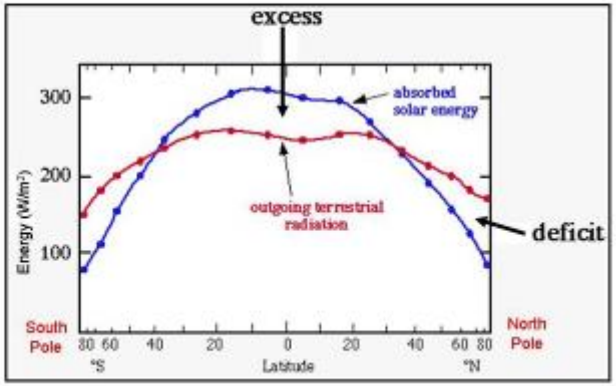
Elements of climatology: The atmospheric general circulation

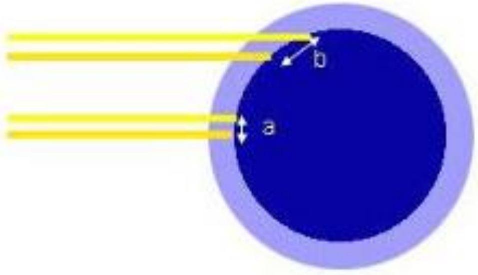
Textbooks and web sites references for this lecture:

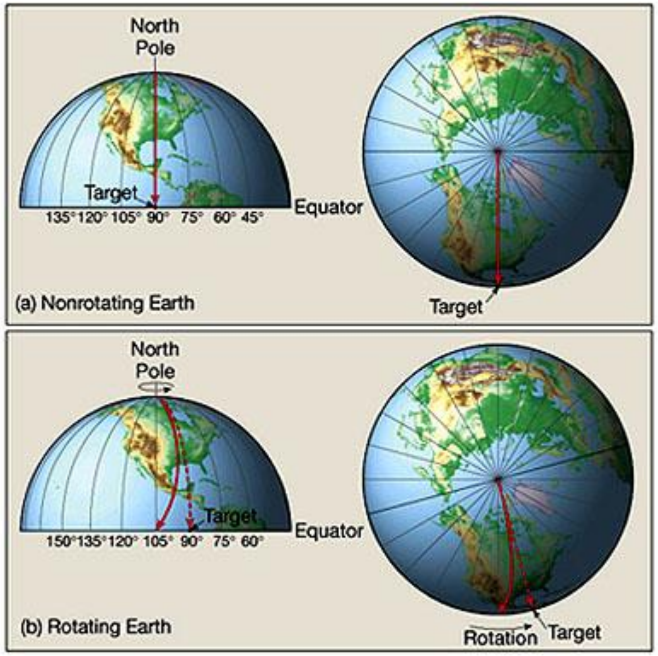
- F.W. Taylor - Elementary Climate Physics, Oxford U. Press, 2007 (§ 3)
- Robert McIlveen, Fundamentals of Weather and Climate, Chapman & Hall, 1995, ISBN 0-412-41160-1 (§ 11)
- Joseph M. Moran e Michael D. Morgan, Meteorology, The Atmosphere and the Science of Weather, Mc Millan College Publishing Company, 1994, ISBN 0-02-383341-6 (§ 10)

Basic features

- Solar radiation hits earth surface with different angles at different latitudes, producing a differential heating with a large gradient between equator and poles
- Infrared radiation emitted by earth, even considering the absorption of atmosphere, has a lower gradient between equator and poles
- As a result, tropical regions have an excess of energy, and polar regions a defect of energy
- This originates near-surface currents from equator to poles, that are deflected by Coriolis acceleration

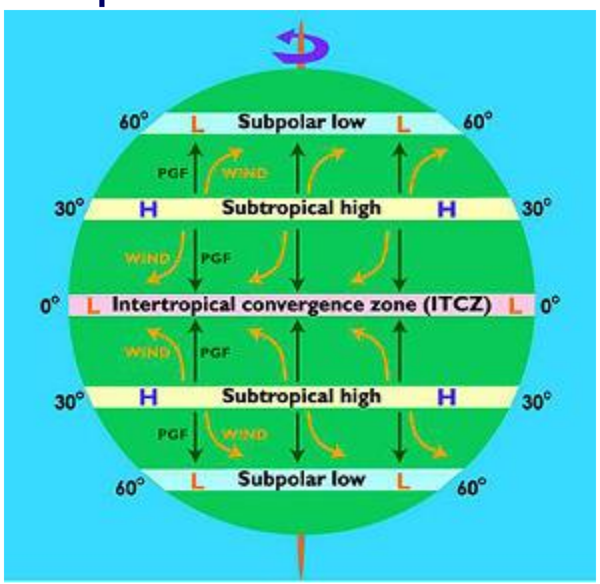


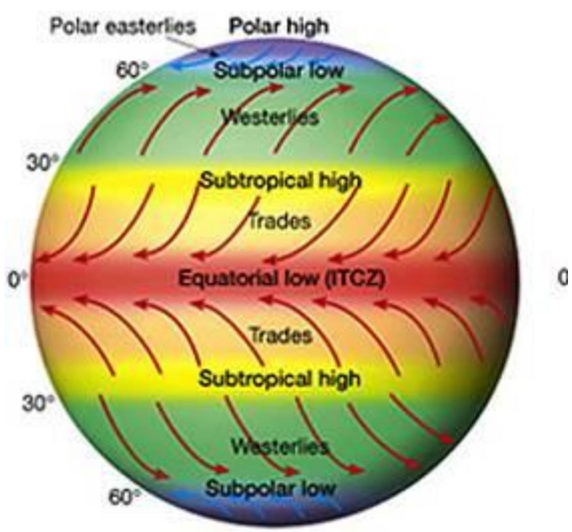




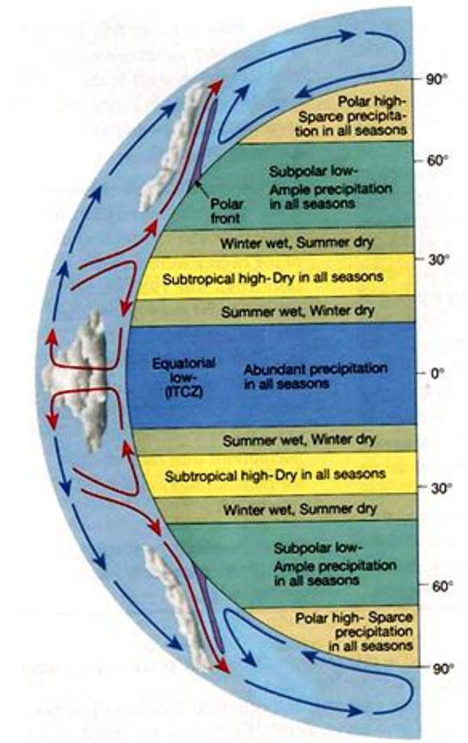
Basic features (2)

- Coriolis acceleration cause the flow to break up into three distinct cells, each with its characteristic circulation pattern
- Note the corresponding distribution of surface pressure, the direction of surface flow, and the vertical flow at the interception of the cells, as well as convergence/divergence patterm





(a)



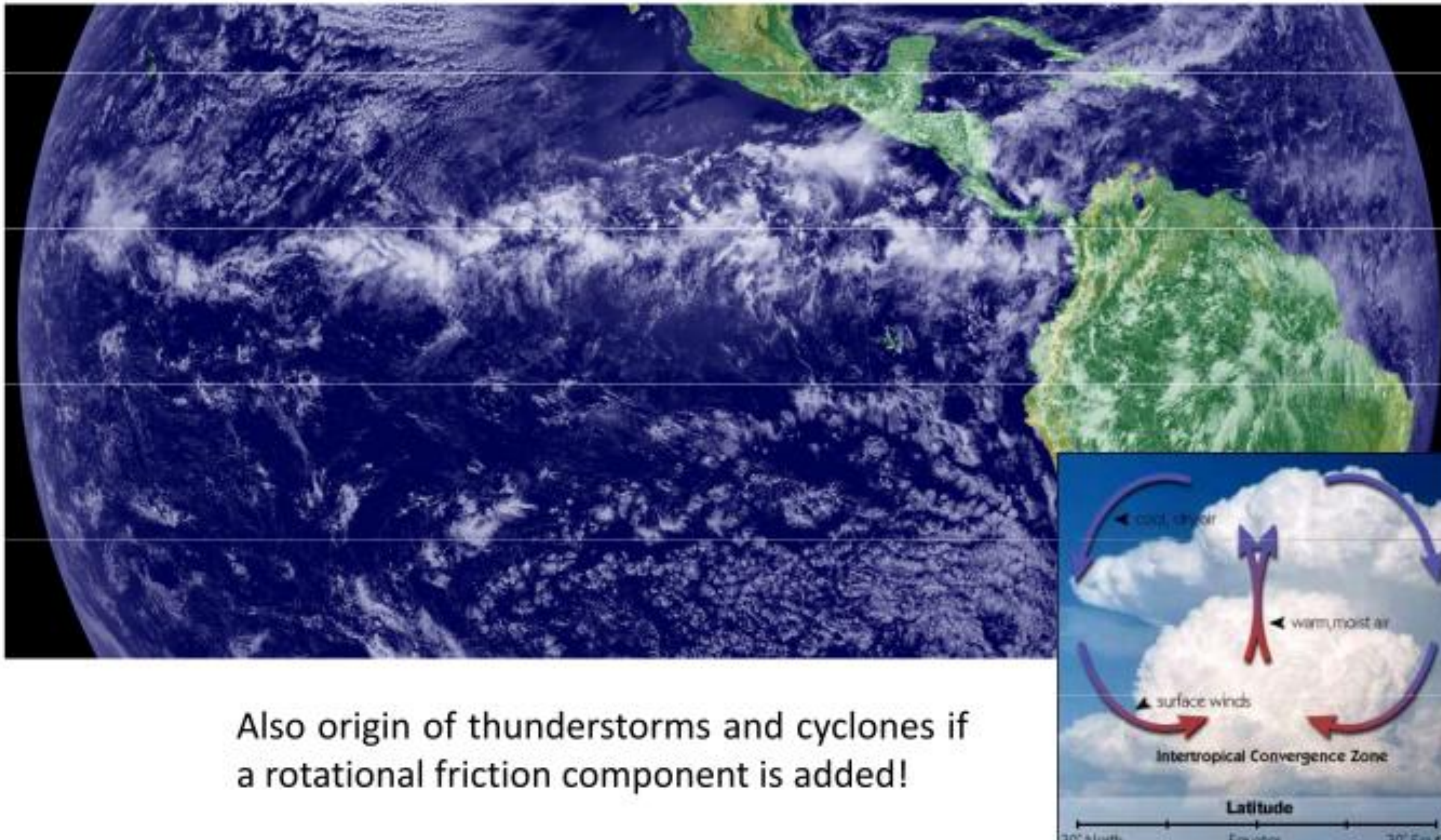
Where air ascends, it is less dense than its surroundings and this creates low atmospheric pressure, and vice versa

Basic features (3)

- Tropical cell are called **Hadley cells**
  - They are thermally direct (they transport heat from Equator to mid latitudes)
  - In those cells air rises near equator and descends near 30° N,S
  - Associated phenomena: deserts; trade winds; ITCZ
- Intermediate cells are called **Ferrel cells**
  - They are thermally indirect (they transport heat from polar to tropical regions)
  - They are driven by wave fluxes of momentum
  - Air rises near 60° N,S (convection) and descends (subsidence) near 30° N,S
  - There are surface westerlies at 45°-60° N,S
- Weak winds found near
  - Equator (doldrums)
  - 30° N,S (horse latitudes)
- Boundary between cold polar air and mid-latitude warmer air is the **polar front**

The intertropical convergence zone

Area of cloud formation because of extended condensation and uprising air masses.

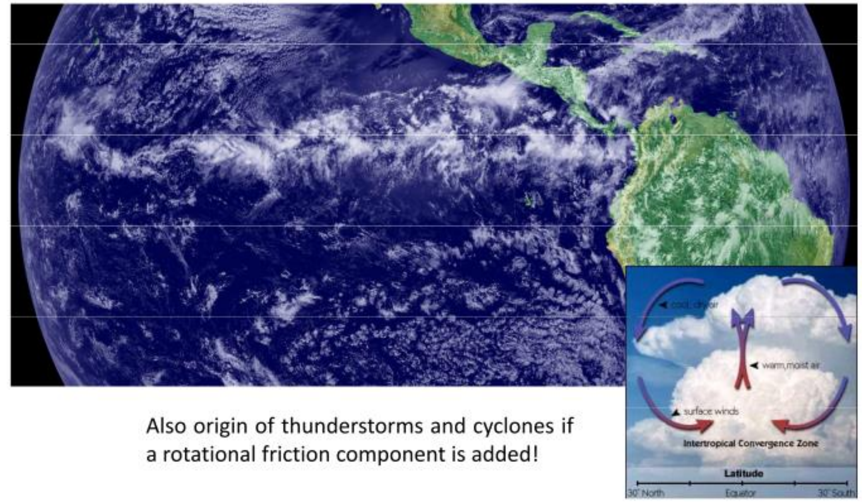


Also origin of thunderstorms and cyclones if a rotational friction component is added!

