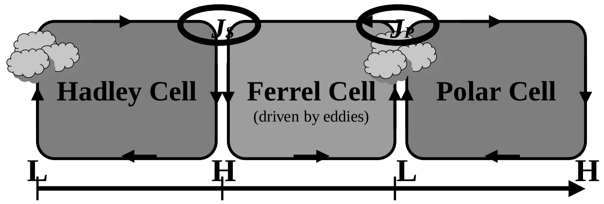
Lecture 3: ATMOSPHERE (Outline)



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

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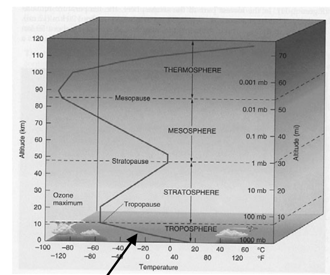
Vertical Structure

Standard Atmosphere



(from *Understanding Weather & Climate*)

lapse rate = 6.5 C/km

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
- very little mass

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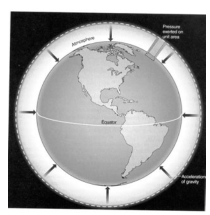
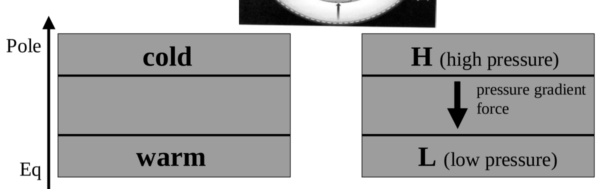
Thermal Energy to Kinetic Energy





(on a horizontal surface)

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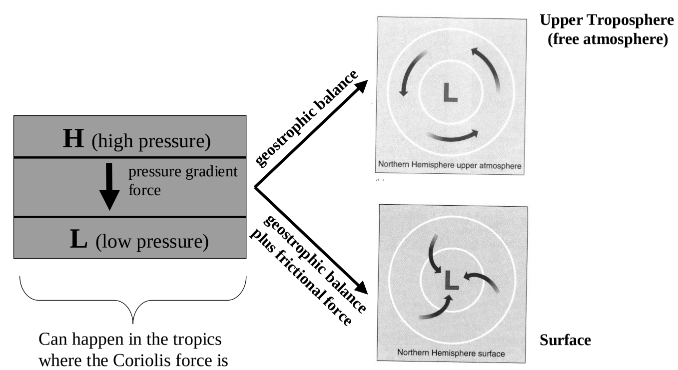
Balance of Force in the Horizontal



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

(from *Weather & Climate*)

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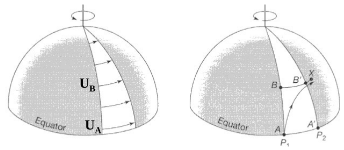
Coriolis Force



(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 $f = 2*\Omega*\mathrm{Sin(lat)}$ and $\Omega = 7.292\times10^{-5}$ rad s^{-1}

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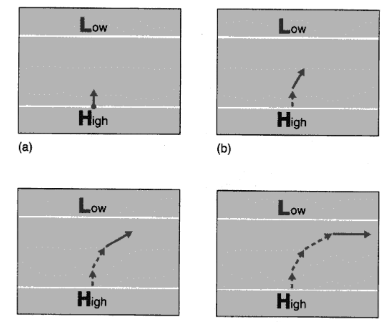
How Does Coriolis Force Affect Wind Motion?



(from *Weather & Climate*)

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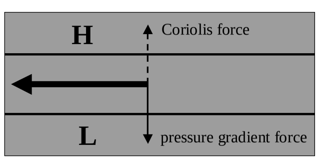
Geostrophic Balance



- ❑ 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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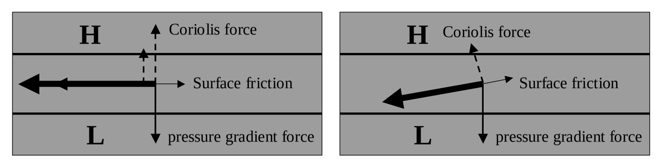
Frictional Effect on Surface Flow



- ❑ 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.

