Lecture 5: Atmospheric General Circulation and Climate

Chapter 6: Atmospheric General Circulation and Climate
- Abstract
- 6.1. The great communicator
- ~~6.2. Energy balance of the atmosphere~~
- 6.3. Atmospheric motions and the meridional transport of energy
- 6.4. The angular-momentum balance
- 6.5. Large-scale circulation patterns and climate

- ❑ Geostrophic balance
- ❑ Zonal-mean circulation
- ❑ Transients and eddies
- ❑ Meridional energy transport
- ❑ Moist static energy
- ❑ Angular momentum balance

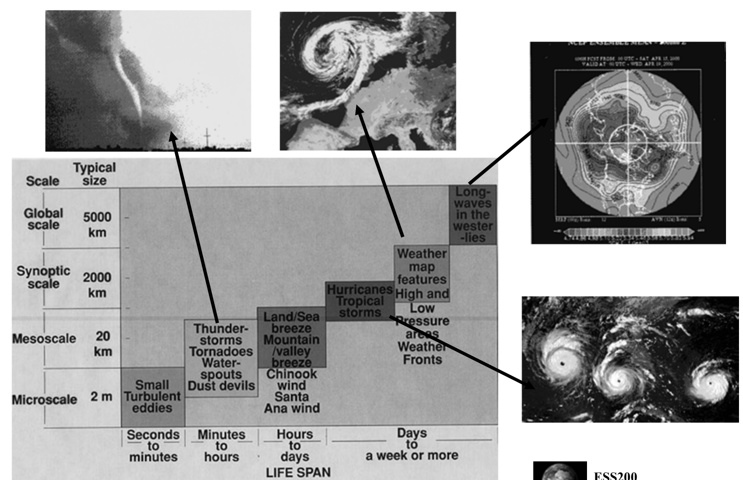
Atmosphere – the Great Communicator

- ❑ 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.

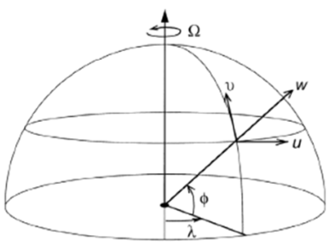
Atmospheric General Circulation

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



Wind Components



$u = a\cos\phi \dfrac{D\lambda}{Dt}$ = zonal or eastward wind speed

$v = a \dfrac{D\phi}{Dt}$ = meridional or northward wind speed

$w = \dfrac{Dz}{Dt}$ = rate of change of altitude following an air parcel

$\omega = \dfrac{Dp}{Dt}$ = rate of change of pressure following an air parcel

$\omega \cong -\rho g w$

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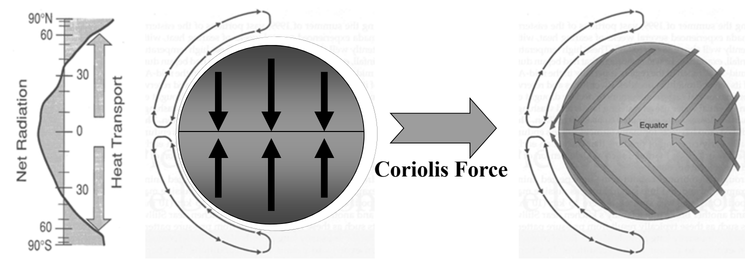
Single-Cell Model: Explains Why There are Tropical Easterlies



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

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Newton's 2nd Law in a Rotating Frame

$$\frac{D_a \mathbf{U}_a}{Dt} = \sum \mathbf{F}$$

using

$$\frac{D_a \mathbf{U}_a}{Dt} = \frac{D\mathbf{U}_a}{Dt} + \mathbf{\Omega} \times \mathbf{U}_a$$

← covert acceleration from an inertial to a rotating frames

$$\mathbf{U}_a = \mathbf{U} + \mathbf{\Omega} \times \mathbf{r}$$

← 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

$$\Rightarrow \frac{D_a \mathbf{U}_a}{Dt} = \frac{D}{Dt}(\mathbf{U} + \mathbf{\Omega} \times \mathbf{r}) + \mathbf{\Omega} \times (\mathbf{U} + \mathbf{\Omega} \times \mathbf{r})$$

[Here $\mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}) = \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{R}) = -\Omega^2 \mathbf{R}$]

$$\Rightarrow \frac{D_a \mathbf{U}_a}{Dt} = \frac{D\mathbf{U}}{Dt} + 2\mathbf{\Omega} \times \mathbf{U} - \Omega^2 \mathbf{R}$$

Coriolis force — Centrifugal force

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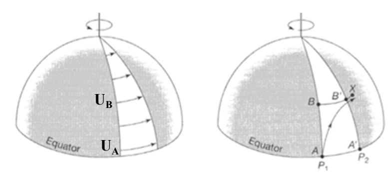
Coriolis Force



(from *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":