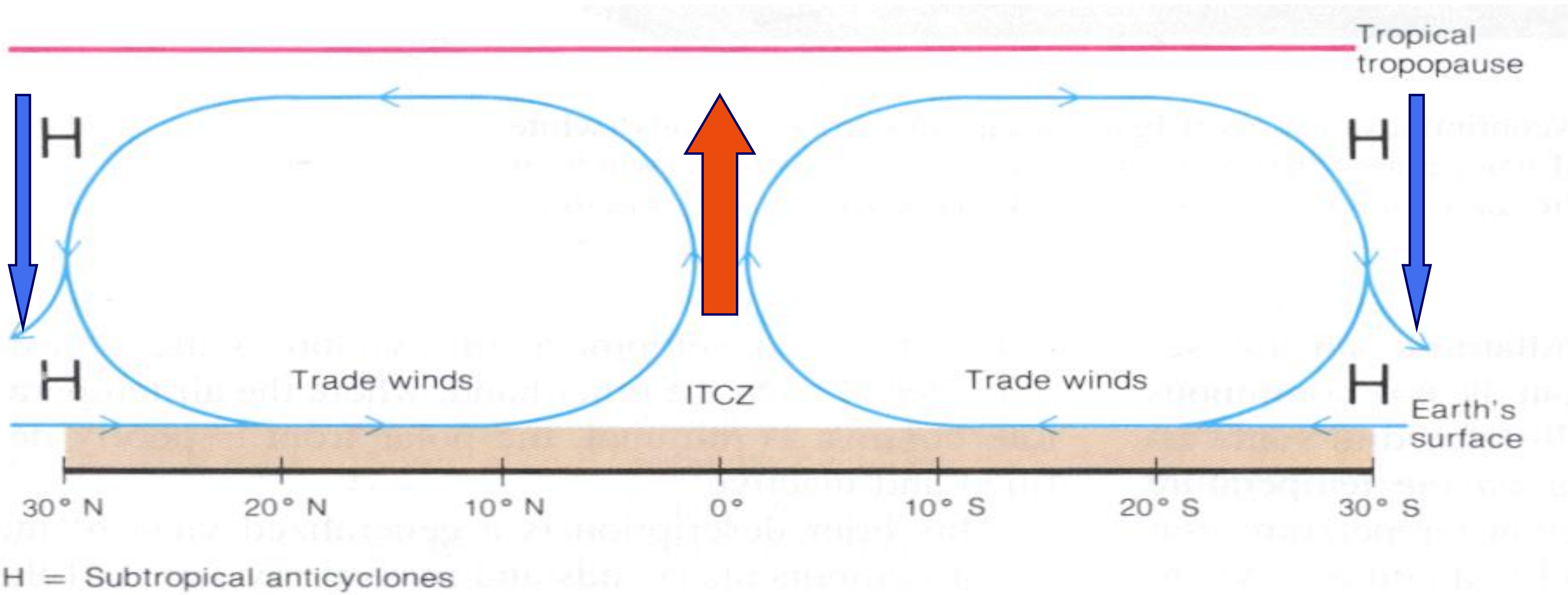
The ITCZ and the Hadley cells

- The ITCZ (InterTropical Convergence Zone) represents the zone in which the trade winds of the two emispheres converge, and on an ideal Earth would coincide with the thermal equator
- Around this line the two Hadley cells encounter each other; above this line there are strong vertical ascending motions

Area of cloud formation because of extended condensation and uprising air masses.



Also origin of thunderstorms and cyclones if a rotational friction component is added!

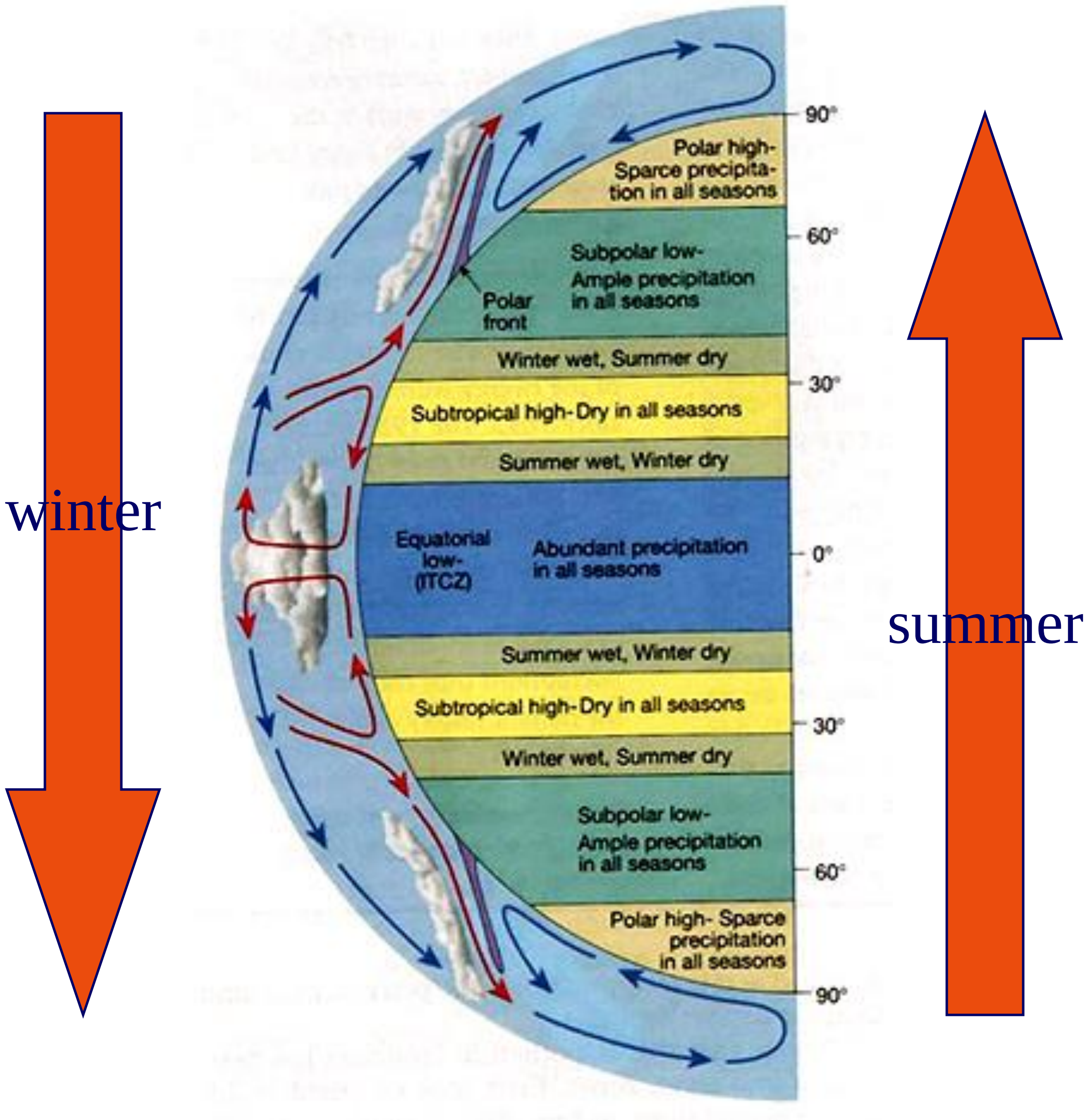


Seasonal Migration of ITCZ

- The Inter Tropical Convergence Zone (ITCZ) shifts toward South in January and toward North in July
- Mean position is somewhat north of Equator
- Strong departures from zonal mean position driven by seasonal heating over land, especially over Asia, S. America, Africa

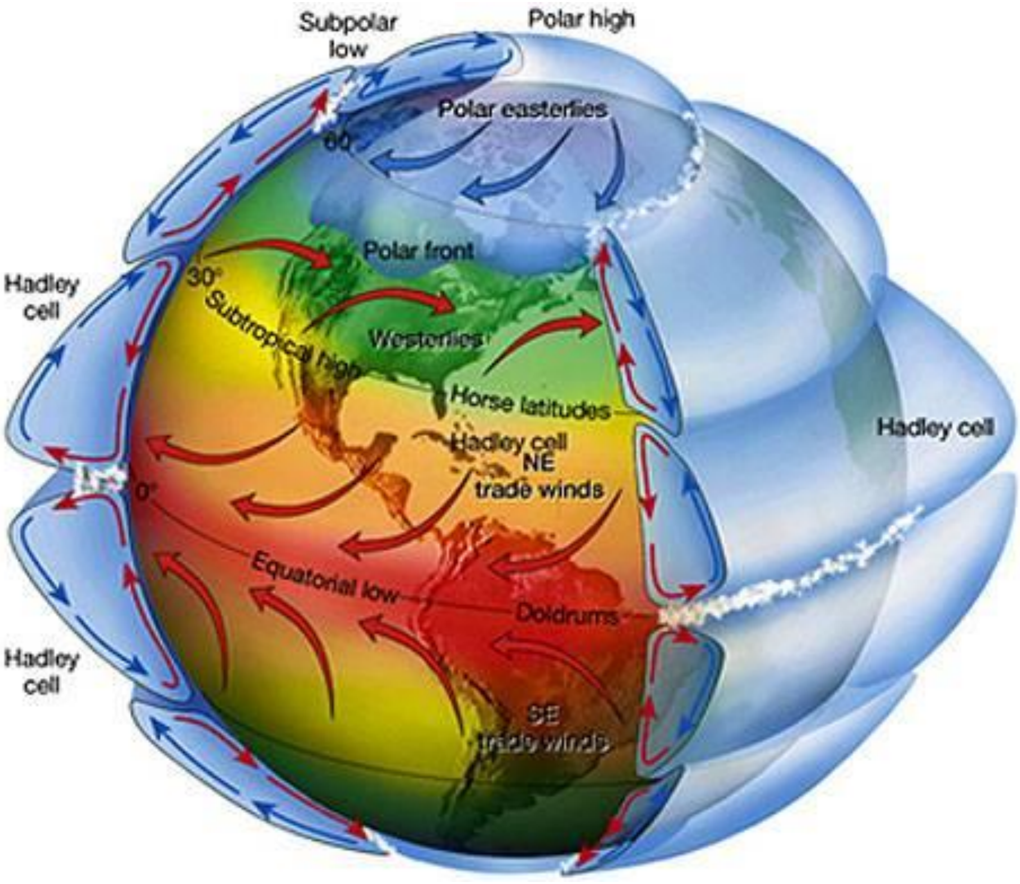
Climatic effects of ITCZ migration

- Equatorial areas climate is nearly constant during the whole year
- At latitudes 5-10° N and S there are two distinct rainy seasons suring the year, when ITCZ crosses these zones
- Tropical areas experience one rainy season
- Subtropical zones are always dry
- …



Wind patterns on a rotating earth

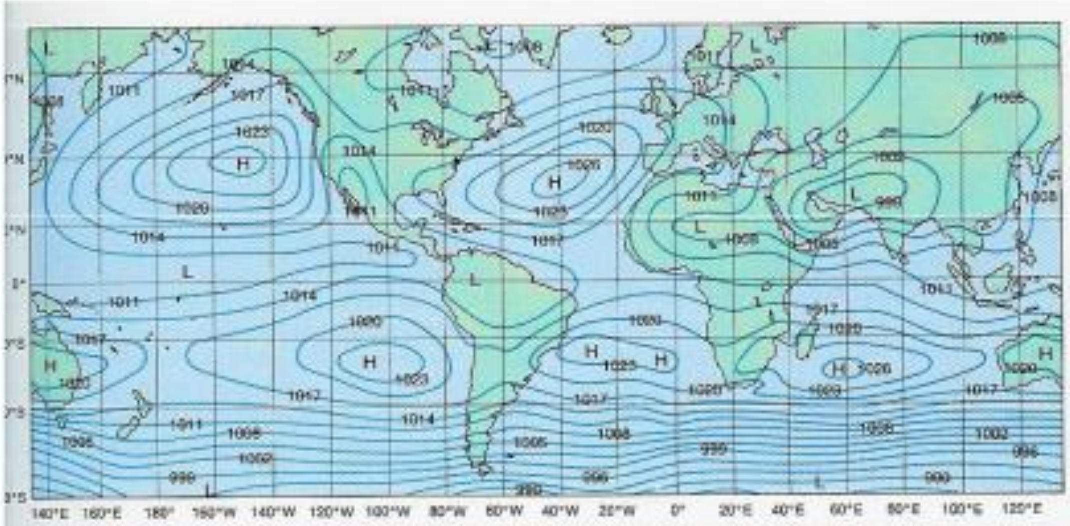
- Many features of the 3 cell model can be observed in the earth's general circulation:
  - polar depressions
  - Subtropical anticyclones
  - ITCZ (Inter Tropical Convergence Zone)
  - Winds of high latitudes (polar)
  - Winds of the mean latitudes, extremely variable
  - Trade winds, very persistent
  - Equatorial eastern winds