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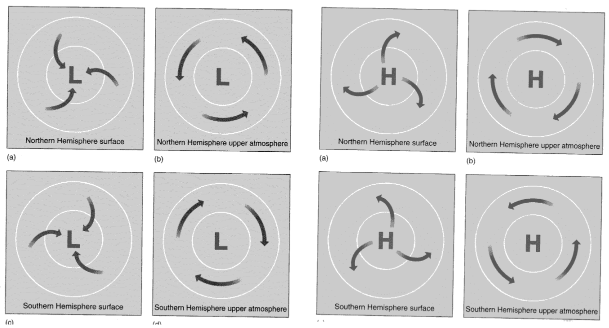
Surface Geostrophic Flow

Cyclonic Flow **Anticyclonic Flow**



(figures from *Weather & Climate*)

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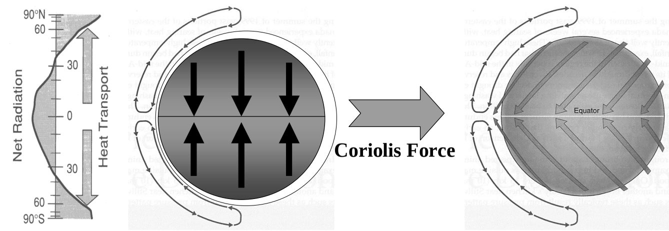
Single-Cell Model: Explains Why There are Tropical Easterlies

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:

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

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

$$\boxed{\mathbf{u_{60N} = 687\ m/sec\ !!!!}}$$

This high wind speed is not observed!

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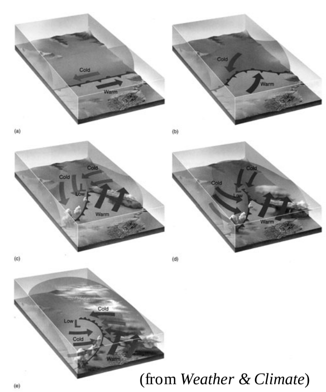
Baroclinic Instability



(from *Weather & Climate*)

- ❑ 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.

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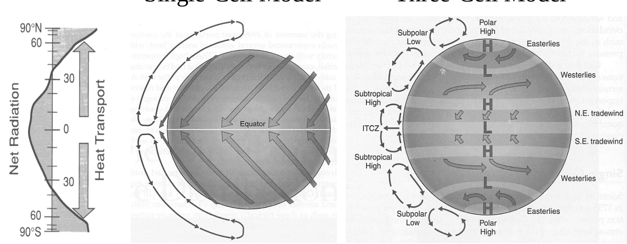
Atmospheric Circulation: Zonal-mean Views

Single-Cell Model | Three-Cell Model



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

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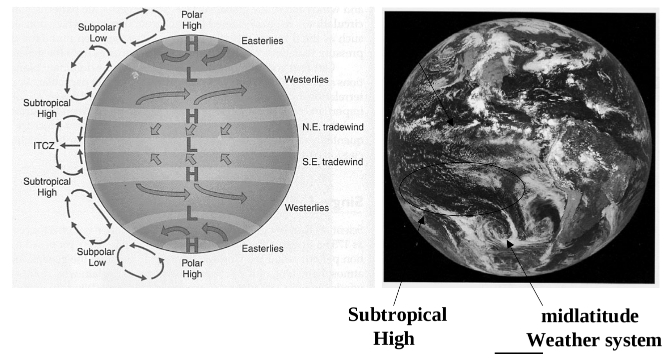
The Three Cells



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

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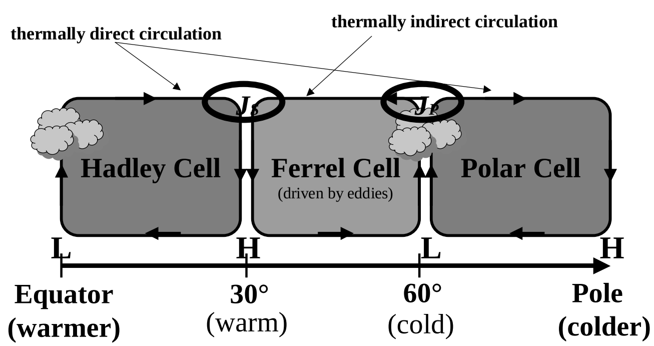
Properties of the Three Cells



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Thermally Direct/Indirect Cells

- **Thermally Direct Cells (Hadley and Polar Cells)**
  Both cells have their rising branches over warm temperature zones and sinking braches 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.

