius, while accretional growth rate increases with increasing radius.

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 droplet accretion model. At t = 0, a population of 100 drops all have the same initial radius. If 90% of the drops undergo accretion and subsequently find other ones accret, 10 of the drops will have grown larger, while 10 of the drops remain at the initial size. At the next second, 90% of the drops in each category undergo collision, thus one of the larger drops will undergo a second collision, while only the larger drops remain their size. This process will continue until all of the drops that have collided meet, and one eventually becomes the drop that will have collimated. (Adapted from 1987.)

Liquid Water Path

which gives the rate of condensation at level z. The liquid water path, \( W_L \), is defined as the vertical integral of the liquid water mixing ratio:

\[
W_L = \int_0^z \rho_L \, dz
\]

with units kg m⁻¹. If all of the adiabatic liquid water were to fall out of the cloud, the depth of the adiabatic precipitation P would be...
**Precipitation Efficiency**

with units kg m⁻³. If all of the adiabatic liquid water were to fall out of the cloud, the depth of the adiabatic precipitation, \( P_{\text{ad}} \), would be

\[
P_{\text{ad}} = \int_{p_1}^{p_2} \left[ T - T_r \right]^{-1} dp
\]

where \( \rho_{\text{lw}} \) is the adiabatic liquid water path. Taking the time derivative of (3.3) and incorporating (8.5) and (6.6) gives

\[
\frac{P_{\text{ad}}}{P_{\text{ad}}} = \frac{\rho_{\text{lw}}}{\rho_{\text{lw}}} \frac{\int_{p_1}^{p_2} \left[ T - T_r \right]^{-1} dp}{\int_{p_1}^{p_2} \left[ T - T_r \right]^{-1} \frac{\partial p}{\partial t} dp}
\]

where \( P_{\text{ad}} \) is therefore the adiabatic precipitation rate in units as m⁻¹. A precipitation efficiency can then be defined as the ratio of the actual precipitation rate to the adiabatic precipitation rate. Even in non-convective precipitation events, precipitation efficiency typically does not exceed 0.5.

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**Current Research: Cloud Drops**

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

Ramanathan et al., 2001

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**Current Research: Global Models**

- Aerosol impacts on rain are not local
  - Change in JJA mean precipitation (mm day⁻¹) between the 6-year perturbation and the 12-year control.

Erlick, Ramaswamy, and Russell, 2005

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**What are the characteristics of “ship tracks”?**

<table>
<thead>
<tr>
<th>Ship Track Observations</th>
<th>Remote/Optical</th>
<th>situ/Aerosol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conover</td>
<td>1966</td>
<td>↓albedo=20%</td>
</tr>
<tr>
<td>Coakley, Bernstein, Burke</td>
<td>1987</td>
<td>↓R(3.9µm)=3.9%</td>
</tr>
<tr>
<td>Radke, Coakley, King</td>
<td>1989</td>
<td>↓R(0.63µm)=1.6%</td>
</tr>
<tr>
<td>King, Radke, Hobbs</td>
<td>1993</td>
<td>↑I(τ,-1)(2.20µm)=87%</td>
</tr>
</tbody>
</table>

**Processes Governing Ship Tracks**

Hypothesis

Radke, Coakley, King 1989 ship stacker ↓CCN
Albrecht 1989 ↓LWC = ↓N<br> Hudson 1991 ↑N = ↑CCN
Ackerman, Toon, Hobbs 1994 ↓LWC = ↓CCN