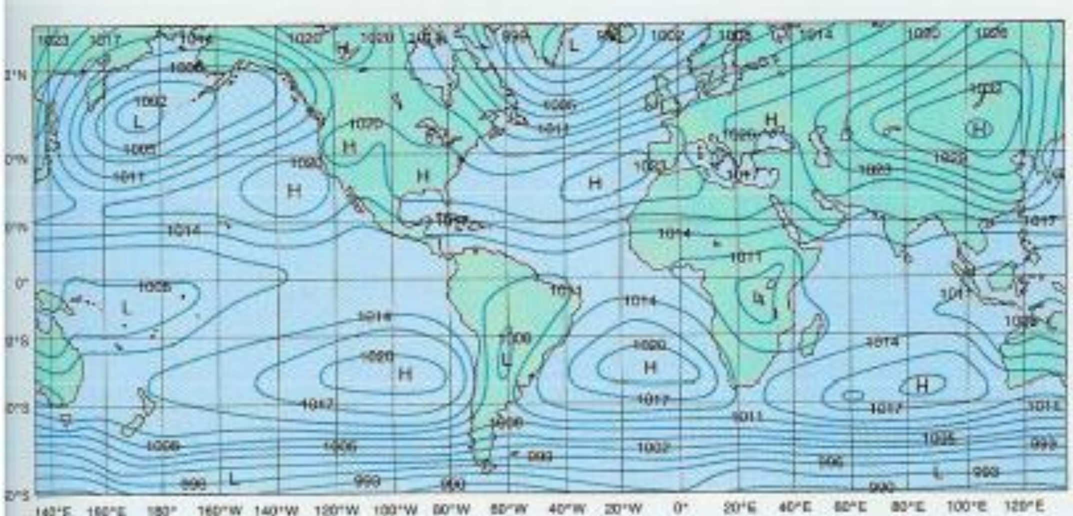
The land/ocean distribution

- Semi-permanent high and low pressure systems persist throughout large periods of the year: high pressures form over cold areas, low pressures over warm areas
  - During wintertime, highs form over lands, lows form over oceans
  - During summertime, highs form over oceans, lows form over lands
- Examples:
  - Bermuda and Pacific highs form near 30°N, in response to air convergence aloft, and are stronger during summer
  - Siberian and Antarctic highs strengthen during winter
  - Iceland and Aleutine lows are stronger during wintertime

Global isobar map



(a) July



(b) January

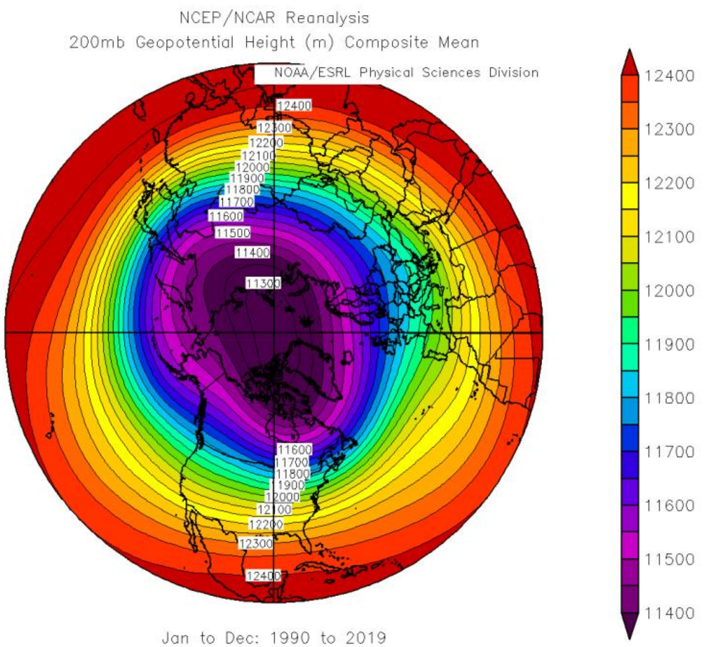
Presence of large continental land areas in the northern hemisphere affects the 'ideal' isobar patterns observed at southern latitudes. During the summer land is warmer than ocean causing the development of low pressure areas, which change northward/southward winds patterns.

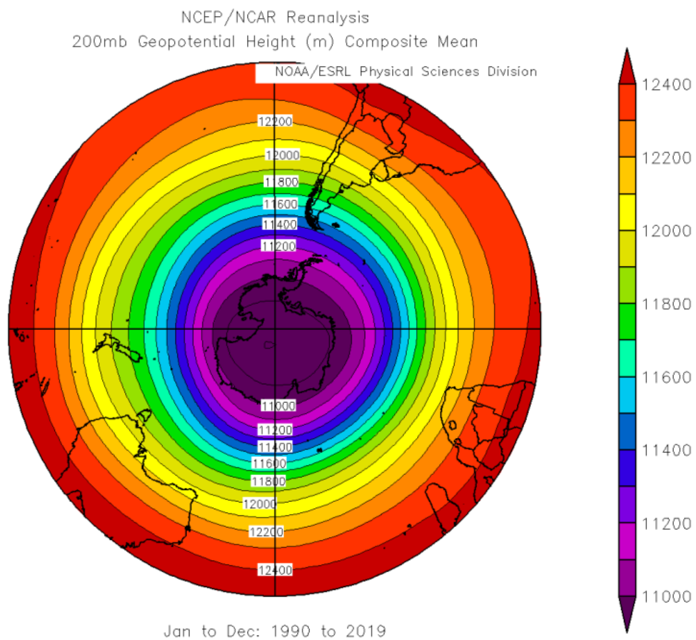
During winter land is colder than ocean water, causing the development of low pressure areas over the ocean regions.

The emergence of localized weather zones is further enhanced by the geographical affects from lakes or mountains.

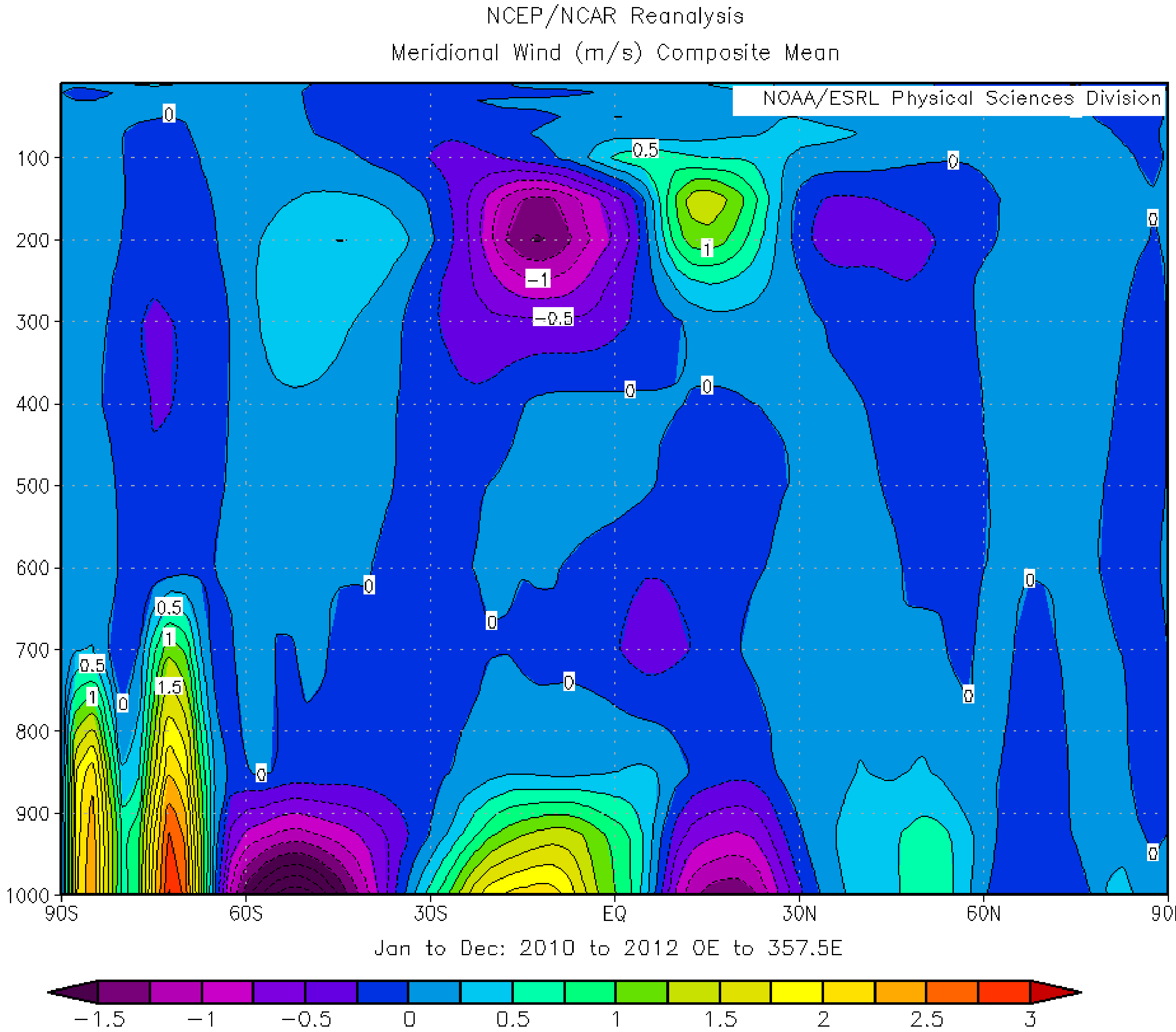
The effect of mountains

- The presence of continents, mountains, and ice fields alters the general circulation from the ideal 3-cell model
  - In Southern hemisphere circulations approaches the ideal one
  - In Northern hemisphere there are waves in correspondence of the main mountain systems: Rocky Mountains, Himalaya, and Eurasian ranges