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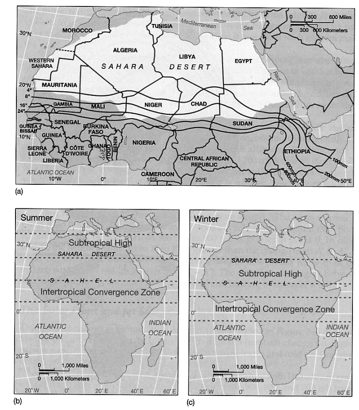
Is the Three-Cell Model Realistic?

❑ ***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 can not explain the circulation pattern in the upper troposphere. (planetary wave motions are important here.)

Sinking Branches and Deserts



(from *Weather & Climate*)

Global Distribution of Deserts

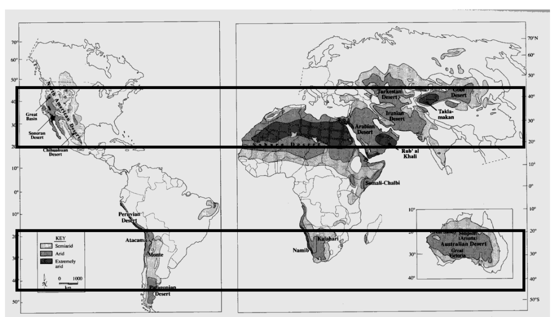
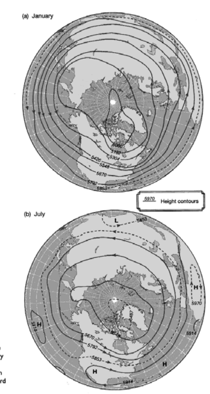


Fig. 6.21 Map showing arid lands around the world. Meigs classification taken from *Mosaic* magazine (Vol. 8, Jan/Feb 1977). [See McGinnies *et al.*, eds., (1968). Permission granted by the Office of Arid Lands Studies.]

(from *Global Physical Climatology*)

Upper Tropospheric Circulation



▶ **Figure 8–5**
The mean heights of the 500 mb levels for January (a) and July (b). The pattern is mostly zonal with decreasing heights toward the poles.

❑ 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

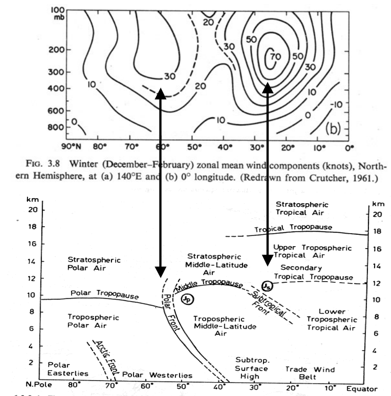


FIG. 3.8 Winter (December–February) zonal mean wind components (knots), Northern Hemisphere, at (a) 140°E and (b) 0° longitude. (Redrawn from Crutcher, 1961.)

(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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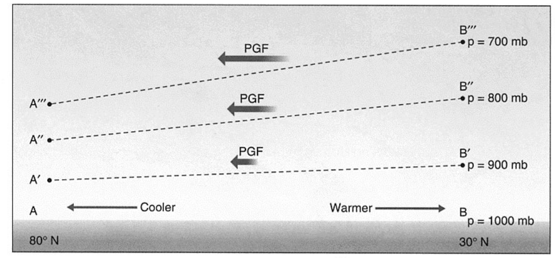
Thermal Wind Relation



(from *Weather & Climate*)

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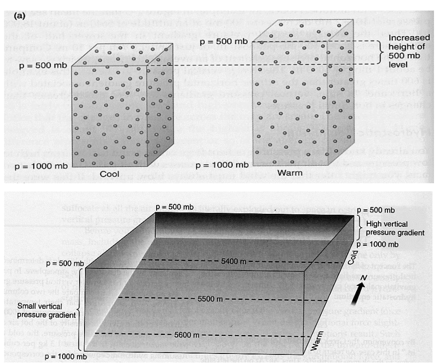
Temperature and Pressure



(from *Weather & Climate*)

- 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.

