Lecture 5: Atmospheric General Circulation and Climate

- Geostrophic balance
- Zonal-mean circulation
- Transients and eddies
- Meridional energy transport
- Moist static energy
- Angular momentum balance
Atmosphere – the Great Communicator

- The movement of air in the atmosphere is of critical importance for climate.
- Atmospheric motions carry heat from the tropics to the polar regions.
- Water from the oceans is evaporated and carried in the air to land, where rainfall supports plant and animal life.
- **Winds supply momentum to ocean surface currents** that transport heat and oceanic trace constituents such as salt and nutrients.
- The atmosphere provides the most rapid communication between geographic regions within the climate system.
Atmospheric General Circulation

The global system of atmospheric motions that is generated by the uneven heating of Earth’s surface area by the Sun is called the general circulation.
Scales of Motions in the Atmosphere

- **Global scale**: 5000 km
  - Typical size

- **Synoptic scale**: 2000 km
  - Typical size

- **Mesoscale**: 20 km
  - Typical size

- **Microscale**: 2 m
  - Typical size

- **Small Turbulent eddies**
  - LIFE SPAN: Days to a week or more

- **Thunderstorms**
  - LIFE SPAN: Hours to days

- **Tornadoes**
  - LIFE SPAN: Minutes to hours

- **Water spouts**
  - LIFE SPAN: Minutes to hours

- **Dust devils**
  - LIFE SPAN: Minutes to hours

- **Land/Sea breeze Mountain/valley breeze**
  - LIFE SPAN: Minutes to hours

- **Chinook wind Santa Ana wind**
  - LIFE SPAN: Hours to days

- **Hurricanes Tropical storms**
  - LIFE SPAN: Days to a week or more

- **Weather map features High and Low pressure areas Weather fronts**
  - LIFE SPAN: Days to a week or more

- **Long-waves in the westerlies**
  - LIFE SPAN: Days to a week or more
Wind Components

\[ u = a \cos \phi \frac{D\lambda}{Dt} \] = zonal or eastward wind speed

\[ v = a \frac{D\phi}{Dt} \] = meridional or northward wind speed

\[ w = \frac{Dz}{Dt} \] = rate of change of altitude following an air parcel

\[ \omega = \frac{Dp}{Dt} \] = rate of change of pressure following an air parcel

\[ \omega \equiv -\rho g w \]
Single-Cell Model: Explains Why There are Tropical Easterlies

Without Earth Rotation

With Earth Rotation

(Figures from Understanding Weather & Climate and The Earth System)
First, Point A rotates faster than Point B (\(U_A > U_B\))

\[U_A > U_B\]

→ 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”:

\[
\text{Coriolis Force} = fV
\]

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

(see Section 6.4 and Eq. 6.15 of Global Physical Climatology)
Newton’s 2\textsuperscript{nd} Law in a Rotating Frame

\[
\frac{D_a U_a}{Dt} = \sum F
\]

using

\[
\frac{D_a U_a}{Dt} = \frac{D U_a}{Dt} + \Omega \times U_a
\]

absolute velocity of an object on the rotating earth is equal to its velocity relative to the earth plus the velocity due to the rotation of the earth

\[
U_a = U + \Omega \times r
\]

covert acceleration from an inertial to a rotating frames

\[
\frac{D_a U_a}{Dt} = \frac{D}{Dt} (U + \Omega \times r) + \Omega \times (U + \Omega \times r)
\]

[Here \( \Omega \times (\Omega \times r) = \Omega \times (\Omega \times R) = -\Omega^2 R \) ]

\[
\frac{D_a U_a}{Dt} = \frac{D U}{Dt} + 2\Omega \times U - \Omega^2 R
\]

Coriolis force

Centrifugal force
Coriolis Force

- Coriolis force causes the wind to deflect to the right of its intent path in the Northern Hemisphere and to the left in the Southern Hemisphere.

- The magnitude of Coriolis force depends on (1) the rotation of the Earth, (2) the speed of the moving object, and (3) its latitudinal location.

- The larger the speed (such as wind speed), the stronger the Coriolis force.

- The higher the latitude, the stronger the Coriolis force.

- The Coriolis force is zero at the equator.

- Coriolis force is one major factor that determine weather pattern.
How Does Coriolis Force Affect Wind Motion?