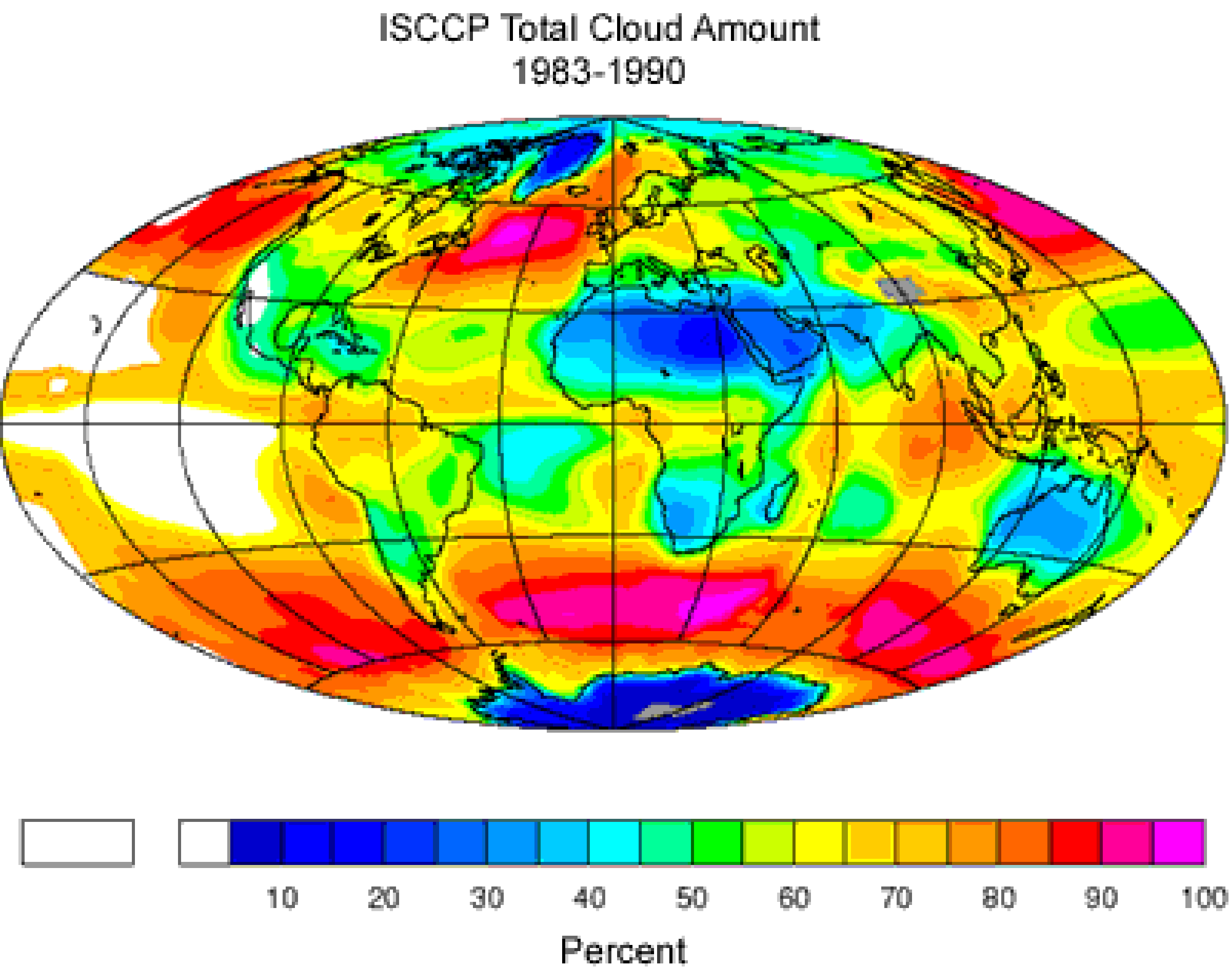




Evidences: meridional winds

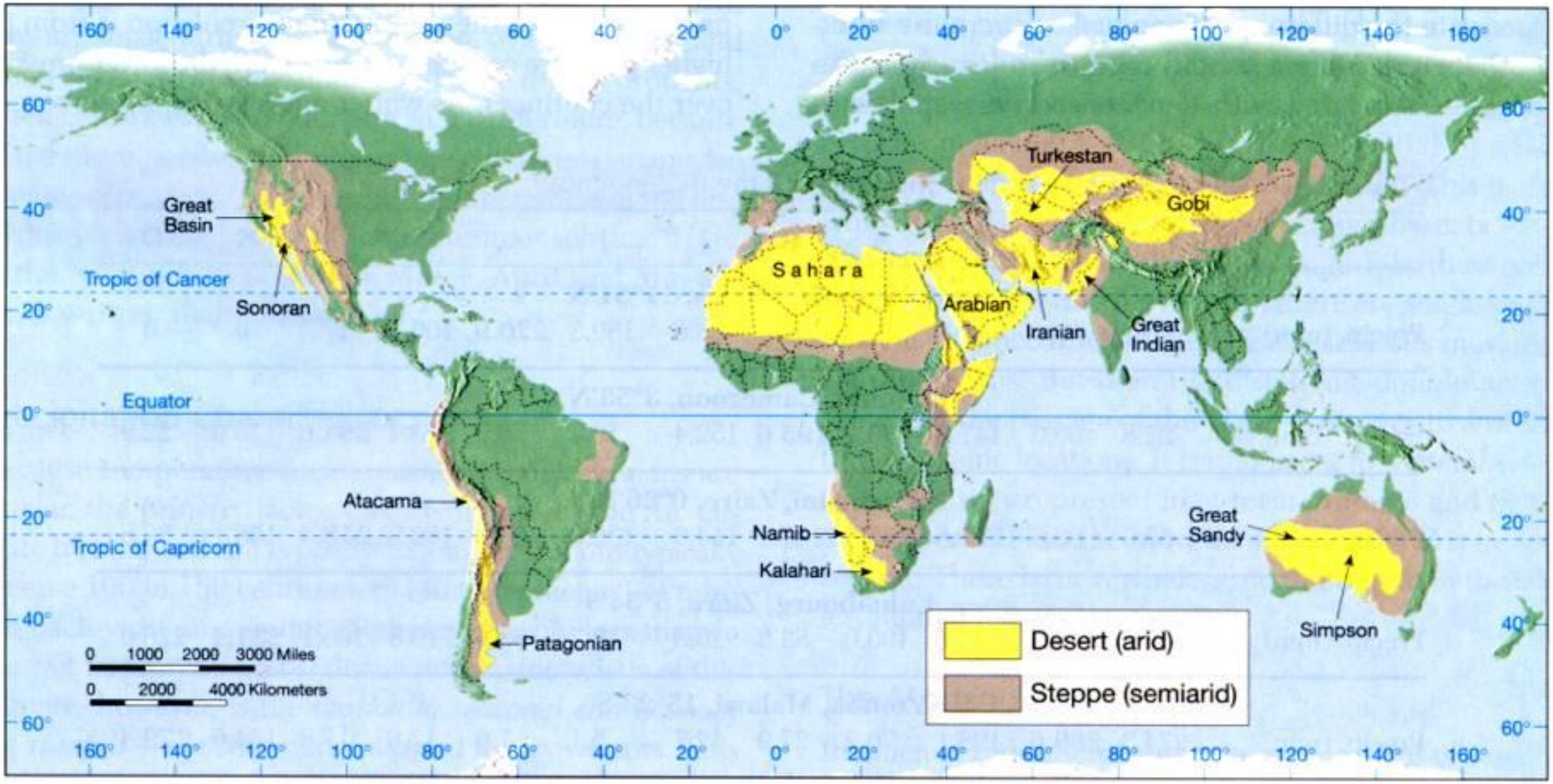


Evidences: atmospheric Cloudiness



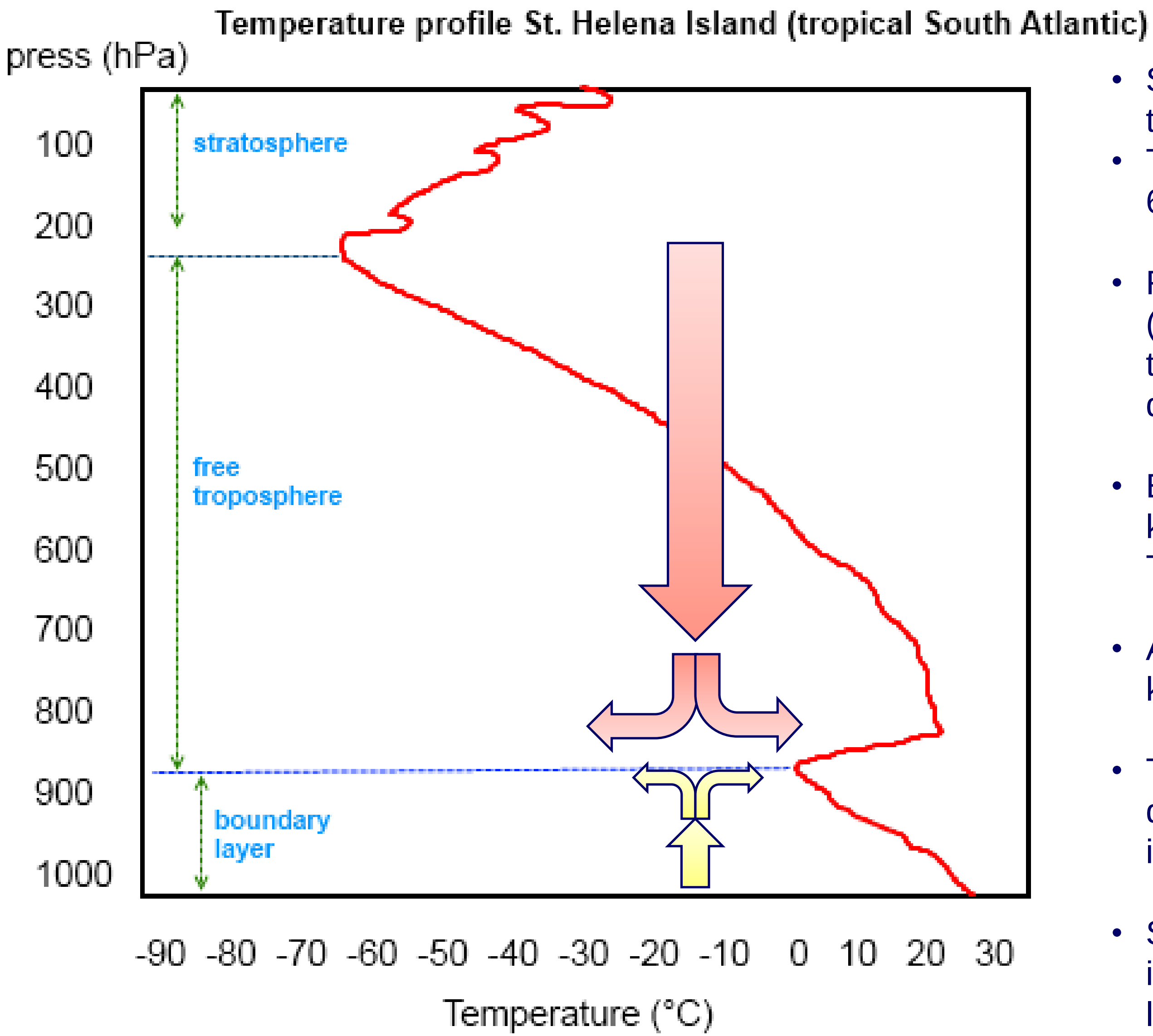
- Persistent clouds over ITCZ
- Cloudiest areas are over mid- to high-latitude oceans
- Clearest areas are subtropical highs

Evidences: desert and semiarid climates



- About 30% of land area of the world
- Most associated with subsidence in Hadley Cell
- Strong zonal asymmetry
- Land-Ocean-Atmospheric feedback

Characteristics of tropical anticyclones



- Subsidence motions in free troposphere
- Temperature profile is nearly -6.5°C/km

- Robust rising motions in the (dry) boundary layer; temperature profile is nearly dry-adiabatic (-10°C/km)

- Example: tropopause at 16 km, T=-60°C → at 1 km: T=37.5°C

- At the surface, T=40°C → at 1 km: T=30°C

- There are about 7.5°C of difference at 1 km: presence of inversion layer

- Similar situations, with lower inversions, occur also at our latitudes in anticyclonic conditions

Characteristics of subpolar lows

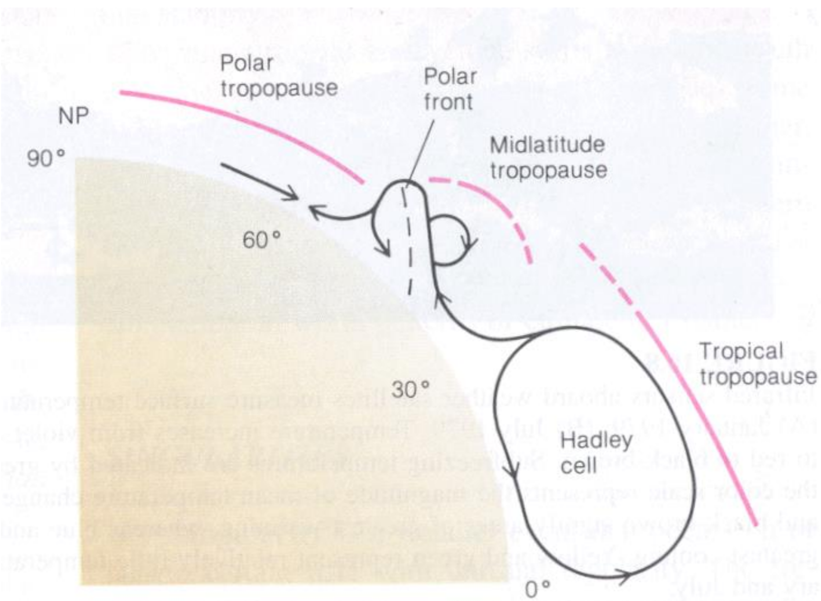
- Mid latitude westerlies converge with polar easterlies along polar circle forming depressions (Aleutine on Pacific ocean, Iceland on Atlantic one)
- High thermal contrast between air masses → cold polar/arctic air and mild mid-latitude air → polar (discontinuous and wavely) front grows → potentially ciclogenetic if ΔT is high
- Polar air is very cold and dense → it flows at low elevation
- Over poles anticyclones are shallow, and more intense in winter (especially over South pole, where anticyclone is persistent, due to very cold temperatures)
- Subpolar depressions are also more intense in winter