Coriolis Force = $f\,V$

where $f = 2*\Omega*\text{Sin(lat)}$ and Ω=7.292x10^{-5} rad s^{-1}

(see Section 6.4 and Eq. 6.15 of Global Physical Climatology)

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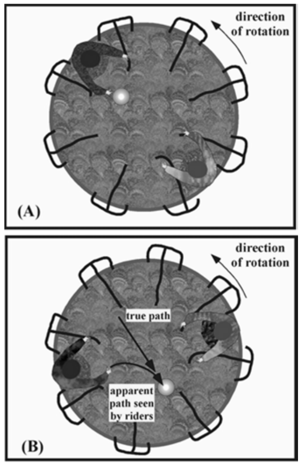
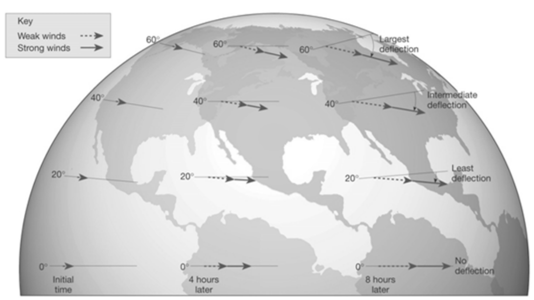
Example on a Merry-Go-Around



Coriolis Force

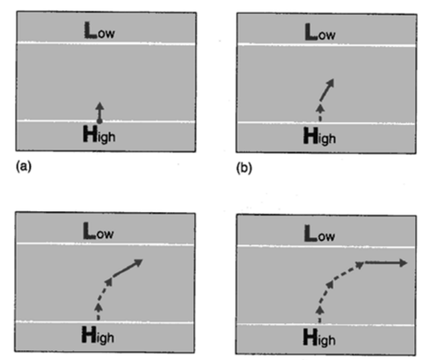
- Coriolis force causes the wind to deflect to the right of its intent path in the Northern Hemisphere and to the left in the Southern Hemisphere.
- The magnitude of Coriolis force depends on (1) the rotation of the Earth, (2) the speed of the moving object, and (3) its latitudinal location.
- The larger the speed (such as wind speed), the stronger the Coriolis force.
- The higher the latitude, the stronger the Coriolis force.
- The Corioils force is zero at the equator.
- Coriolis force is one major factor that determine weather pattern.

Coriolis Force Change with latitudes



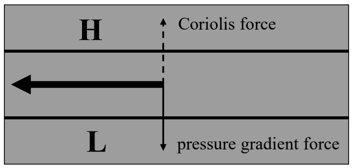
(from *The Atmosphere*)

How Does Coriolis Force Affect Wind Motion?



(from *Weather & Climate*)

Geostrophic Balance



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

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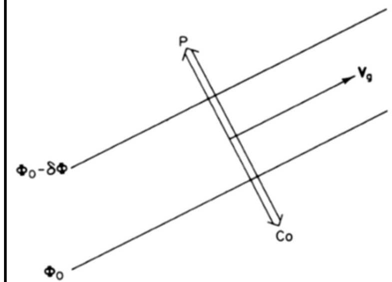
Geostrophic Balance



$$fV_g = -\partial\Phi/\partial n$$

Flow in a straight line (R → ± ∞) parallel to height contours is referred to as *geostrophic motion*. In geostrophic motion the horizontal components of the Coriolis force and pressure gradient force are in exact balance so that *V* = *Vg*.

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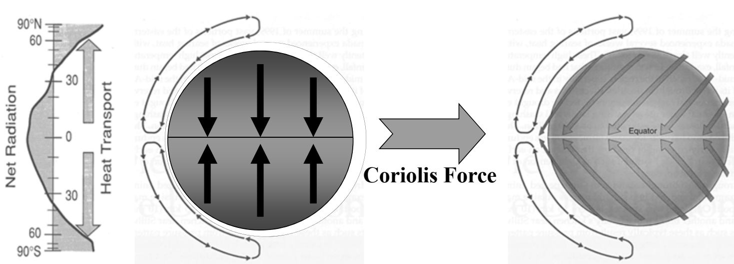
Single-Cell Model: Explains Why There are Tropical Easterlies

Without Earth Rotation **With Earth Rotation**



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

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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 equatoru 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:

$$(U_0 + u_{Eq}) * a * Cos(0^\circ) = (U_{60N} + u_{60N}) * a * Cos(60^\circ)$$

$$(\Omega*a*Cos0^\circ - 5) * a * Cos0^\circ = (\Omega*a*Cos60^\circ + u_{60N}) * a * Cos(60^\circ)$$

u_{60N} = 687 m/sec !!!!

This high wind speed is not observed!

