Chapter 8: Atmospheric Circulation and Pressure Distributions

- General Circulation in the Atmosphere
- General Circulation in Oceans
- Air-Sea Interaction: El Nino

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 \( U = \text{rotational velocity} + u_{eq} \).
- The zonal wind velocity at 60°N \( (u_{60N}) \) can be determined by the following:
  \[
  (U_0 + u_{eq}) \times a \times \cos(0°) = (U_{60N} + u_{60N}) \times a \times \cos(60°) \\
  (\Omega \times a \times \cos(0°) - 5) \times a \times \cos(0°) = (\Omega \times a \times \cos(60°) + u_{60N}) \times a \times \cos(60°) \\
  u_{60N} = 687 \text{ m/sec} !!!!
  \]
This high wind speed is not observed!
Properties of the Three Cells

- **Hadley Cell**: Thermally direct circulation, rising over the Equator (warmer), sinking at 30° (warm).
- **Ferrel Cell**: Thermally indirect circulation, rising at 30° (warm), sinking at 60° (cold).
- **Polar Cell**: Thermally indirect circulation, rising at 60° (cold), sinking at the Pole (colder).

The Three Cells

- **ITCZ (Intertropical Convergence Zone)**: subtropical high, midlatitude weather system.

Precipitation Climatology

- **Mean Jan GPCP Precipitation (79–03)**: ITCZ

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 the cold temperature zone and sinks over the 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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**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 wave patterns (wave number 3 in the Northern hemisphere).

(from Weather & Climate)

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**Bottom Line**

- Pressure and winds associated with Hadley cells are close approximations of real world conditions
- Ferrel and Polar cells do not approximate the real world as well
- Surface winds poleward of about 30° do not show the persistence of the trade winds, however, long-term averages do show a prevalence indicative of the westerlies and polar easterlies
- For upper air motions, the three-cell model is unrepresentative
- The Ferrel cell implies easterlies in the upper atmosphere where westerlies dominate
- Overturning implied by the model is false
- The model does give a good, simplistic approximation of an earth system devoid of continents and topographic irregularities

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**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
Global Distribution of Deserts

Sinking Branches and Deserts

(from Global Physical Climatology)

(from Weather & Climate)
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).

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).

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.
**Scales of Motions in the Atmosphere**

**Cold and Warm Fronts**

- **Mid-Latitude Cyclone**: (From Weather & Climate)

**Tropical Hurricane**

- The hurricane is characterized by a strong thermally direct circulation with the rising of warm air near the center of the storm and the sinking of cooler air outside.

**They Are the Same Things…**

- **Hurricanes**: extreme tropical storms over Atlantic and eastern Pacific Oceans.
- **Typhoons**: extreme tropical storms over western Pacific Ocean.
- **Cyclones**: extreme tropical storms over Indian Ocean and Australia.
Monsoon: Another Sea/Land-Related Circulation of the Atmosphere

- Monsoon is a climatic 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*)

How Many Monsoons Worldwide?

- North America Monsoon
- East Africa Monsoon
- South America Monsoon
- Asian Monsoon
- Australian Monsoon

(figure from *Weather & Climate*)

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*)

Valley and Mountain Breeze

(figure from *The Earth System*)
Basic Ocean Structures

- **Upper Ocean (~100 m)**
  Shallow, warm upper layer where light is abundant and where most marine life can be found.

- **Deep Ocean**
  Cold, dark, deep ocean where plenty supplies of nutrients and carbon exist.

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Six Great Current Circuits in the World Ocean

- 5 of them are geostrophic gyres:
  - North Pacific Gyre
  - South Pacific Gyre
  - North Atlantic Gyre
  - South Atlantic Gyre
  - Indian Ocean Gyre

- The 6th and the largest current:
  - Antarctic Circumpolar Current (also called West Wind Drift)

(From Oceanography by Tom Garrison)

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Characteristics of the Gyres

- Currents are in geostrophic balance
- Each gyre includes 4 current components:
  - two boundary currents: western and eastern
  - two transverse currents: eastward and westward

  **Western boundary current** (jet stream of ocean)
  - the fast, deep, and narrow current moves warm water polarward (transport ~ 50 Sverdrup or greater)

  **Eastern boundary current**
  - the slow, shallow, and broad current moves cold water equatorward (transport ~ 10-15 Sverdrup)

  **Trade wind-driven current**
  - the moderately shallow and broad westward current (transport ~ 30 Sverdrup)

  **Westerly-driven current**
  - the wider and slower (than the trade wind-driven current) eastward current

Volume transport unit:

1 Sverdrup = 1 million m³/sec

(The Amazon river has a transport of ~0.17 Sverdrup)

(Figure from Oceanography by Tom Garrison)
Major Current Names

- **Western Boundary Current**
  - Gulf Stream (in the North Atlantic)
  - Kuroshio Current (in the North Pacific)
  - Brazil Current (in the South Atlantic)
  - Eastern Australian Current (in the South Pacific)
  - Agulhas Current (in the Indian Ocean)

- **Eastern Boundary Current**
  - Canary Current (in the North Atlantic)
  - California Current (in the North Pacific)
  - Benguela Current (in the South Atlantic)
  - Peru Current (in the South Pacific)
  - Western Australian Current (in the Indian Ocean)

- **Trade Wind-Driven Current**
  - North Equatorial Current
  - South Equatorial Current

- **Westerly-Driven Current**
  - North Atlantic Current (in the North Atlantic)
  - North Pacific Current (in the North Pacific)

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**Step 1: Surface Winds**

(Figure from *Oceanography* by Tom Garrison)

**Step 2: Ekman Layer**

(frictional force + Coriolis Force)

(Figure from *Oceanography* by Tom Garrison)
Ekman Spiral – A Result of Coriolis Force

Step 3: Geostrophic Current
(Pressure Gradient Force + Coriolis Force)

Ekman Transport

Thermohaline Conveyor Belt

- Typical speed for deep ocean current: 0.03-0.06 km/hour.
- Antarctic Bottom Water takes some 250-1000 years to travel to North Atlantic and Pacific.