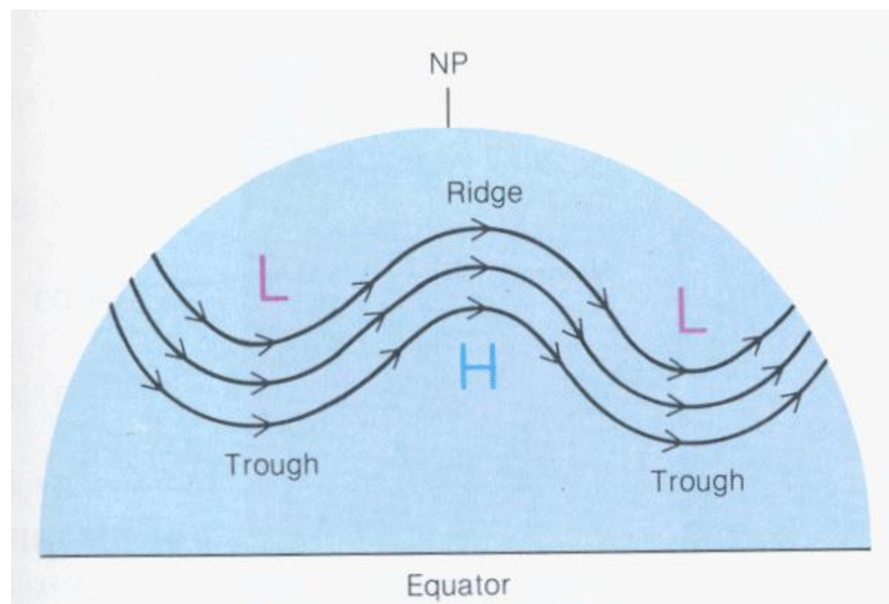
Characteristics of equatorial lows

- Doldrums converge at ITCZ (near Equator, in average) → convergence of two air masses with similar temperature and a common eastwards component
- Vertical rising motions result: being warm air, motions occur up to the tropopause, where temperature inversion blocks the vertical movement, and divergence creates
- As, at the equator, Coriolis force is null, depressions are not too deep (otherwise no forces can balance them), excepting tropical systems

The effective general circulation

- Near ITCZ two **close cells** (Hadley cells, discovered in 1935) develop, one per hemisphere, extended up to ≈ 30° N, S
- Other 2+2 cells (polar, Ferrel) do not exist, or are very weak
- One reason is that there are a series of waves (Rossby waves) with alternate **troughs** and **ridges** driving synoptic scale systems, generated by dynamic instability and mountains



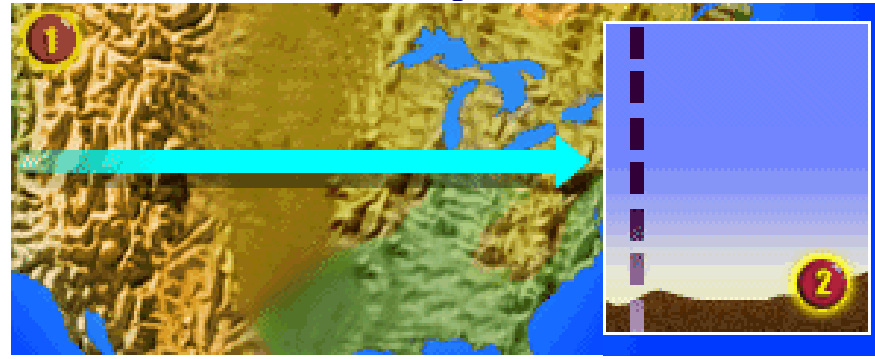


Weather in ridges and troughs

Ridge

- Ridges, depending on their strength and how fast they move, can bring record summer heat and stifling air pollution to a region for several days
- A ridge is an elongated area of high pressure. They occur both at the Earth's surface and at higher altitudes
- Upper level ridges can have a major impact on the weather at the surface. Sunny, dry weather usually prevails to the east of the upper-level ridge axis while cloudy, wet weather can dominate the weather picture to the west of the upper-level ridge axis. Air tends to sink to the east of the ridge axis, which inhibits clouds and precipitation. Air tends to rise to the west of the ridge axis, leading to form clouds and precipitation
- Extremely hot weather during the summer and unusually mild weather during the winter are often associated with a strong, slow moving, upper-level ridge

Trough



- A trough is an elongated area of low atmospheric pressure that can occur either at the Earth's surface or at higher altitudes
- Upper-level troughs influence many surface weather features, including formation and movement of surface low pressures and the locations of clouds and precipitation
- Precipitation tends to fall to the east of the trough axis while colder, drier air tends to prevail to the west of the trough. This happens because air rises to the east of troughs. As air rises, it cools, and its humidity begins condensing into clouds and precipitation. Air sinks on the west side of troughs, which inhibits clouds and precipitation
- Strong upper-level troughs can be become negatively tilted and are associated with Arctic outbreaks and major snowstorms during winter
- Surface low pressure areas tend to develop to the east of upper-level troughs in the rising air

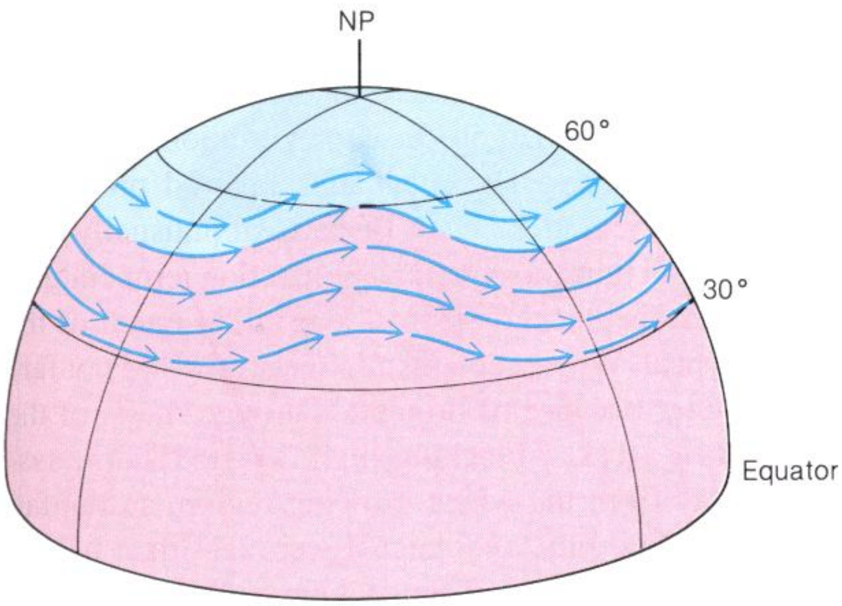
Rossby waves

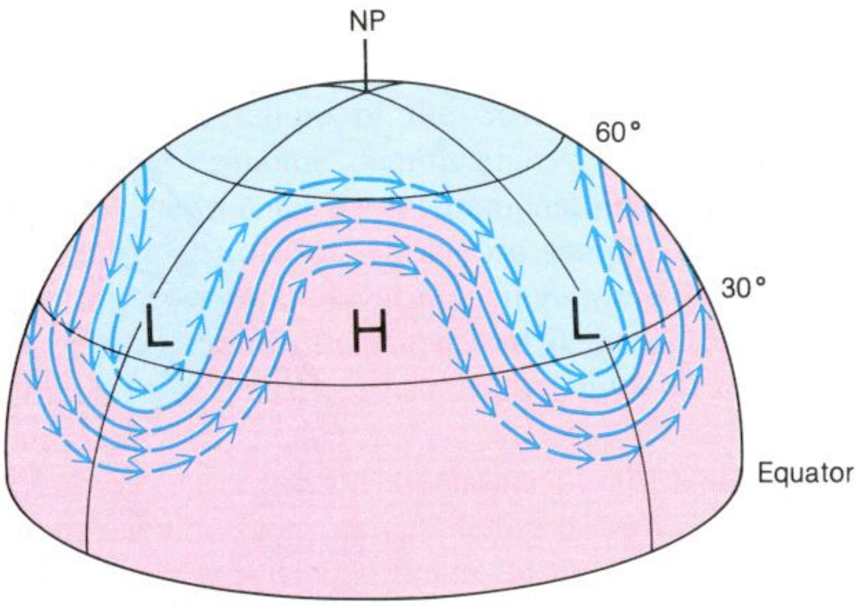
- Rossby (1930) discovered that, under specific hypotheses (barotropic atmosphere), at mid latitudes, synoptic flow shows alternate troughs and ridges
- On average, Earth contains 2-5 (Rossby) waves at 500 hPa
- The relation between wave length λ, air wind speed u and (zonal) wave phase velocity c_x is:

$$c_x = u - K\lambda^2 \, , \quad K = \frac{\Omega \cos\phi}{2\pi^2 R_T} \xrightarrow{\phi=45^\circ} 4.1\ 10^{-13} m^{-1} s^{-1}$$

- In winter, waves are larger and less numerous (> amplitude, > λ) due to greatest thermal and baric gradients
- Imposing u~10 m/s and searching λ for which c_x=0 we get λ~4900 km
- If wave amplitude is large, there is motion along meridians, thus **meridional** component is not negligible (large meridional heat exchange)
- On the contrary, the motion occurs mainly along parallels (**zonal**)

Zonal and meridional flows





ZONAL flow

- zonal >> meridional component
- Flow separates cold from warm air masses

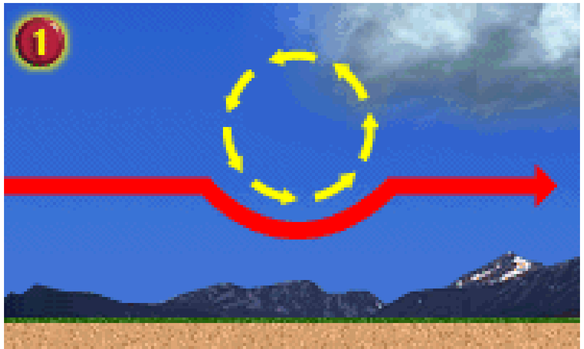
MERIDIONAL flow

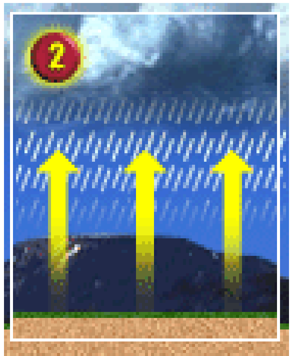
- zonal ≥ meridional component
- Air masses mix → big thermal contrasts → cyclogenesis

Normally westerlies oscillate irregularly between these two extremes

Upper level disturbances

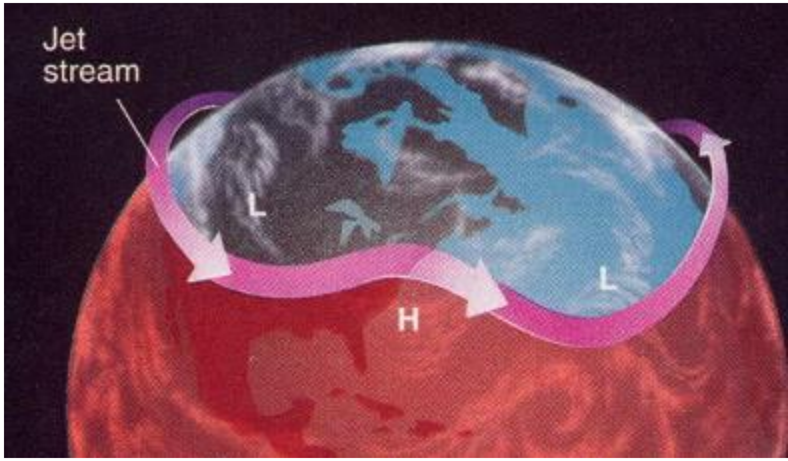
- Upper-level disturbances ride along the high-altitude winds far above the Earth's surface
- Sometimes they can pass by without any sign; at other times they can spawn unexpected showers, or trigger thunderstorms, or also help make thunderstorms stronger than they would otherwise be
- An upper-level disturbance is a pocket of rotating air that ripples along with the generally west-to-east, upper-altitude winds.
- As a disturbance moves along toward the East, air rises along its eastern side. The rising air generates upward motions at ground. Rising air cools → (if enough humidity) clouds & precipitation
- The air on a disturbance's west side is sinking. Since sinking air warms and warmer air evaporates clouds, the sky can rapidly clear as a disturbance passes by



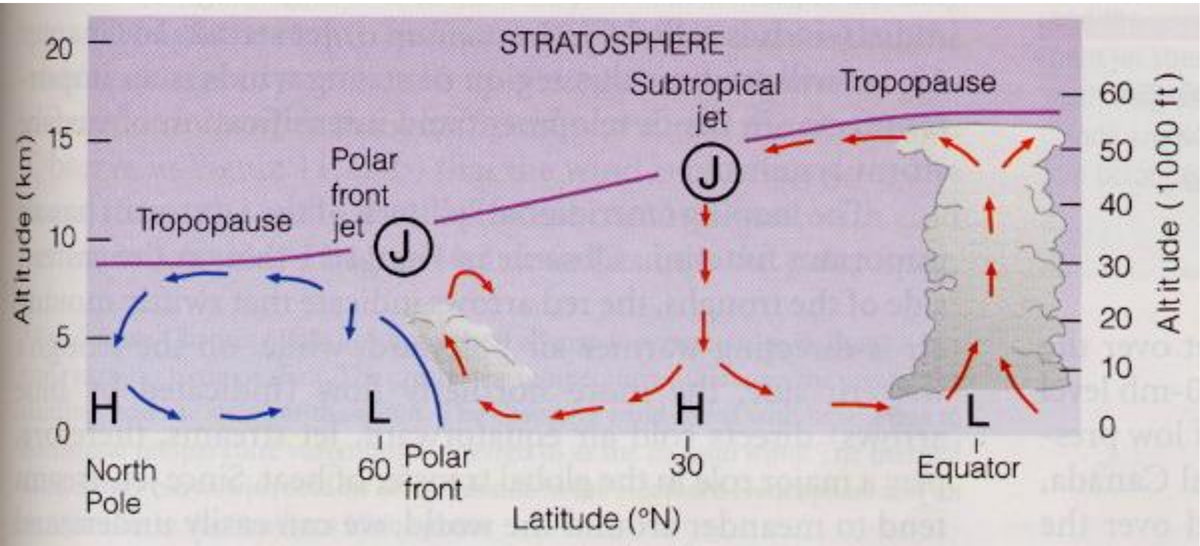


Jet streams

- Associated to westerlies, and located just below tropopause, there are small wavy corridors of very intense flow (> 100 km/h, sometimes 300 km/h), named **jet streams**
- Jet stream can consist of one or more branches, not uniformly distributed (there are local maxima propagating within them), sometimes contoured by Cirrus clouds