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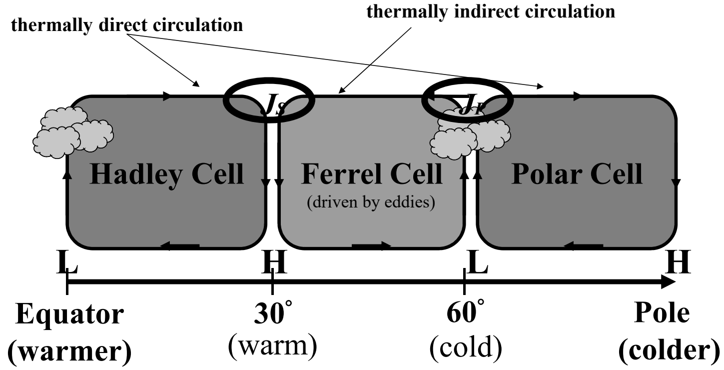
Properties of the Three Cells



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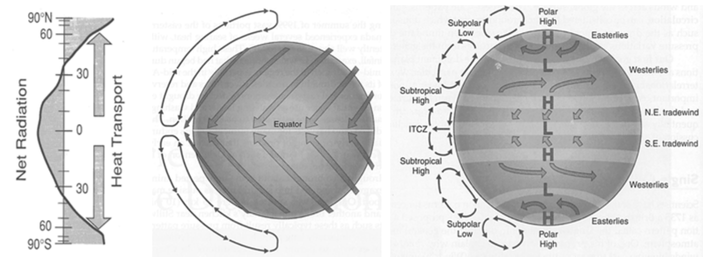
Atmospheric Circulation: Zonal-mean Views

Single-Cell Model Three-Cell Model



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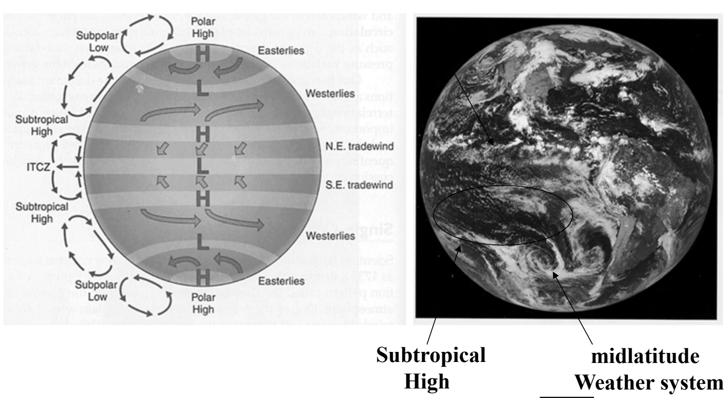
The Three Cells



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

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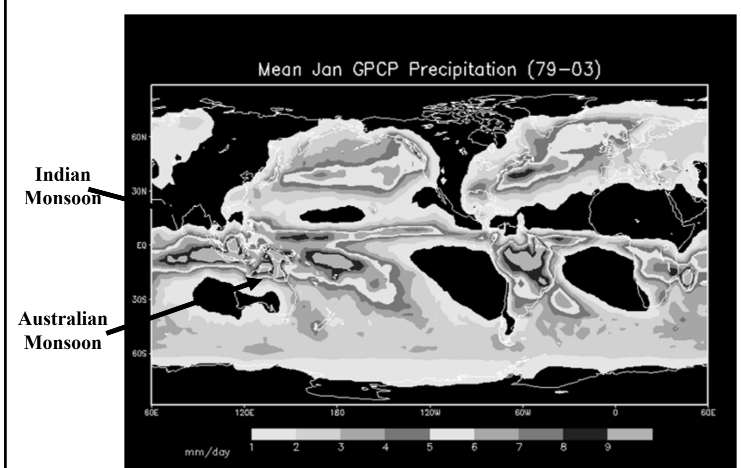
Seasonal Cycle of Rainfall



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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

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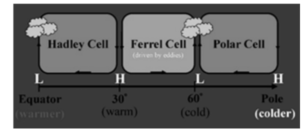
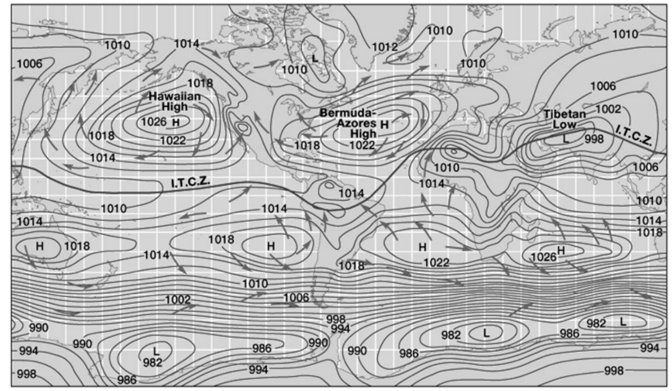
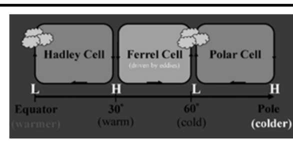
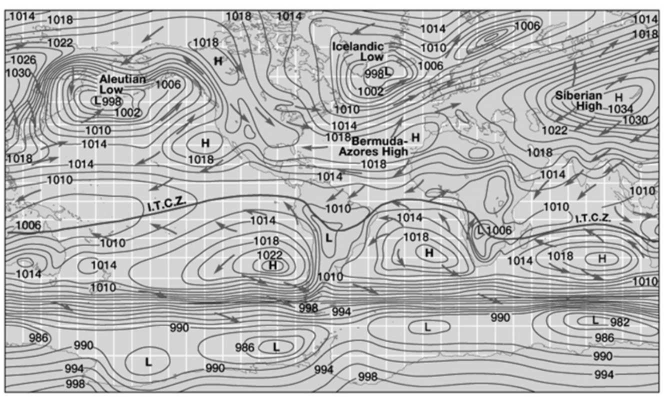