(from Weather & Climate)
By doing scale analysis, it has been shown that large-scale and synoptic-scale weather systems 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.
Single-Cell Model: Explains Why There are Tropical Easterlies

(Figures from Understanding Weather & Climate and The Earth System)
Breakdown of the Single Cell \( \rightarrow \) Three-Cell Model

- **Absolute angular momentum at Equator** = Absolute angular momentum at 60°N

- The observed zonal velocity at the equator is \( u_{eq} = -5 \) m/sec. Therefore, the total velocity at the equator is \( U = \) rotational velocity \( (U_0 + u_{Eq}) \)

- The zonal wind velocity at 60°N \( (u_{60N}) \) can be determined by the following:

\[
(U_0 + u_{Eq}) \times a \times \cos(0°) = (U_{60N} + u_{60N}) \times a \times \cos(60°)
\]

\[
(\Omega \times a \times \cos(0°) - 5) \times a \times \cos(0°) = (\Omega \times a \times \cos(60°) + u_{60N}) \times a \times \cos(60°)
\]

\[
\text{\color{red}{\underline{u_{60N} = 687 m/sec}}} \text{!!!!}
\]

This high wind speed is not observed!
Properties of the Three Cells

- **Hadley Cell**
  - Equator (warmer)
  - Thermally direct circulation

- **Ferrel Cell**
  - 30° (warm)
  - Driven by eddies

- **Polar Cell**
  - 60° (cold)
  - Thermally indirect circulation
  - Pole (colder)
Atmospheric Circulation: Zonal-mean Views

Single-Cell Model

Three-Cell Model

(Figures from Understanding Weather & Climate and The Earth System)
The Three Cells

(Figures from *Understanding Weather & Climate* and *The Earth System*)
Semi-Permanent Pressure Cells

- **The Aleutian, Icelandic, and Tibetan lows**
  - The oceanic (continental) lows achieve maximum strength during winter (summer) months
  - The summertime Tibetan low is important to the east-Asia monsoon

- **Siberian, Hawaiian, and Bermuda-Azores highs**
  - The oceanic (continental) highs achieve maximum strength during summer (winter) months
Sinking Branches and Deserts

(from *Weather & Climate*)
Global Distribution of Deserts

(from *Global Physical Climatology*)
**Subtropical and Polar Jet Streams**

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

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

(from *Atmospheric Circulation Systems*)
Jet Streams Near the Western US

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

(from Riehl (1962), Palmen and Newton (1969))
Extratropical Cyclones in North America

Cyclones preferentially form in five locations in North America:

1. East of the Rocky Mountains
2. East of Canadian Rockies
3. Gulf Coast of the US
4. East Coast of the US
5. Bering Sea & Gulf of Alaska
The Zonal Mean Circulation

Zonal average: \[ [x] = \frac{1}{2\pi} \int_{0}^{2\pi} x \, d\lambda \]

Temporal average: \[ \bar{x} = \frac{1}{\Delta t} \int_{0}^{\Delta t} x \, dt \]

Climatological zonal averages are usually obtained by averaging over both longitude and time.

Eddies = deviations from zonal averages
Transients = deviations from time averages
Atmospheric Circulation and Temperature

Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind (m s\(^{-1}\)) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

Fig. 1.3. Schematic latitude-height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)
Atmospheric Circulation

Zonal Wind

Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind (m s\(^{-1}\)) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

(from *Global Physical Climatology*)
Properties of the Three Cells

- **Hadley Cell** (driven by eddies)
  - Equator (warmer)
  - 30° (warm)

- **Ferrel Cell**
  - Jersey (JS)
  - 30° (warm)
  - London (JP)

- **Polar Cell**
  - Equator (colder)
  - 60° (cold)
  - Pole (colder)

thermally direct circulation

thermally indirect circulation
Hadley Cell

Ferrel Cell
(driven by eddies)

Polar Cell

Equator
(warmer)

30° (warm)

60° (cold)

Pole (colder)

(from Global Physical Climatology)
Off-Equatorial Heating

“.. We find that moving peak heating even 2 degree off the equator leads to profound asymmetries in the Hadley circulation, with the winter cell amplifying greatly and the summer cell becoming negligible.”

--- Lindzen and Hou (1988; JAS)
(from *Global Physical Climatology*)

- **Equator**
- **summer**
- **winter hemisphere**
In the annual mean, the rising branch is displaced slightly into the Northern Hemisphere, and the Hadley cell in the Southern Hemisphere is stronger.

This asymmetry corresponds to a weak transport of energy from the Northern to the Southern Hemisphere.
Stationary and Transient Eddies

\[
[vT] = [v][T] + [v^*T^*] + [v'T']
\]

- total heat transport
- heat transport by mean flows
- heat transport by stationary eddies
- heat transport by transient eddies
Stationary Eddies

- Stationary eddies result from the east–west variations in (1) surface elevation and (2) surface temperature associated with the continents and oceans.

- Stationary eddy fluxes are largest in the Northern Hemisphere where the Himalaya and Rocky Mountain ranges provide mechanical forcing of east–west variations in the time mean winds and temperatures.