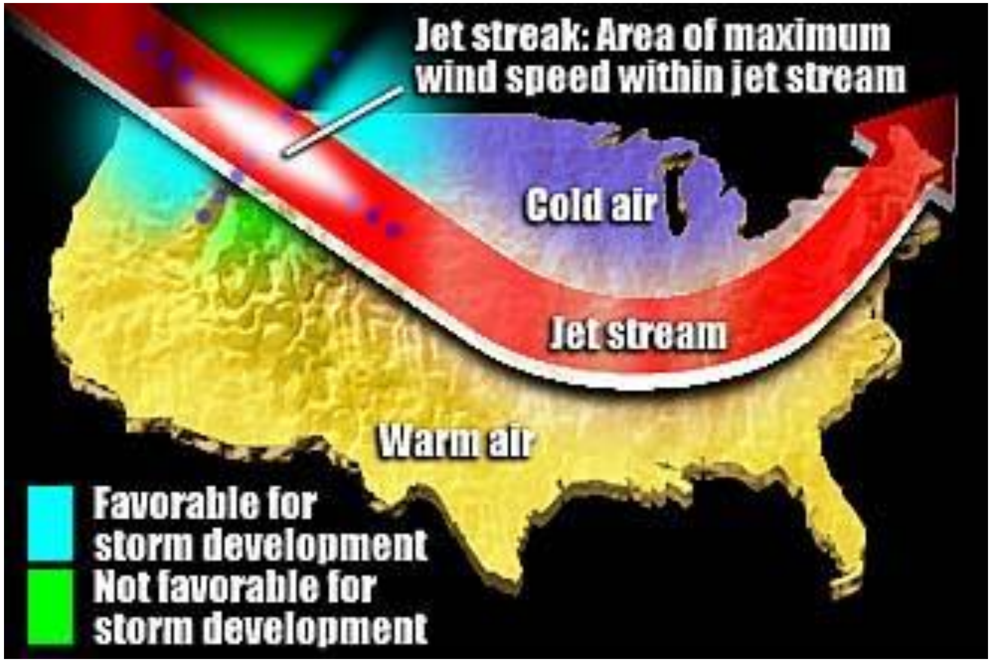


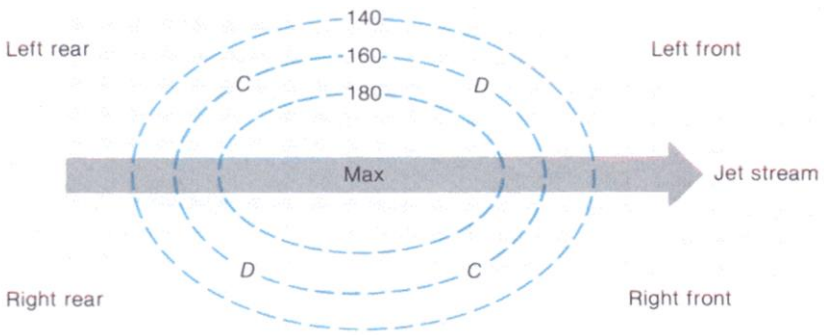
- Typically there are two jet streams (subtropical and polar front) at tropopause in NH
- Subpolar jet stream is more wavy and has a strong seasonal behavior; it is at ~60° N,S
- Subtropical jet stream is located at about 30° N,S



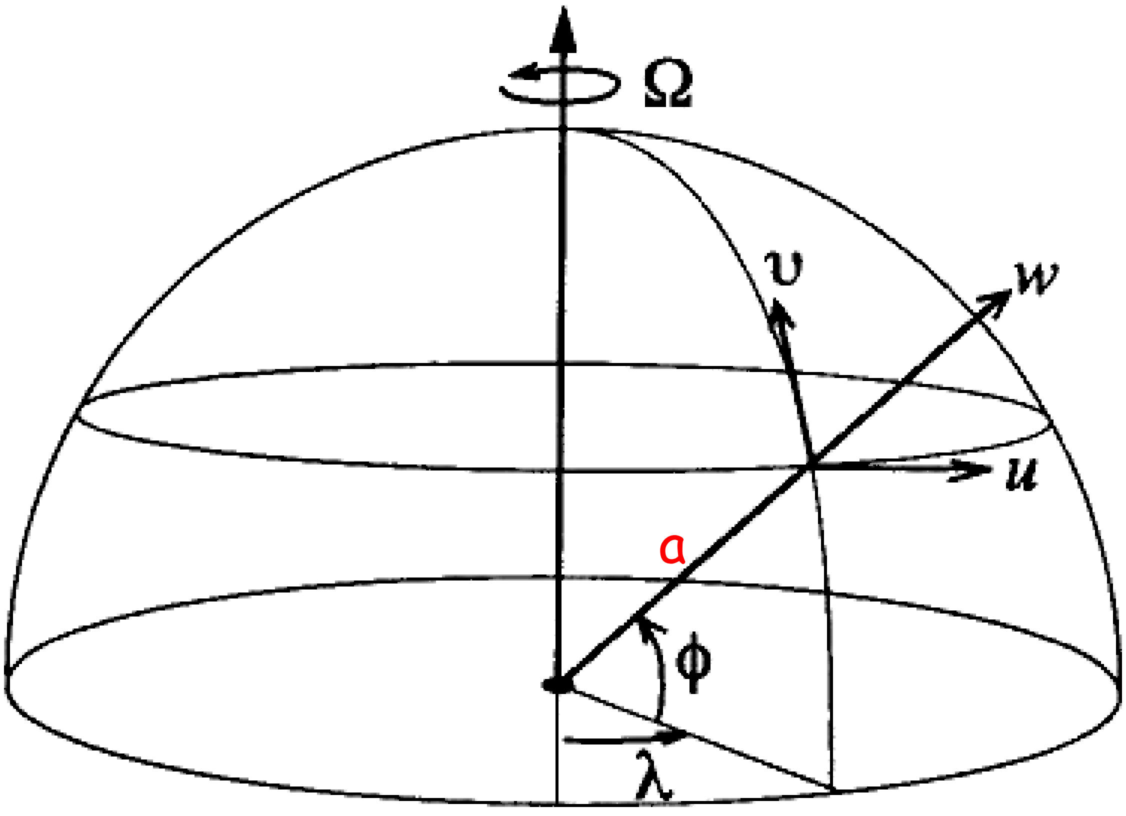
Jet streaks

- Often, the jet stream contains **jet streaks** of wind speeds faster than the surrounding regions. Jet streaks can play a very important role in precipitation and storm formation
- The area ahead and to the left of the flow and the area behind and to the flow right ("D" → divergence) are favourable for precipitation and storm development
- Depending on atmospheric conditions, air motions in both of these areas tend to enhance upward (convective) motions of air from the ground below





Memo: earth coordinates



horizontal wind components

$$u = a\cos\phi \frac{D\lambda}{Dt} \qquad \upsilon = a \frac{D\phi}{Dt}$$

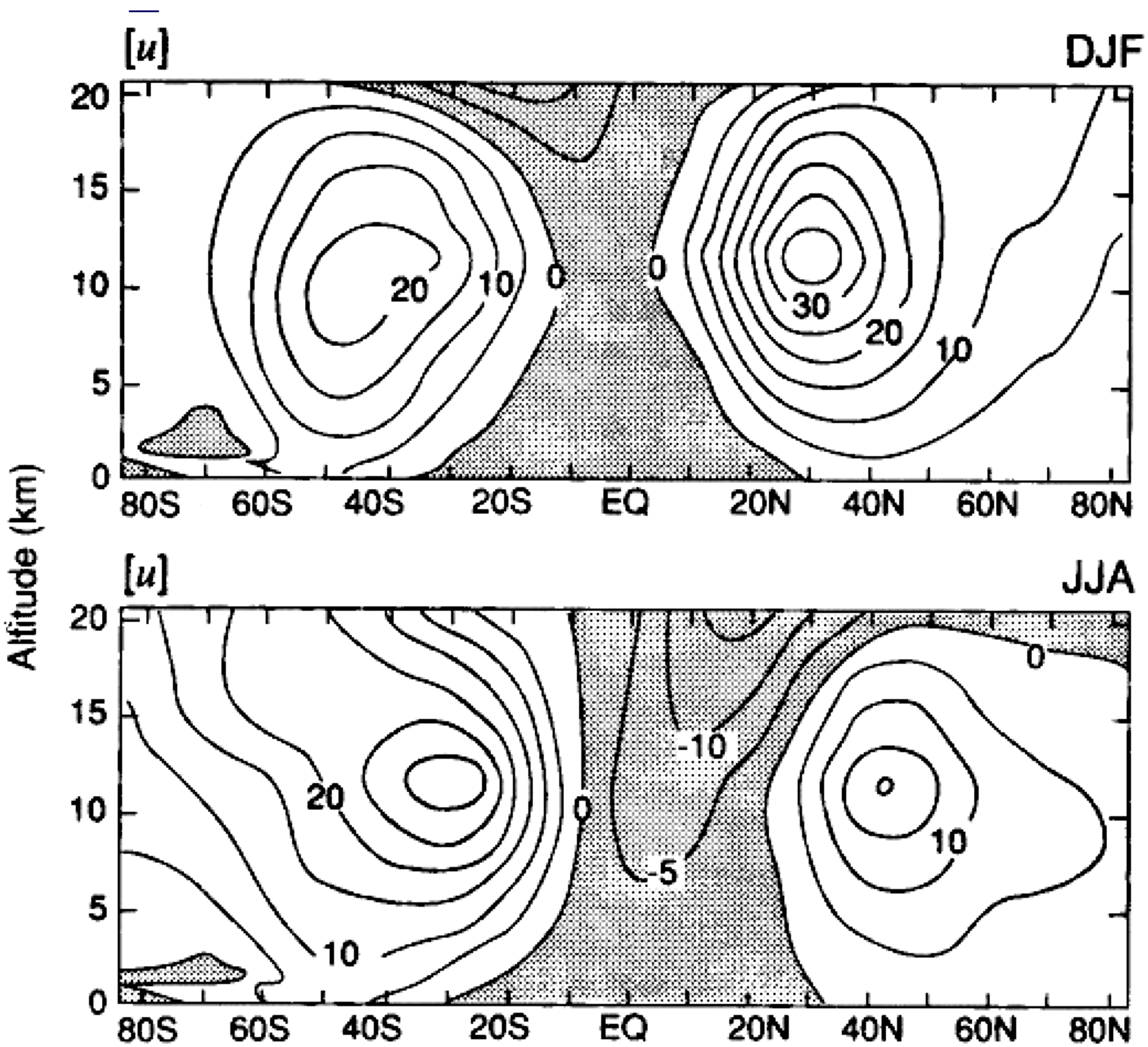
vertical motion

$$w = \frac{Dz}{Dt} \qquad \omega = \frac{Dp}{Dt}$$

$$\omega \cong -\rho g w$$

φ = latitude
λ = longitude
a = sphere radius

[u] - Mean Zonal Wind



Time mean zonal wind u-component (m/s)

- Midlatitude westerly (W→E) winds
- Deep tropical easterlies (E→W)
- Well-defined winter wind max at ~30º and ~12 km ("jet stream")
- Summer jet is weaker and further poleward
- Zonal-average meridional and vertical wind components are much weaker than zonal wind (maxima respectively of 1 m/s and 1 cm/s)

The streamfunction

To calculate mean meridional circulation, it is possible to define a mass streamfunction:

$$\Psi_M = \frac{2\pi a \cos\phi}{g} \int_0^p [v]\, dp$$

zonal mean meridional wind

vertical mass-weighted integral from TOA

Then meridional and vertical winds can be written:

$$[v] = \frac{g}{2\pi a \cos\phi} \frac{\partial \Psi_M}{\partial p}$$

$$[\omega] = \frac{-g}{2\pi a^2 \cos\phi} \frac{\partial \Psi_M}{\partial \phi}$$

- Streamfunction Ψ is the total northward mass flux above pressure $\boldsymbol{p}$
- Useful for understanding atmospheric flow in y-z plane