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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).

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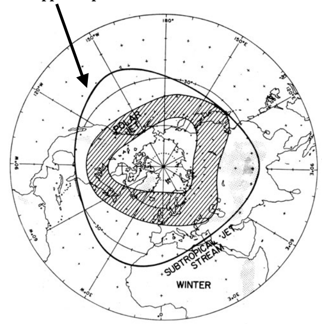
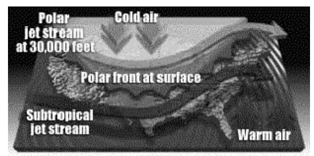
Jet Streams Near the Western US





- ❑ 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)*)

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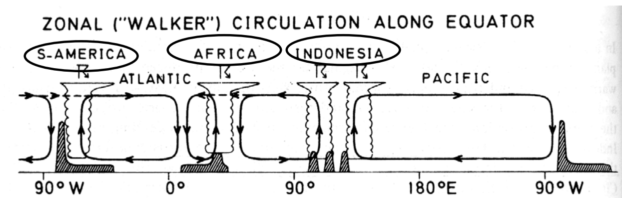
East-West Circulation

(from *Flohn (1971)*)



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

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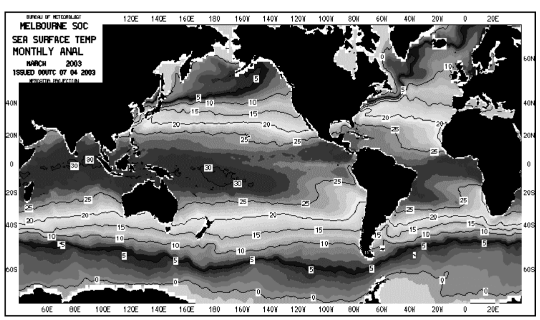
Walker Circulation and Ocean Temperature



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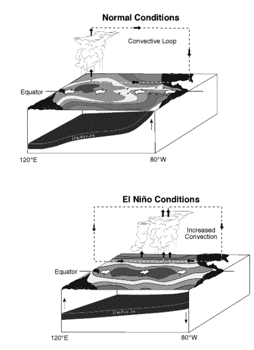
Walker Circulation and Ocean



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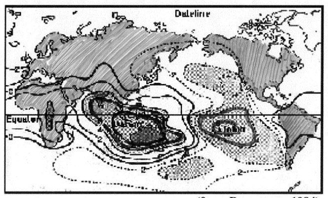
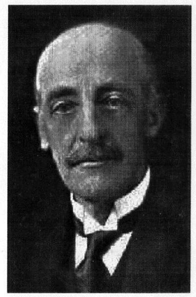
Southern Oscillation: an atmospheric phenomenon

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

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History of El Niño

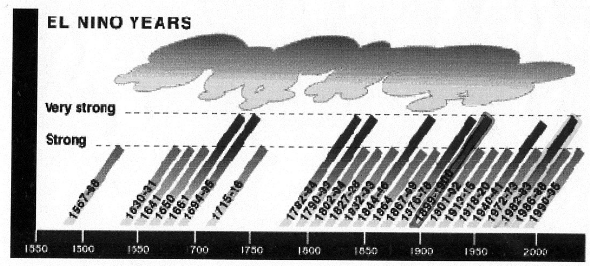

Table from Environmental News Network

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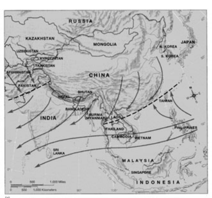
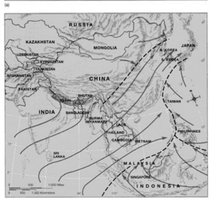
Monsoon: Another Sea/Land-Related Circulation of the Atmosphere

Winter



Summer



- 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*)

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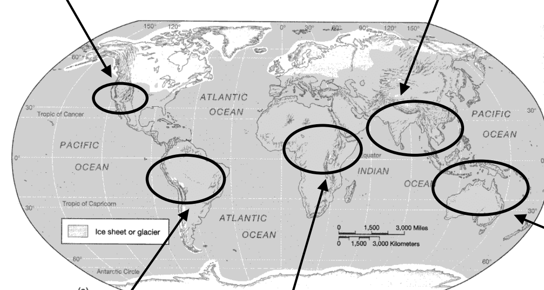
How Many Monsoons Worldwide?