July

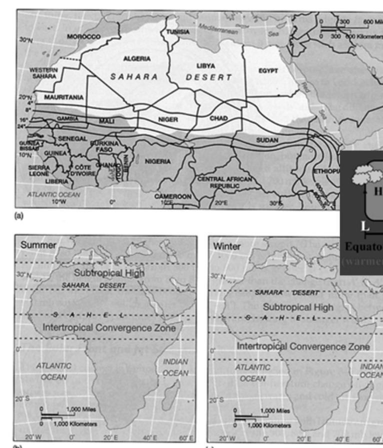


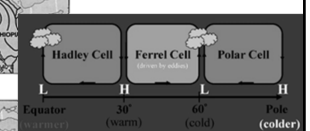


January



Sinking Branches and Deserts





(from *Weather & Climate*)

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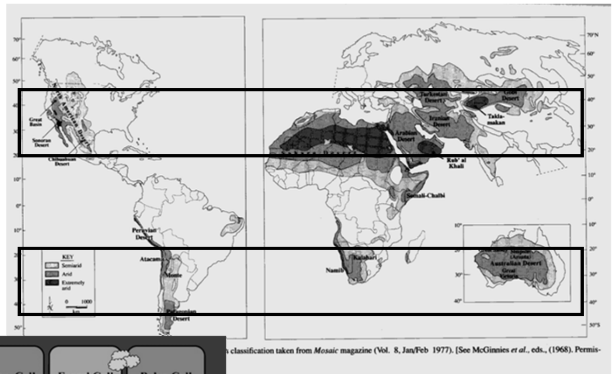
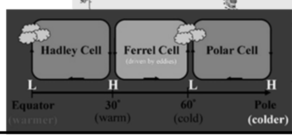
Global Distribution of Deserts





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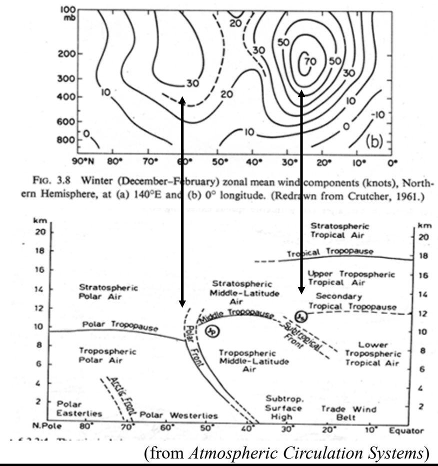
Subtropical and Polar Jet Streams



(from *Atmospheric Circulation Systems*)

- **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).

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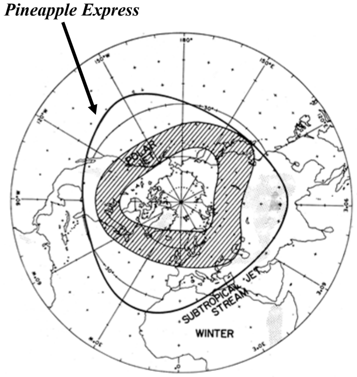
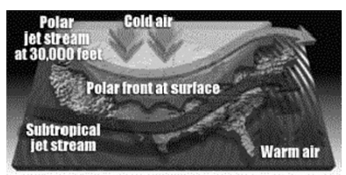
Jet Streams Near the Western US

Pineapple Express



(from *Riehl (1962), Palmen and Newton (1969)*)



- 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.

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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

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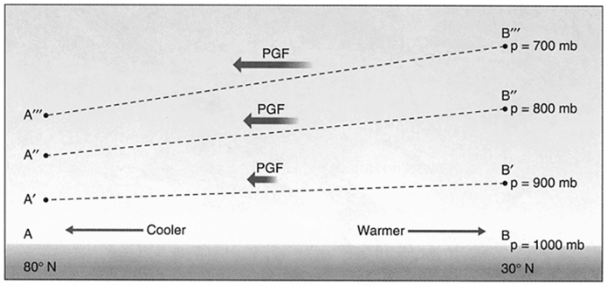
Thermal Wind Equation

$$\partial U/\partial z \propto -\partial T/\partial y$$

- ❑ 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).