(Efigure from The Earth System)

(Figure from Oceanography by Tom Garrison)
Thermohaline Circulation

- Thermo ⇒ temperature
- Haline ⇒ salinity

Density-Driven Circulation

- Cold and salty waters go down
- Warm and fresh waters go up

Global Warming and Thermohaline Circulation

- **If the warming is slow**
  - The salinity is high enough to still produce a thermohaline circulation
  - The circulation will transfer the heat to deep ocean
  - The warming in the atmosphere will be deferred.

- **If the warming is fast**
  - Surface ocean becomes so warm (low water density)
  - No more thermohaline circulation
  - The rate of global warming in the atmosphere will increase.

Mid-Deglacial Cooling: The Younger Dryas

- The mid-deglacial pause in ice melting was accompanied by a brief climate oscillation in records near the subpolar North Atlantic Ocean.
- Temperature in this region has warmed part of the way toward interglacial levels, but this reversal brought back almost full glacial cold.
- Because an Arctic plant called “Dryas” arrived during this episode, this mid-deglacial cooling is called the Younger Dryas event.

Interaction Within Climate System

- This hypothesis argues that millennial oscillations were produced by the internal interactions among various components of the climate system.
- One most likely internal interaction is the one associated with the deep-water formation in the North Atlantic.
- Millennial oscillations can be produced from changes in northward flow of warm, salty surface water along the conveyor belt.
- Stronger conveyor flow releases heat that melts ice and lowers the salinity of the North Atlantic, eventually slowing or stopping the formation of deep water.
- Weaker flow then causes salinity to rise, completing the cycle.
The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

Walker Circulation and Ocean Temperature

Precipitation Climatology

Walker Circulation and Ocean
El Nino and Southern Oscillation

- Jacob Bjerknes was the first one to recognize that El Nino is not just an oceanic phenomenon (in his 1969 paper).
- Instead, he hypothesized that the warm waters of El Nino and the pressure seasaw of Walker’s Southern Oscillation are part and parcel of the same phenomenon: the ENSO.
- Bjerknes’s hypothesis of coupled atmosphere-ocean instability laid the foundation for ENSO research.

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.
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.

Coupled Atmosphere-Ocean System

- Normal Condition
- El Nino Condition
  - (from NOAA)

**ENSO’s Phase-Lock to the Annual Cycle**

- Composition analyses have shown that ENSO events tend to onset, grow, and decay at certain seasons of the year (Rasmusson and Carpenter 1982)
Delayed Oscillator: Wind Forcing

The delayed oscillator suggested that oceanic Rossby and Kevin waves forced by atmospheric wind stress in the central Pacific provide the phase-transition mechanism (i.e., memory) for the ENSO cycle.

The propagation and reflection of waves, together with local air-sea coupling, determine the period of the cycle.

Why Only Pacific Has ENSO?

Based on the delayed oscillator theory of ENSO, the ocean basin has to be big enough to produce the “delayed” from ocean wave propagation and reflection.

It can be shown that only the Pacific Ocean is “big” (wide) enough to produce such delayed for the ENSO cycle.

It is generally believed that the Atlantic Ocean may produce ENSO-like oscillation if external forcing are applied to the Atlantic Ocean.

The Indian Ocean is considered too small to produce ENSO.

Wave Propagation and Reflection

- It takes Kevin wave (phase speed = 2.9 m/s) about 70 days to cross the Pacific basin (17,760 km).
- It takes Rossby wave about 200 days (phase speed = 0.93 m/s) to cross the Pacific basin.

North Atlantic Oscillation

- The NAO is the dominant mode of winter climate variability in the North Atlantic region ranging from central North America to Europe and much into Northern Asia.
- The NAO is a large scale seesaw in atmospheric mass between the subtropical high and the polar low.
- The corresponding index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years.

(from http://www.ldeo.columbia.edu/res/pi/NAO/)

北極圏を含む大気圏の変動の指標，北大西洋オシレーション（NAO）

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Positive and Negative Phases of NAO

Positive Phase
- A stronger and more northward storm track.
- A deeper than normal Icelandic low.
- More and stronger winter storms crossing the Atlantic Ocean on a more northerly track.
- Cold winters in northern Canada and Greenland
- The eastern US experiences mild and wet winter conditions

Negative Phase
- A weaker and more zonal storm track.
- Weak subtropical high and weak Icelandic low.
- Fewer and weaker winter storms crossing on a more west-east zonal pathway.
- Moist air into the Mediterranean and cold air to northern Europe
- US east coast experiences more cold air outbreaks and hence snowy weather conditions.
- Greenland, however, will have milder winter temperatures

North Atlantic Oscillation
= Arctic Oscillation
= Annular Mode