(figure from *Weather & Climate*)

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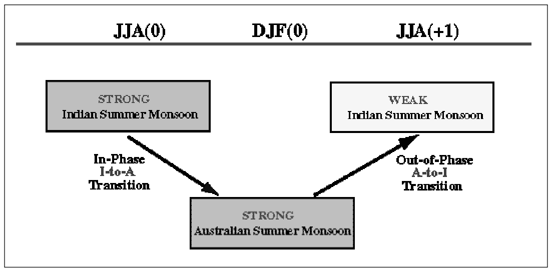
Tropospheric Biennial Oscillation (TBO)

❑ 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.



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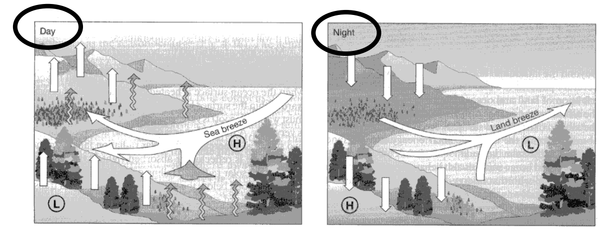
Sea/Land Breeze



❑ 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 costal phenomenon) than monsoon (a seasonal and continental-scale phenomenon).

(figure from *The Earth System*)

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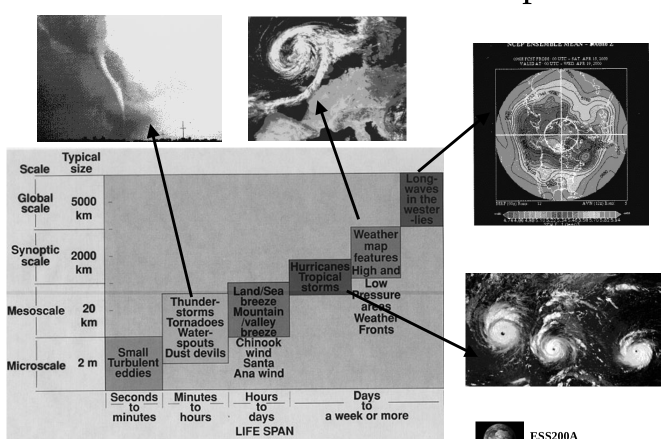
Scales of Motions in the Atmosphere



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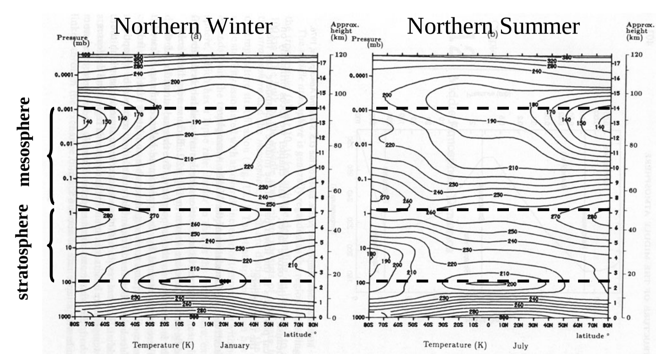
Temperatures in Stratosphere



(from *Dynamic Meteorology*)