Thermal Wind Relation



(from *Weather & Climate*)

Atmospheric Circulation and Temperature

Zonal Wind

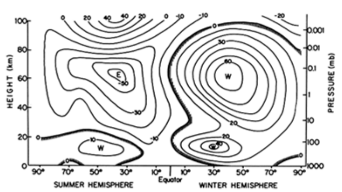


Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind ($m\,s^{-1}$) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

Temperature

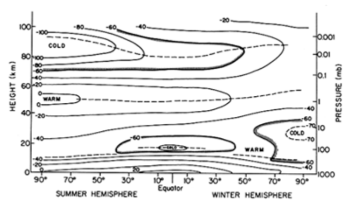


Fig. 1.3. Schematic latitude-height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)

Atmospheric Circulation

Zonal Wind

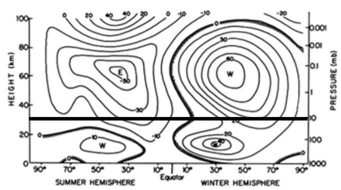
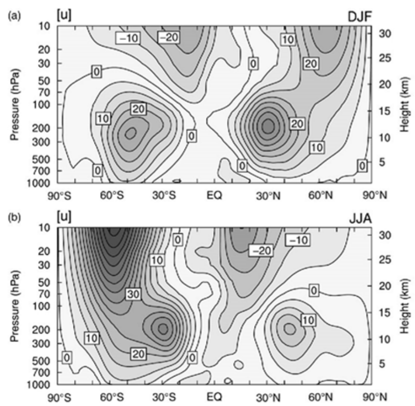
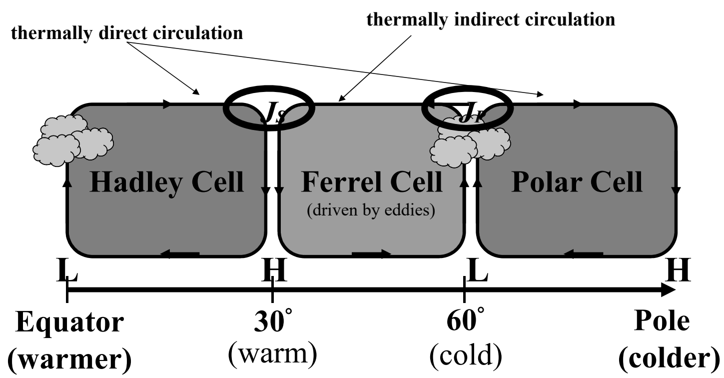


Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind ($m\,s^{-1}$) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)



(from *Global Physical Climatology*)

Properties of the Three Cells



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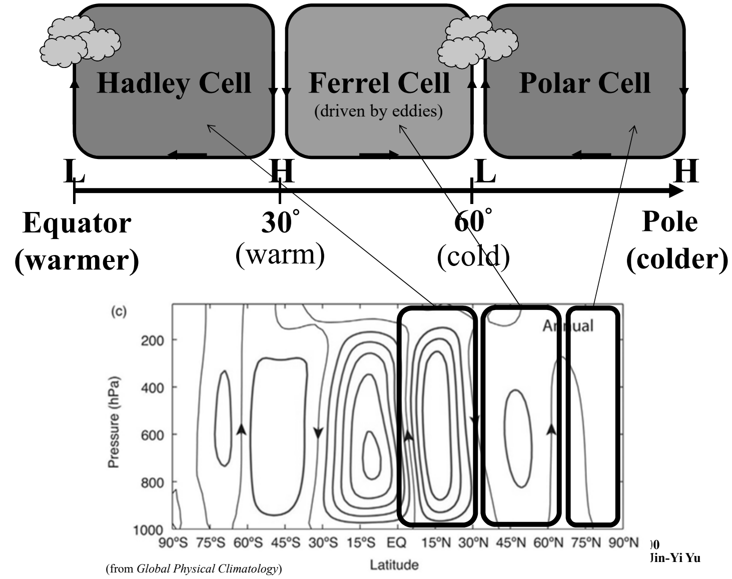
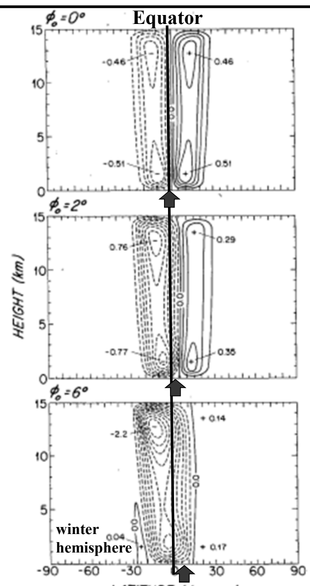
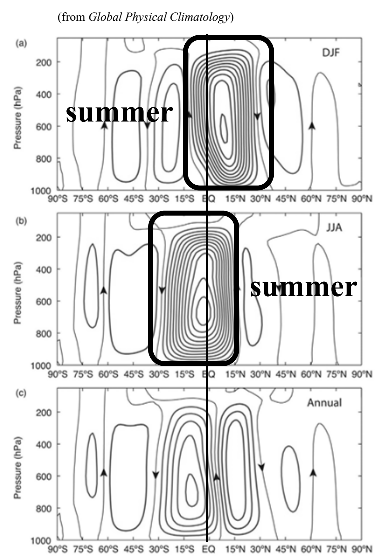