- The thermal contrast between the warm waters of the Kuroshio and Gulf Stream ocean currents and the cold temperatures in the interiors of the continents also provides strong thermal forcing of stationary planetary waves during winter.

(from Riehl (1962), Palmen and Newton (1969))
Transient Eddies

- Transient eddy fluxes are associated with the rapidly developing and decaying weather disturbances of mid-latitudes.

- They generally move eastward with the prevailing flow.

- These disturbances are very apparent on weather maps and have typical periods of several days to 1 week.

- The positive correlation between poleward velocity and temperature enables these transient eddies to produce efficient poleward transports of heat (and moisture).
Poleward Heat Flux by Eddies

(stationary eddies)

(transient eddies)

(from *Global Physical Climatology*)
Four Types of Energy in Atmosphere

**TABLE 6.1  Kinds and Amounts of Energy in the Global Atmosphere**

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Formula</th>
<th>Amount (J m⁻²)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal energy</td>
<td>IE</td>
<td>cₜT</td>
<td>1800 × 10⁶</td>
<td>70</td>
</tr>
<tr>
<td>Potential energy</td>
<td>PE</td>
<td>gz</td>
<td>700 × 10⁶</td>
<td>27</td>
</tr>
<tr>
<td>Latent energy</td>
<td>LH</td>
<td>Lq</td>
<td>70 × 10⁶</td>
<td>2.7</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>KE</td>
<td>1/2(u² + v²)</td>
<td>1.3 × 10⁶</td>
<td>0.05</td>
</tr>
<tr>
<td>Total energy</td>
<td>IE + PE + LH + KE</td>
<td></td>
<td>2571 × 10⁶</td>
<td>100</td>
</tr>
</tbody>
</table>

- Internal energy: associated with the temperature of the atmosphere.
- Potential energy: associated with the gravitational potential of air at some distance above the surface.
- Kinetic energy: associated with air motion.
- Latent energy: associated with moisture.
- Together internal and potential energy constitute about 97% of the energy of the atmosphere.
- Kinetic energy comprises a small fraction of the total energy.
Moist Static Energy

\[
\text{moist static energy} = c_p T + gz + Lq = \text{sensible} + \text{potential} + \text{latent}
\]

- The meridional transport of energy by the atmosphere may be divided into contributions from sensible, geopotential and latent forms that comprise the moist static energy.

- Moist static energy is moved around by the motions of the atmosphere and these transports can be integrated through the mass of the atmosphere to reveal the total meridional flux of energy in various forms.

- The Hadley cell transports both sensible and latent heat equatorward in the tropics. (read pages 175-176 for a discussion of how moist static energy is transported by the Hadley cell).
Angular Momentum Balance

- The general circulation of the atmosphere is heavily constrained by the conservation of angular momentum.

- In the tropical surface easterlies, where the atmosphere rotates more slowly than Earth’s surface, eastward angular momentum is transferred from Earth to the atmosphere via frictional forces and pressure forces acting on mountains.

- Atmospheric eddies transport angular momentum poleward and downward into the mid-latitude westerlies. Where the surface winds are westerly, the atmosphere is rotating faster than Earth’s surface and the eastward momentum is returned to Earth.

- This westerly angular momentum is transported upward and then poleward in the Hadley cell.
Parameters Determining Mid-latitude Weather

- Temperature differences between the equator and poles
- The rate of rotation of the Earth.
Rotating Annulus Experiment

(from "Is The Temperature Rising?")
New Understanding of Cyclone after WWII

- Carl Rossby mathematically expressed relationships between mid-latitude cyclones and the upper air during WWII.
- Mid-latitude cyclones are a large-scale waves (now called Rossby waves) that grow from the “baroclinic” instability associated with the north-south temperature differences in middle latitudes.

Carl Gustav Rossby (1898-1957)
Polar Front Theory

- Bjerknes, the founder of the Bergen school of meteorology, developed polar front theory during WWI to describe the formation, growth, and dissipation of mid-latitude cyclones.

Vilhelm Bjerknes (1862-1951)
The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.
Southern Oscillation: an atmospheric phenomenon

In 1910s, Walker found a connection between barometer readings at stations on the eastern and western sides of the Pacific (Tahiti and Darwin). He coined the term Southern Oscillation to dramatize the ups and downs in this east-west seesaw effect.
Walker Circulation and Ocean
Monsoon: Sea/Land-Related Circulation

- Monsoon (Arabic “season”)
- 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.
January

[Image of a weather map showing pressure systems, including Aleutian Low, Icelandic Low, Bermuda-Azores High, and Siberian High.]
How Many Monsoons Worldwide?

North America Monsoon

South America Monsoon

Africa Monsoon

Asian Monsoon

Australian Monsoon

(figure from *Weather & Climate*)
Seasonal Cycle of Rainfall

(from IRI)