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Ozone Distribution

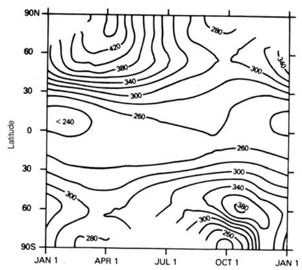
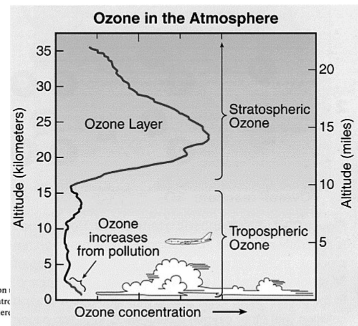


Fig. 12.13 Time-latitude section showing the seasonal variation of total ozone (Dobson based on total ozone mapping spectrometer (TOMS) data. Note the extratro springtime maxima in both hemispheres and the minimum at 90°S center October 1. (After Bowman and Krueger, 1985.)



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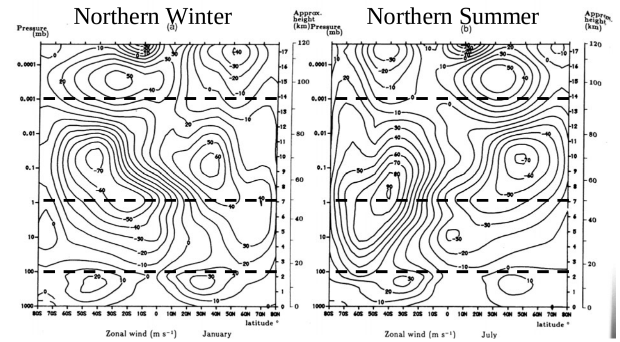
Circulation in Stratosphere



(from *Dynamic Meteorology*)

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Stratosphere: Circulation and Temperature

Zonal Wind

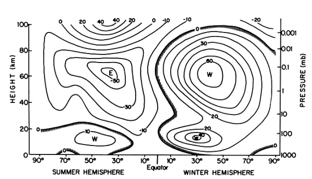

Fig. 1.4. Schematic latitude-height section of zonal mean zonal wind ($m\ s^{-1}$) for solstice conditions; W and E designate centers of westerly (from the west) and easterly (from the east) winds, respectively. (Courtesy of R. J. Reed.)

Temperature

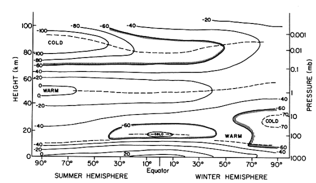

Fig. 1.3. Schematic latitude-height section of zonal mean temperatures (°C) for solstice conditions. Dashed lines indicate tropopause, stratopause, and mesopause levels. (Courtesy of R. J. Reed.)

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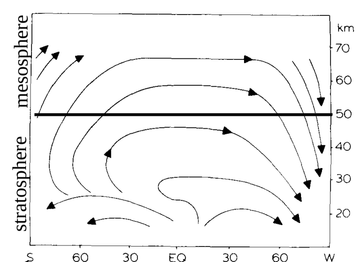
Zonal-Mean Circulation in the Stratosphere



summer

winter

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Ozone Production and Destruction

(from *The Earth System*)

The Chapman Mechanism of Ozone Production and Destruction

Reaction*		Rate
1)	O_2 + UV photon $\rightarrow$ O + O	Slow
2)	O + O_2 + M $\rightarrow$ O_3 + M	Fast
3)	O_3 + photon $\rightarrow$ O_2 + O	Fast
4)	O + O_3 $\rightarrow$ 2 O_2	Slow

Photodissociation (or photolysis)

production

destruction

visible light

destroy O3 permanently

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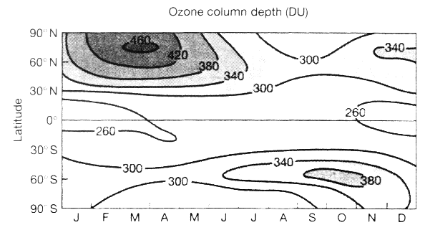
Ozone Distribution



(from *The Earth System*)

- ❑ 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.