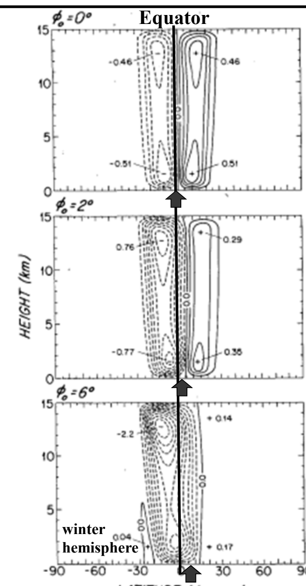
Off-Equatorial Heating

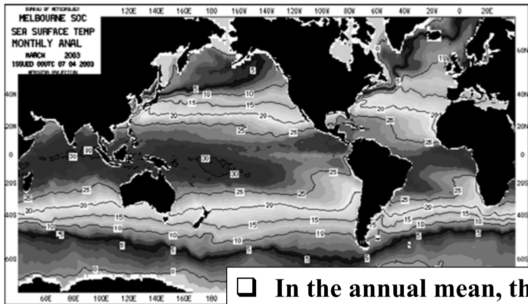
" .. We find that moving peak heating even 2 degree off the equator leads to profound asymmetries in the Hadley circulation, *with the winter cell amplifying greatly and the summer cell becoming negligible*."

--- Lindzen and Hou (1988; JAS)









- 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.

The Zonal Mean Circulation

Zonal average: $[x] = \frac{1}{2\pi}\int_0^{2\pi} x\,d\lambda$

Temporal average: $\overline{x} = \frac{1}{\Delta t}\int_0^{\Delta t} x\,dt$

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

Eddies = deviations from zonal averages
Transients = deviations from time averages

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Stationary and Transient Eddies

$$[\overline{vT}] = [\overline{v}][\overline{T}] + [\overline{v}^*\overline{T}^*] + [\overline{v'T'}]$$

total heat transport

heat transport by mean flows

heat transport by stationary eddies

heat transport by transient eddies

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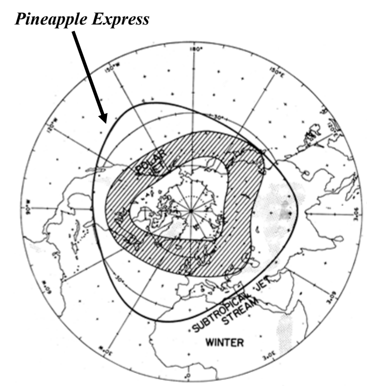
Stationary Eddies



(from *Riehl (1962), Palmen and Newton (1969)*)

- 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.

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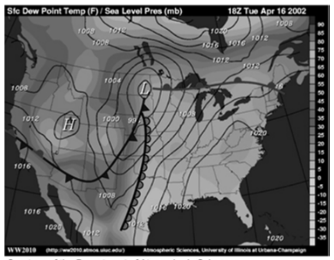
Transient Eddies



Courtesy of the Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign

- 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).

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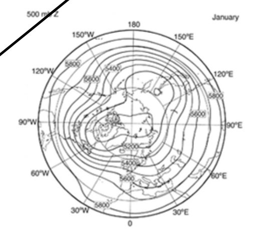
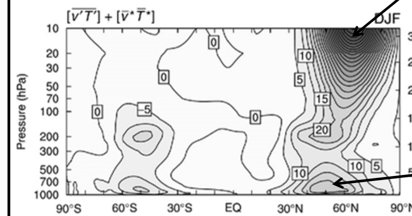
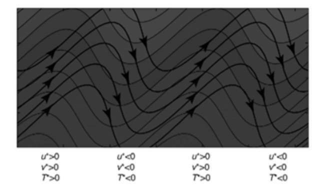
Poleward Heat Flux by Eddies

Stationary Eddies



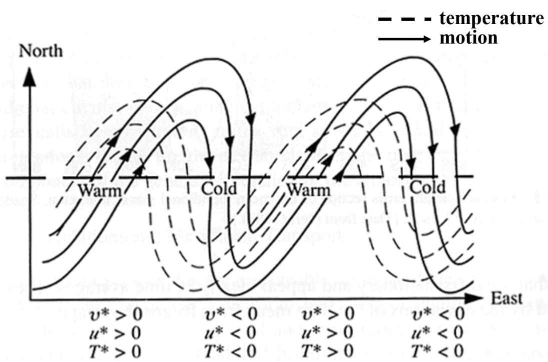


Transient Eddies



(from *Global Physical Climatology*)

