Lecture 3: ATMOSPHERE (Outline)

- Hadley Cell
- Ferrel Cell (driven by eddies)
- Polar Cell

Basic Structures and Dynamics
- General Circulation in the Troposphere
- General Circulation in the Stratosphere

Vertical Structure

Standard Atmosphere

- Troposphere (“overturning” sphere)
  - contains 80% of the mass
  - surface heated by solar radiation
  - strong vertical motion
  - where most weather events occur

- Stratosphere (“layer” sphere)
  - weak vertical motions
  - dominated by radiative processes
  - heated by ozone absorption of solar ultraviolet (UV) radiation
  - warmest (coldest) temperatures at summer (winter) pole

- Mesosphere
  - heated by solar radiation at the base
  - heat dispersed upward by vertical motion

- Thermosphere
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Balance of Force in the Horizontal

Can happen in the tropics where the Coriolis force is small.

Thermal Energy to Kinetic Energy

- Polar
  - cold
  - warm

  (on a horizontal surface)
Coriolis Force

- First, Point A rotates faster than Point B (UA > UB).
- A northward motion starting at A will arrive to the east of B.
- It looks like there is a "force" pushing the northward motion toward right.

This apparent force is called "Coriolis force":

\[
\text{Coriolis Force} = f V
\]

where \( f = 2\Omega \sin(\text{lat}) \) and \( \Omega = 7.292 \times 10^{-5} \text{ rad s}^{-1} \)

(from The Earth System)

Geostrophic Balance

- By doing scale analysis, it has been shown that large-scale and synoptic-scale weather system are in geostrophic balance.
- Geostrophic winds always follow the constant pressure lines (isobar). Therefore, we can figure out flow motion by looking at the pressure distribution.

How Does Coriolis Force Affect Wind Motion?

- Surface friction force slows down the geostrophic flow.
- The flow turns into (out of) the low (high) press sides.
- Convergence (divergence) is produced with the flow.

Frictional Effect on Surface Flow
Surface Geostrophic Flow

Cyclonic Flow

Anticyclonic Flow

(figures from Weather & Climate)

Breakdown of the Single Cell → Three-Cell Model

- Absolute angular momentum at Equator = Absolute angular momentum at 60°N
- The observed zonal velocity at the equator is \( u_{eq} = -5 \text{ m/sec.} \)
  Therefore, the total velocity at the equator is \( \mathbf{U} = \text{rotational velocity} (U_0 + u_{eq}) \)
- The zonal wind velocity at 60°N (\( u_{60N} \)) can be determined by the following:
  \[
  (U_0 + u_{eq}) \cdot a \cdot \cos(0°) = (U_{60N} + u_{60N}) \cdot a \cdot \cos(60°)
  \]
  \[
  (\Omega \cdot a \cdot \cos(0°) - 5) \cdot a \cdot \cos(0°) = (\Omega \cdot a \cdot \cos(60°) + u_{60N}) \cdot a \cdot \cos(60°)
  \]
  \[ u_{60N} = 687 \text{ m/sec} \]
  
This high wind speed is not observed!

Baroclinic Instability

- Baroclinic instability is related to the latitudinal gradient of temperature.
- The instability gives rise to wave motions that can convert the thermal energy associated with the temperature gradient into kinetic energy of air motion.
- This instability is the primary mechanism to generate weather systems in midlatitudes.
Atmospheric Circulation: Zonal-mean Views

The Three Cells

Properties of the Three Cells

Thermally Direct/Indirect Cells

- **Thermally Direct Cells (Hadley and Polar Cells)**
  Both cells have their rising branches over warm temperature zones and sinking branches over the cold temperature zone. Both cells directly convert thermal energy to kinetic energy.

- **Thermally Indirect Cell (Ferrel Cell)**
  This cell rises over cold temperature zone and sinks over warm temperature zone. The cell is not driven by thermal forcing but driven by eddy (weather systems) forcing.
Is the Three-Cell Model Realistic?

- **Yes and No!**
  
  *(Due to sea-land contrast and topography)*

**Yes:** the three-cell model explains reasonably well the surface wind distribution in the atmosphere.

**No:** the three-cell model cannot explain the circulation pattern in the upper troposphere. (Planetary wave motions are important here.)

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Sinking Branches and Deserts

*(From Weather & Climate)*

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Global Distribution of Deserts

*(From Global Physical Climatology)*

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Upper Tropospheric Circulation

- Only the Hadley Cell can be identified in the lower latitude part of the circulation.
- Circulation in most other latitudes are dominated by westerlies with wave patterns.
- Dominated by large-scale waver patterns (wave number 3 in the Northern hemisphere).

*(From Weather & Climate)*
Subtropical and Polar Jet Streams

- **Subtropical Jet**: Located at the higher-latitude end of the Hadley Cell. The jet obtains its maximum wind speed (westerly) due to the conservation of angular momentum.

- **Polar Jet**: Located at the thermal boundary between the tropical warm air and the polar cold air. The jet obtains its maximum wind speed (westerly) due to the latitudinal thermal gradient (thermal wind relation).

Thermal Wind Relation

\[ \frac{\partial U}{\partial z} \propto \frac{\partial T}{\partial y} \]

- The vertical shear of zonal wind is related to the latitudinal gradient of temperature.
- Jet streams usually are formed above baroclinic zone (such as the polar front).