[v,w]: the Mean Meridional Circulation (MMC)

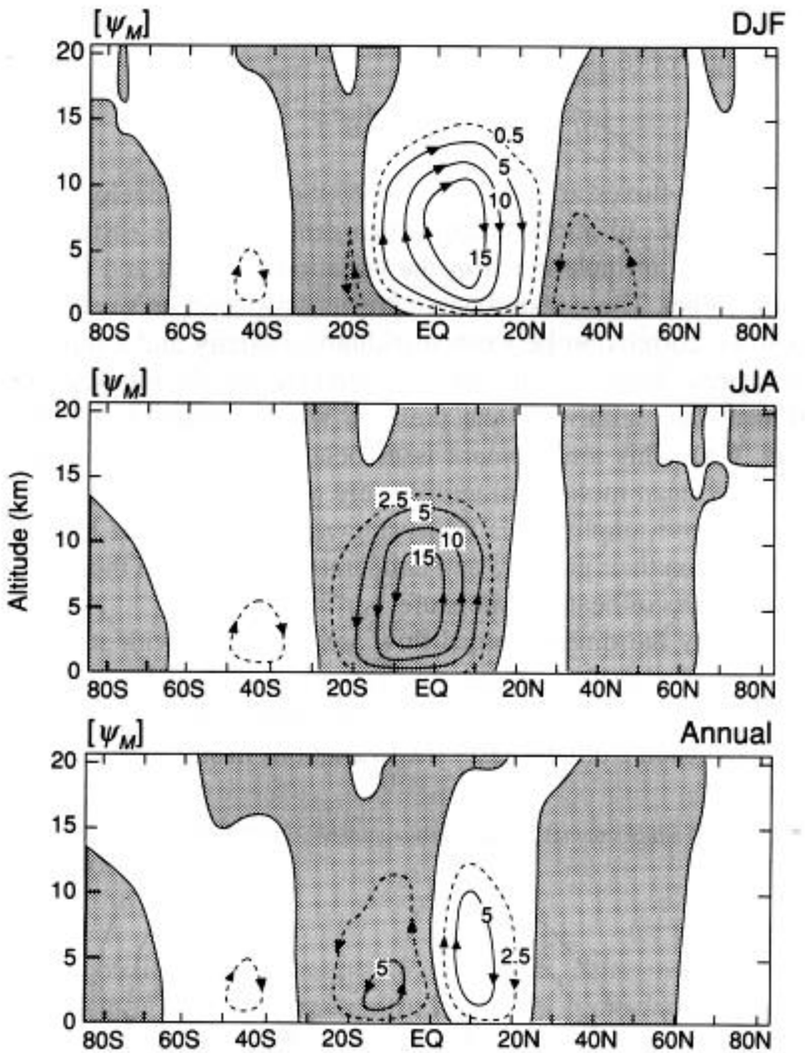


Fig. 6.5 Latitude–height cross section of the mean meridional mass circulation. Shaded values are negative; units are 10^{10} kg s^{-1}. [Data from Oort (1983).]

Mean meridional mass streamfunction (10^{10} kg s^{-1})

- Strongest feature is the Hadley Cell
  - Rising air in tropics
  - Poleward flow aloft into winter hemisphere
  - Sinking air in winter subtropics
  - Surface flow equatorward
  - Rising branch slightly displaced into summer hemisphere
- Much weaker Ferrel Cells in midlatitudes
  - "Thermally indirect" as they circulate in the opposite direction than Hadley cells
  - A byproduct of much stronger eddy fluxes

Decompose Variables

Let consider zonal averages, i.e. average over longitude λ

time mean

$$\bar{x} = \frac{1}{\Delta t}\int_0^{\Delta t} x\,dt$$

instantaneous departure from zonal mean

$$x' = x - \bar{x}$$

large wind and temperature variations on scale of several thousand kilometers, which do not appear in a zonal average

zonal mean

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

local departure from zonal mean

$$\bar{x}^* = \bar{x} - [\bar{x}]$$

variations associated with continents and oceans; these ones are latitudinal and quasi-stationary, and appear clearly in time averages; they are characterizes by deviations in the time mean from its zonal average

- Analogous to decomposition into mean and turbulent components
- Rules for manipulating integrals apply (like Reynold's averaging)

Latitudinal and time mean

$$v = \overline{v} + \overline{v}^* + v'$$

Velocità meridionale del vento

$$T = \overline{T} + \overline{T}^* + T'$$

temperatura

Moltiplichiamole tra loro (→ flusso di calore sensibile)

$$vT = \overline{v}\left(\overline{T} + \overline{T}^* + T'\right) + \overline{v}^*\left(\overline{T} + \overline{T}^* + T'\right) + v'\left(\overline{T} + \overline{T}^* + T'\right)$$

$$= \overline{v}\,\overline{T} + \overline{v}\,\overline{T}^* + \overline{v}T' + \overline{v}^*\,\overline{T} + \overline{v}^*\,\overline{T}^* + \overline{v}^*T' + v'\overline{T} + v'\overline{T}^* + v'T'$$

Facciamone la media temporale: i termini con la X rossa spariscono

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

Facciamone la media zonale: i termini con la X blu spariscono

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

Northward Heat Flux

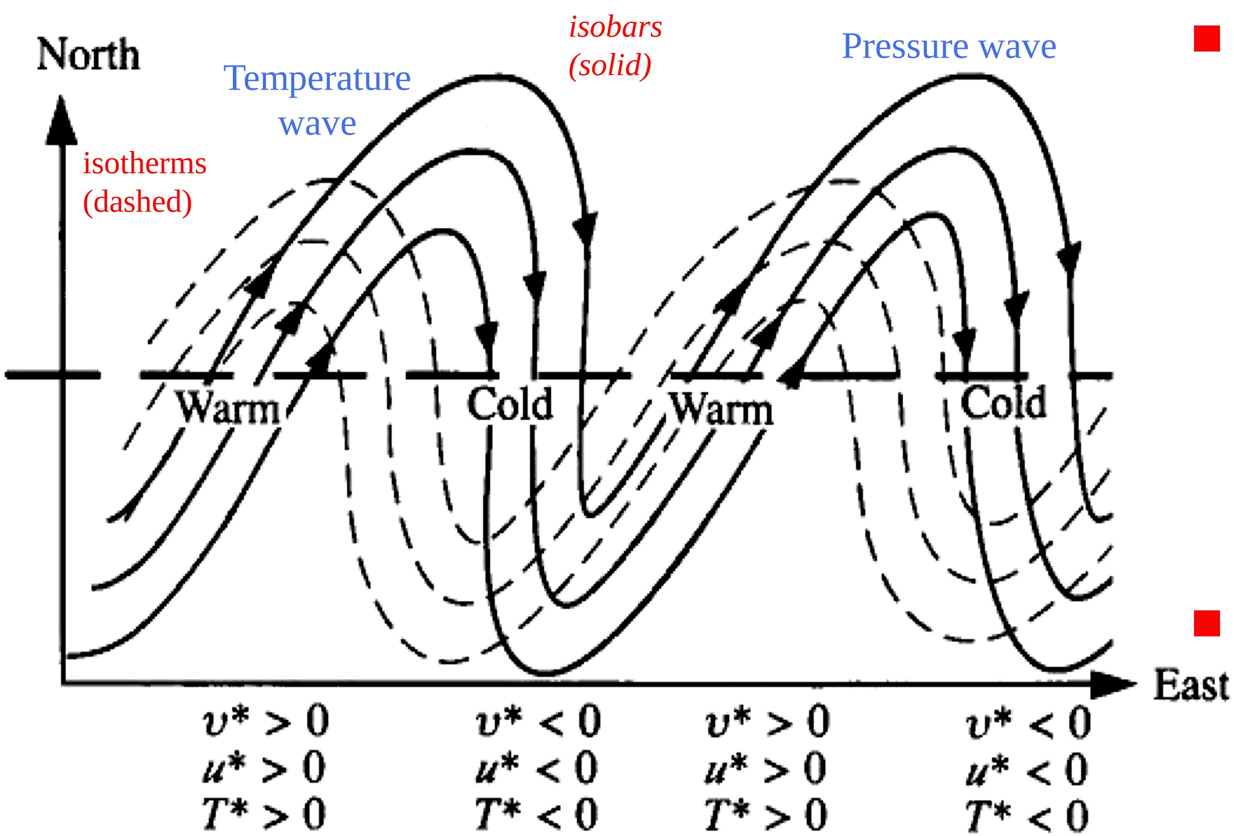
Latitudinal and time mean

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

total — MMC — "stationary eddies" — "transients"

- Mean of product is decomposed and rules of averaging are applied, leaving product of means plus means of products of two kinds of perturbations
- Mean of products is heat flux associated with Mean Meridional Circulation (Hadley and Ferrel Cells)
- Heat flux by stationary eddies is associated with large-scale features produced by land-sea contrasts and topography that don't move around
- "Transients" are traveling weather disturbances (waves and fronts), which move a lot of heat!

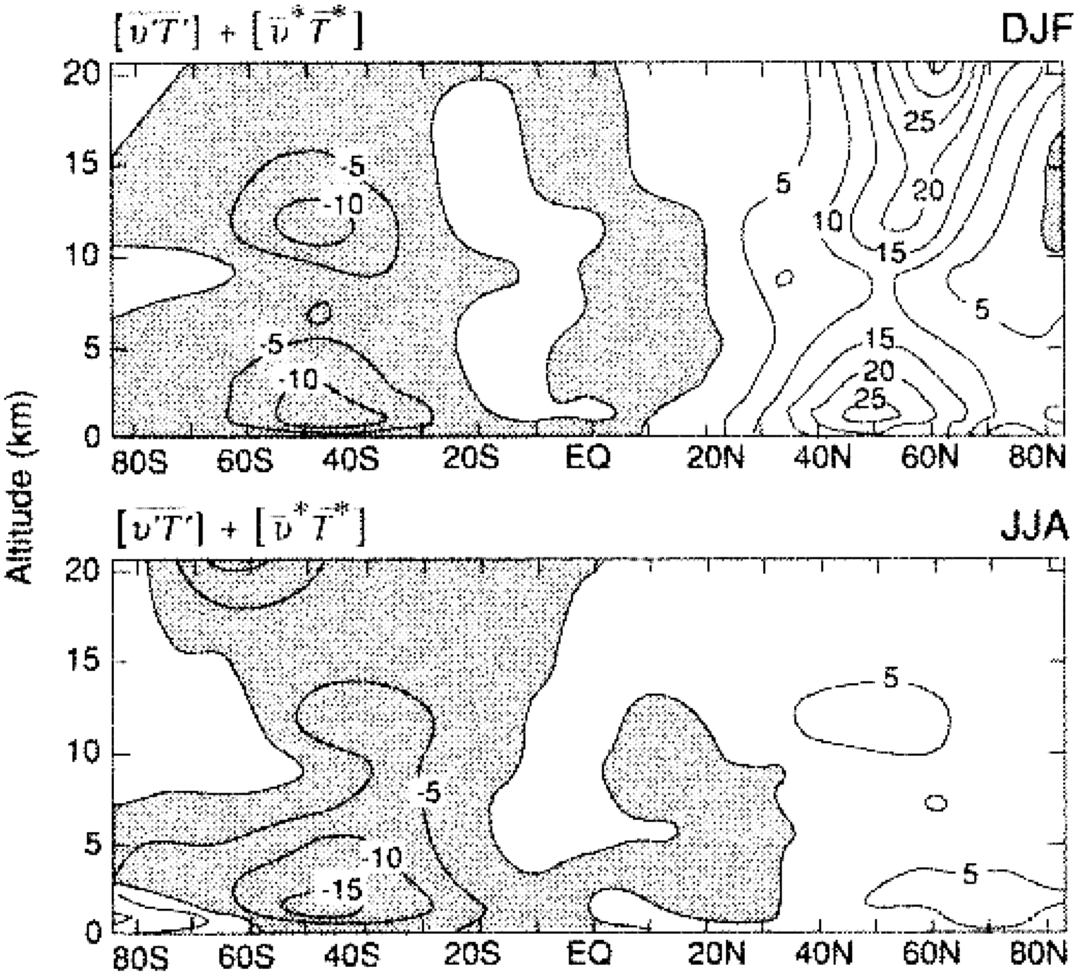
Northward Heat Flux by Eddies



- Temperature waves tend to be displaced westward relative to pressure waves (especially at lower levels) → Positive correlation between meridional velocity and temperature
- Energy available in the mean meridional temperature gradient is converted in energy of waves

- Warm air moves northwards, cold air moves southwards
- Both cause northward heat transport ($v^*T^* > 0$)

Eddy Heat Fluxes [v'T' + v*T*]



Zonal mean northward heat flux (K m/s)
Shaded areas are negative (southward) only because in Southern Hemisphere v is negative