Transient/Eddy Flux



[V*T*] > 0 ➔ On zonal average, eddies transport heat northward.
➔ Eddies contribute to zonal-mean heat transport

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Four Types of Energy in Atmosphere

TABLE 6.1 Kinds and Amounts of Energy in the Global Atmosphere

Name	Symbol	Formula	Amount (J m^{-2})	Total (%)
Internal energy	IE	c_vT	1800×10^6	70
Potential energy	PE	gz	700×10^6	27
Latent energy	LH	Lq	70×10^6	2.7
Kinetic energy	KE	$1/2(u^2 + v^2)$	1.3×10^6	0.05
Total energy	IE + PE + LH + KE		2571×10^6	100

- Internal energy: associated with the temperature of the atmosphere.
- Potential energy: associated with the gravitational potential of air 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).

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Angular Momentum Balance

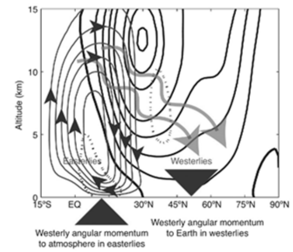

FIGURE 6.17 **Schematic illustration of the flow of angular momentum from the Earth through the atmosphere and back to Earth.** Blue contours with arrows are the mean meridional stream function. Solid black lines are zonal mean wind. Dotted contours indicate negative values of zonal wind and stream function. Wavy arrows indicate poleward and downward angular momentum transport by eddies. Wind and stream function are for January.

- 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.
- 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.
- This westerly angular momentum is transported upward and then poleward in the Hadley cell.

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Parameters Determining Mid-latitude Weather

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

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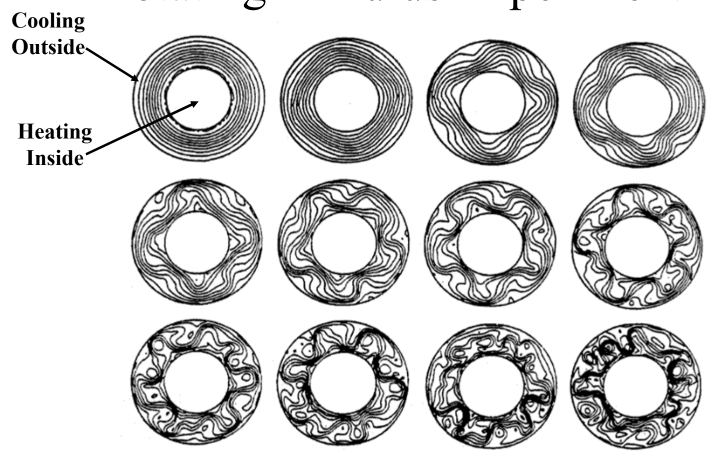
Rotating Annulus Experiment



(from ***"Is The Temperature Rising?"***)

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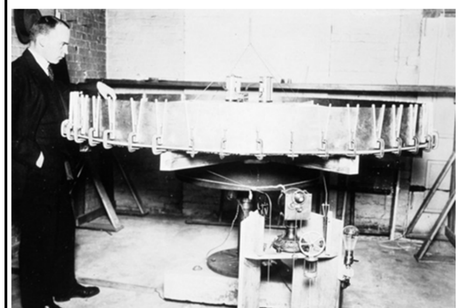
Polar Front Theory

Vilhelm Bjerknes (1862-1951)

- ***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.

New Understanding of Cyclone after WWII

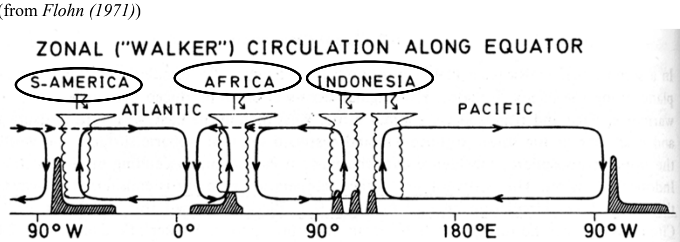


Carl Gustav Rossby (1898-1957)

- 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" instabiloity associated with the north-south temperature differences in middle latitudes.

East-West Circulation

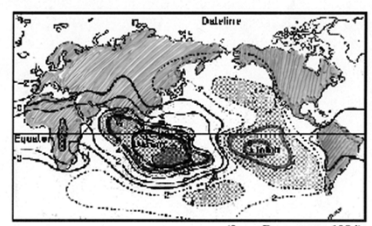
(from *Flohn (1971)*)



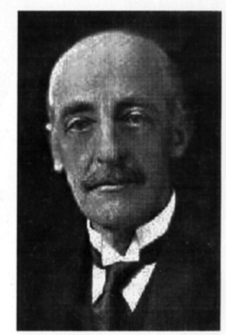
- The east-west circulation in the atmosphere is related to the sea/land distribution on the Earth.