Temperature and Pressure

- Hydrostatic balance tells us that the pressure decrease with height is determined by the temperature inside the vertical column.
- Pressure decreases faster in the cold-air column and slower in the warm-air column.
- Pressure drops more rapidly with height at high latitudes and lowers the height of the pressure surface.

Thermal Wind Equation
Both the polar and subtropical jet streams can affect weather and climate in the western US (such as California). El Niño can affect western US climate by changing the locations and strengths of these two jet streams.

The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

Walker Circulation and Ocean Temperature
**Monsoon: Another Sea/Land-Related Circulation of the Atmosphere**

- Monsoon is a climate feature that is characterized by the *seasonal reversal in surface winds*.
- The very different heat capacity of land and ocean surface is the key mechanism that produces monsoons.
- During summer seasons, land surface heats up faster than the ocean. Low pressure center is established over land while high pressure center is established over oceans. Winds blow from ocean to land and bring large amounts of water vapor to produce heavy precipitation over land: a rainy season.
- During winters, land surface cools down fast and sets up a high pressure center. Winds blow from land to ocean: a dry season.

(figures from Weather & Climate)
Tropospheric Biennial Oscillation (TBO)

- TBO is referred to the tendency that years with above normal monsoon rainfall tend to be followed by ones with below normal rainfall and vice versa.

Sea/Land Breeze

- Sea/land breeze is also produced by the different heat capacity of land and ocean surface, similar to the monsoon phenomenon.
- However, sea/land breeze has much shorter timescale (day and night) and space scale (a coastal phenomenon) than monsoon (a seasonal and continental-scale phenomenon).

*Figure from The Earth System*
Scales of Motions in the Atmosphere

Temperatures in Stratosphere

(from Dynamic Meteorology)
Ozone Distribution

Circulation in Stratosphere

Stratosphere: Circulation and Temperature

Zonal-Mean Circulation in the Stratosphere
**Ozone Production and Destruction**

*From The Earth System*

**The Chapman Mechanism of Ozone Production and Destruction**

<table>
<thead>
<tr>
<th>Reaction*</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) ( \text{O}_2 + \text{UV photon} \rightarrow \text{O} + \text{O} )</td>
<td>Photodissociation (or photolysis)</td>
</tr>
<tr>
<td>2) ( \text{O} + \text{O}_3 + \text{M} \rightarrow \text{O}_2 + \text{M} )</td>
<td>Production</td>
</tr>
<tr>
<td>3) ( \text{O}_3 ) + photon ( \rightarrow \text{O}_2 + \text{O} )</td>
<td>Destruction</td>
</tr>
<tr>
<td>4) ( \text{O} + \text{O}_3 \rightarrow 2 \text{O}_2 )</td>
<td></td>
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</tbody>
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*Ozone Distribution*  

- The greatest production of ozone occurs in the tropics, where the solar UV flux is the highest.
- However, the general circulation in the stratosphere transport ozone-rich air from the tropical upper stratosphere to mid-to-high latitudes.
- Ozone column depths are highest during springtime at mid-to-high latitudes.
- Ozone column depths are the lowest over the equator.

**Climate Variations in Stratosphere**

- Quasi-Biennial Oscillation (QBO)
- Sudden Warming: in Northern Pole
- Ozone Hole: in Southern Pole

**QBO**

- Quasi-Biennial Oscillation: Easterly and westerly winds alternate every other years (approximately) in the lower to middle stratosphere.
Why QBO?
- Kevin Waves accelerate westerly.
- Rossby-Gravity Wave accelerate easterly.

Why Sudden Warming?
- Planetary-scale waves propagating from the troposphere (produced by big mountains) into the stratosphere.
- Those waves interact with the polar vortex to break down the polar vortex.
- There are no big mountains in the Southern Hemisphere to produce planetary-scale waves.
- No (?) sudden warming in the southern polar vortex.

Sudden Warming
- Every other year or so the normal winter pattern of a cold polar stratosphere with a westerly vortex is interrupted in the middle winter.
- The polar vortex can completely disappear for a period of a few weeks.
- During the sudden warming period, the stratospheric temperatures can rise as much as 40°K in a few days!

Antarctic Ozone Hole
- The decrease in ozone near the South Pole is most striking near the spring time (October).
- During the rest of the year, ozone levels have remained close to normal in the region.
**Why No Ozone Hole in Arctic?**

In winter, the polar stratosphere is so cold (-80°C or below) that certain trace atmospheric constituents can condense. These clouds are called "polar stratospheric clouds" (PSCs). The particles that form typically consist of a mixture of water and nitric acid (HNO₃). The PSCs alter the chemistry of the lower stratosphere in two ways:

1. By coupling between the odd nitrogen and chlorine cycles.
2. By providing surfaces on which heterogeneous reactions can occur.

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**The 1997 Ozone Hole**

Ozone Hole Depletion

- **Long Antarctic winter (May through September)**
  - The stratosphere is cold enough to form PSCs.
  - PSCs deplete odd nitrogen (NO).
  - Help convert unreactive forms of chlorine (CINO₂ and HCl) into more reactive forms (such as Cl₂).
  - The reactive chlorine remains bound to the surface of clouds particles.
  - Sunlight returns in springtime (September).
  - The sunlight releases reactive chlorine from the particle surface.
  - The chlorine destroys ozone in October.
  - Ozone hole appears.
  - At the end of winter, the polar vortex breaks down.
  - Allow fresh ozone and odd nitrogen to be brought in from low latitudes.
  - The ozone hole recovers (disappears) until next October.