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Climate Variations in Stratosphere

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

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QBO

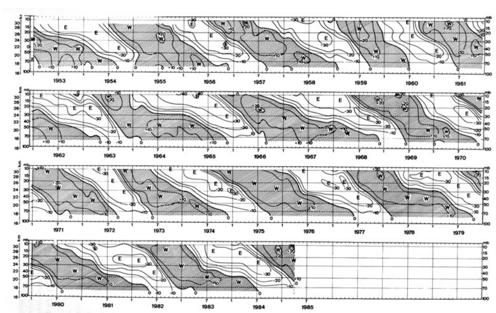

Fig. 8.1. Time-height section of monthly mean zonal winds ($m\,s^{-1}$) at equatorial stations (Jan. 1953–Aug. 1967: Canton Island, 3°S/172°W; Sept. 1967–Dec. 1975: Gan/Maldive Islands, 1°S/73°E; Jan. 1976–Apr. 1985: Singapore, 1°N/104°E). Isopleths are at 10-$m\,s^{-1}$ intervals. Note the alternating downward propagating westerly (W) and easterly (E) regimes. [From Naujokat (1986), with permission.]

❑ Quasi-Biennial Oscillation: Easterly and westerly winds alternate every other years (approximately) in the lower to middle stratosphere.

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Why QBO?

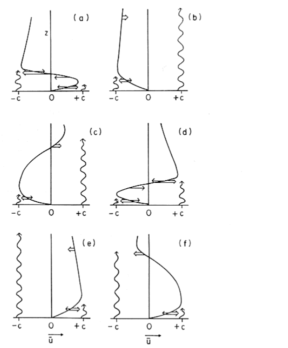

Fig. 8.7. Schematic representation of the evolution of the mean flow in Plumb's analog of the QBO. Six stages of a complete cycle are shown. Double arrows show wave-driven accelerations and single arrows show viscously driven accelerations. Wavy lines indicate relative penetration of easterly and westerly waves. See text for details. [After Plumb (1984).]

- ❑ Kevin Waves accelerate westerly.
- ❑ Rossby-Gravity Wave accelerate easterly.

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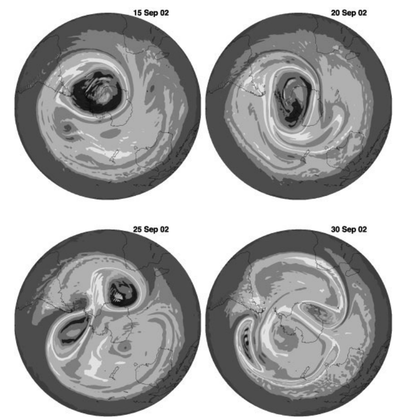
Sudden Warming



- ❑ 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!

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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.

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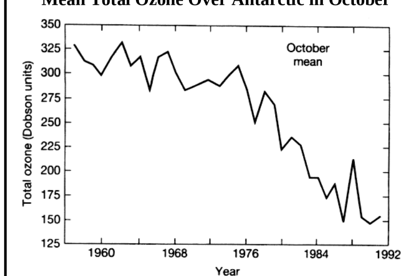
Antarctic Ozone Hole

Mean Total Ozone Over Antarctic in October



(from *The Earth System*)

- ❑ 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.

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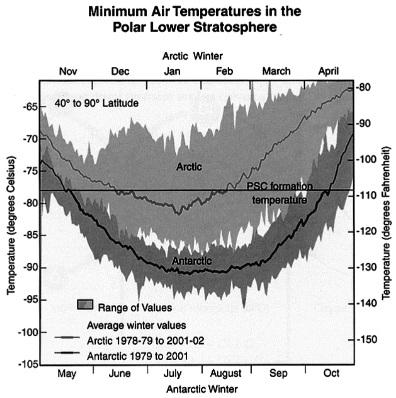
Why No Ozone Hole in Artic?



(from WMO Report 2003)

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Polar Stratospheric Clouds (PSCs)

(Sweden, January 2000; from NASA website)

- 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 (HNO_3).
- 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

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Ozone Hole Depletion

- Long Antarctic winter (May through September)
- ➔ The stratosphere is cold enough to form PSCs
- ➔ PCSs deplete odd nitrogen (NO)
- ➔ Help convert unreactive forms of chlorine ($ClONO_2$ and HCl) into more reactive forms (such as Cl_2).
- ➔ 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 destroy 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.

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