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.

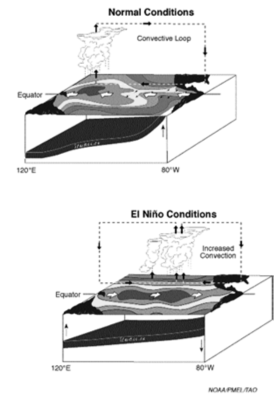


(from Rasmusson 1984)



Sir Gilbert Walker

Walker Circulation and Ocean



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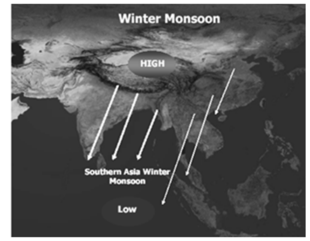
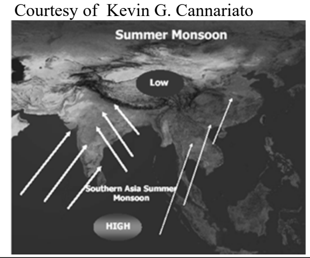
Monsoon: Sea/Land-Related Circulation



Courtesy of Kevin G. Cannariato



- ❑ 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.

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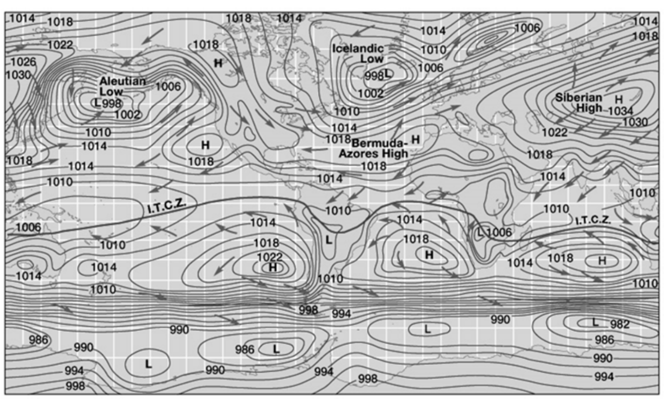
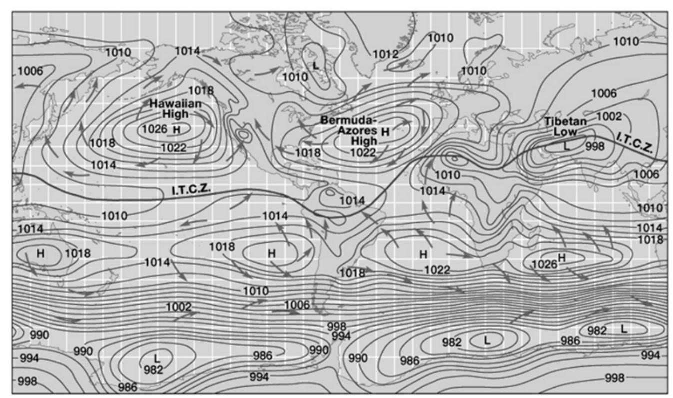
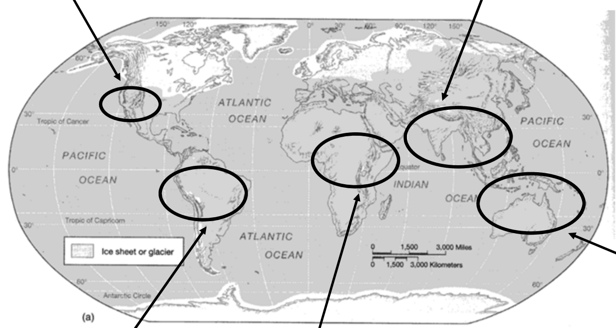
January



July



How Many Monsoons Worldwide?



(figure from *Weather & Climate*)

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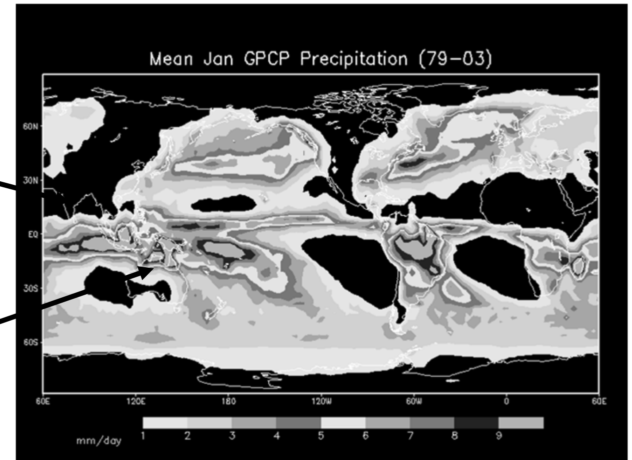
Seasonal Cycle of Rainfall



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