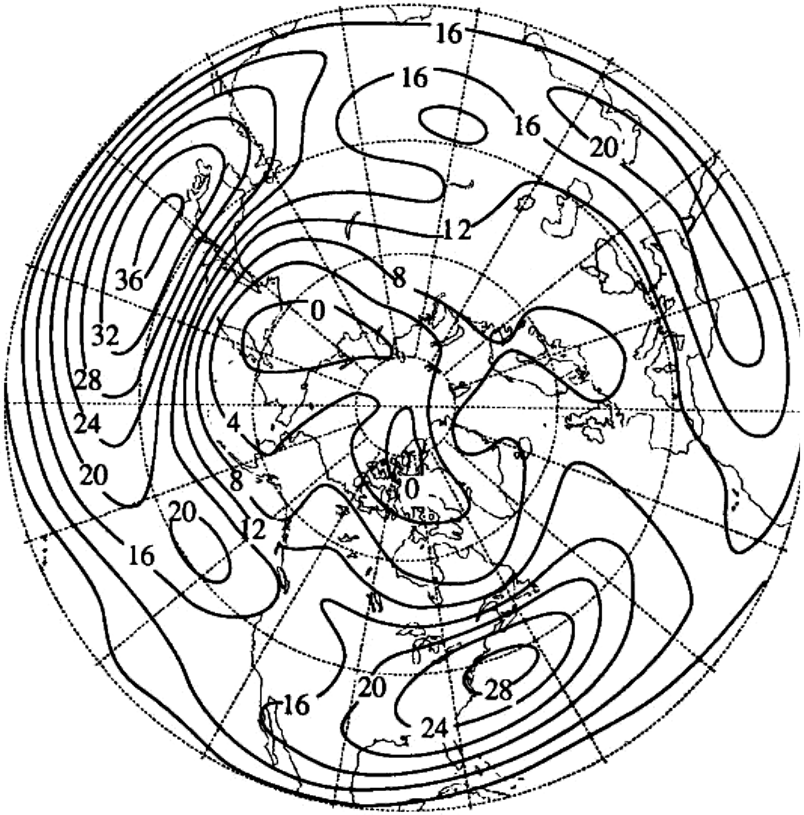
- Strongest fluxes ~50º near surface in winter hemisphere
  - Associated with amplifying cyclones
- NH eddies more energetic than SH (more continents)
- Minimum near tropopause
- Standing waves in stratosphere move heat polewards too

Large scale circulation patterns and climate

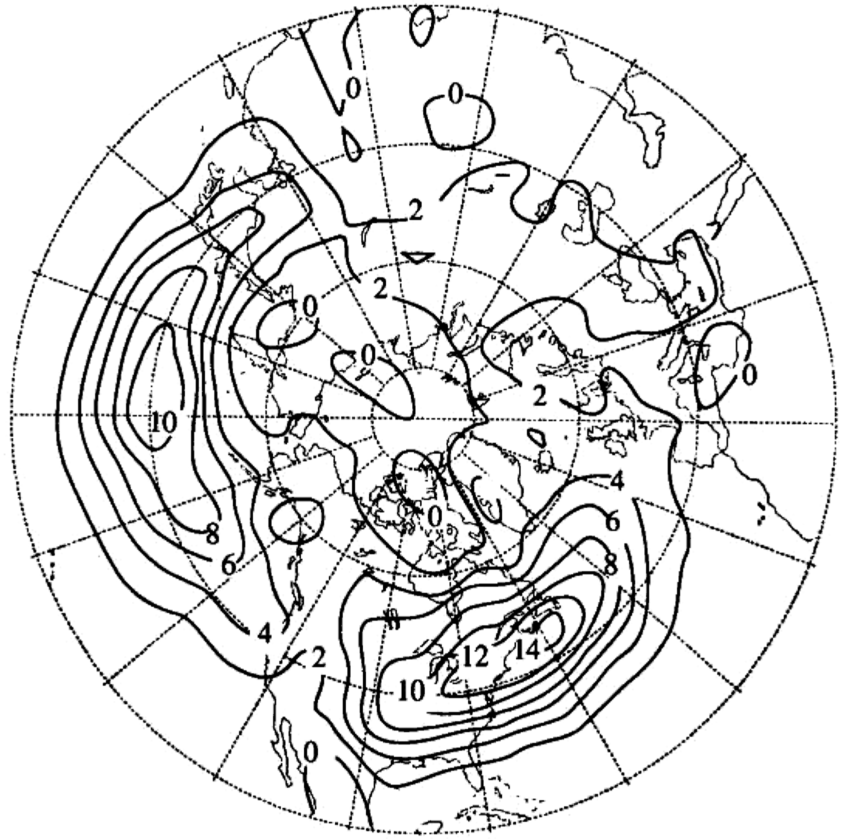
- Circulation of atmosphere is not zonally symmetric
- Subtropical jet of midlatitudes is not equally strong at all longitudes
- Local maxima are associated with distribution of land and ocean: during winter subtropical jet stream has two local wind-speed maxima downstream of Tibetan Plateau and Rocky mountains (over Pacific and Atlantic Ocean)
- These maxima of wind-speed are associated with maxima in the transient eddy activity (storm trakcs: points in which cyclonic activity is stronger) and eddy fluxes of heat and moisture

Heat Transport by Transient Eddies

500 hPa wind speed (DJF)



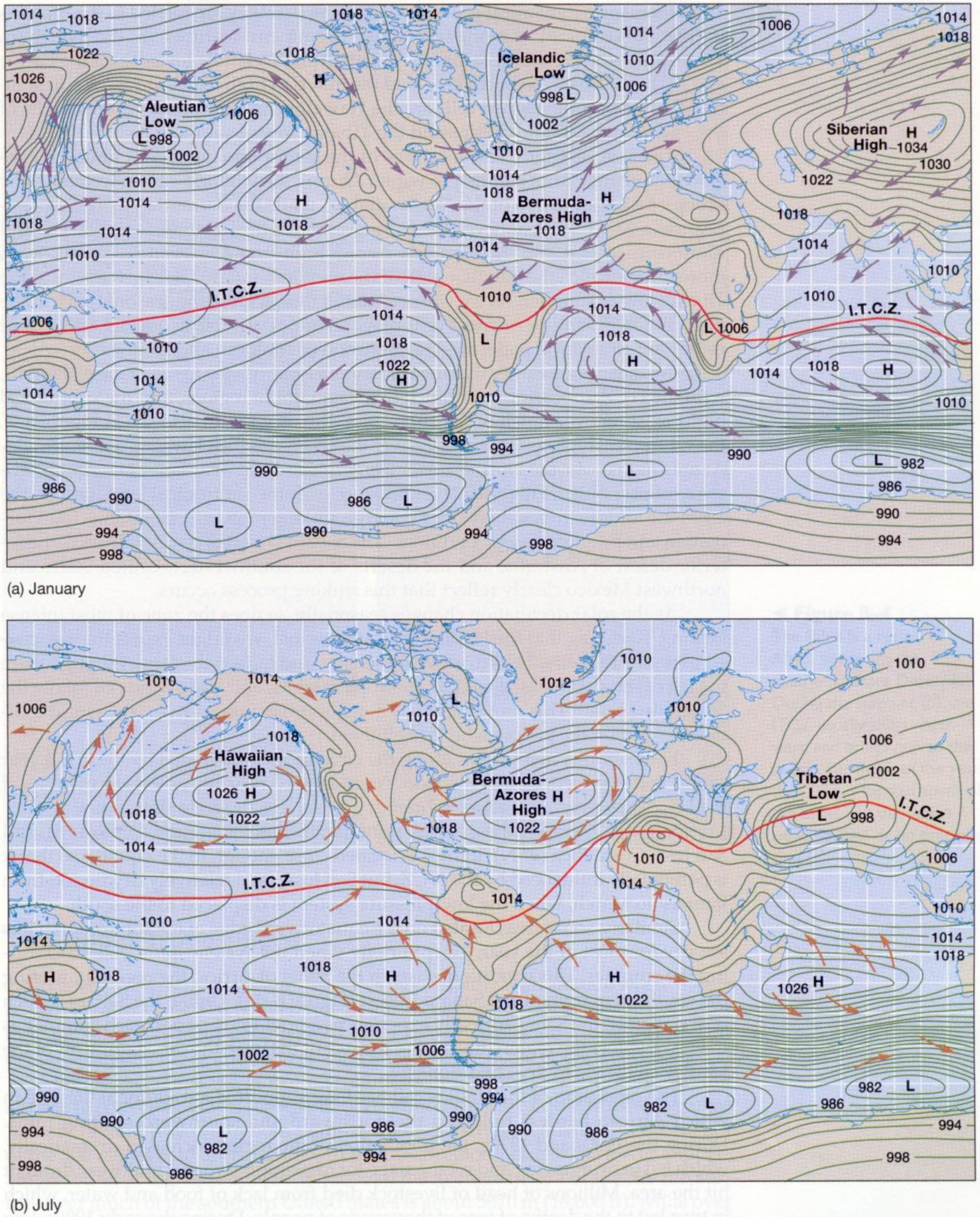
850 hPa Heat Transport



by eddies < 6 days

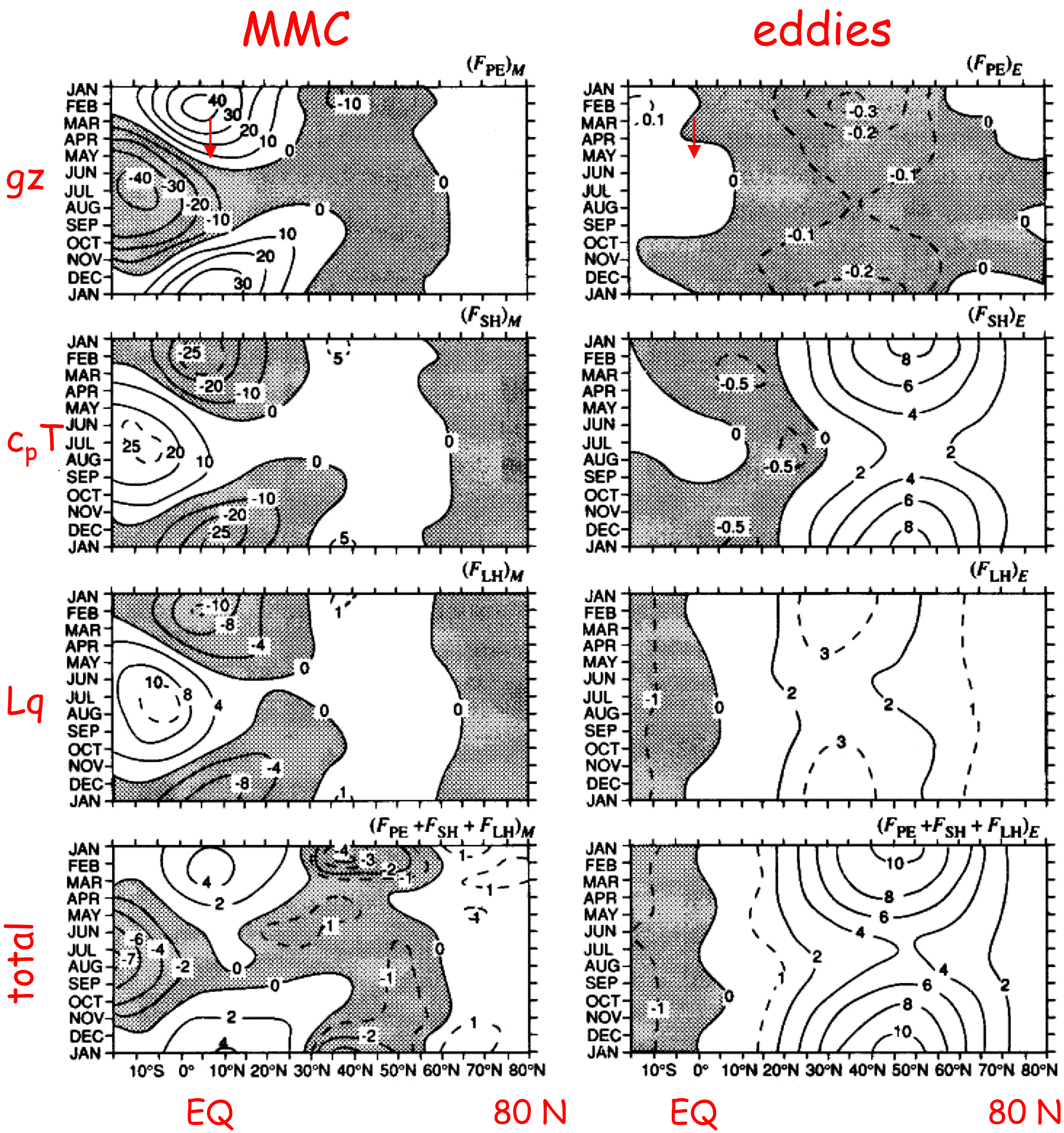
Very strong influence of "storm track" regions associated with air-sea temperature contrasts

Surface Pressure and Wind Patterns



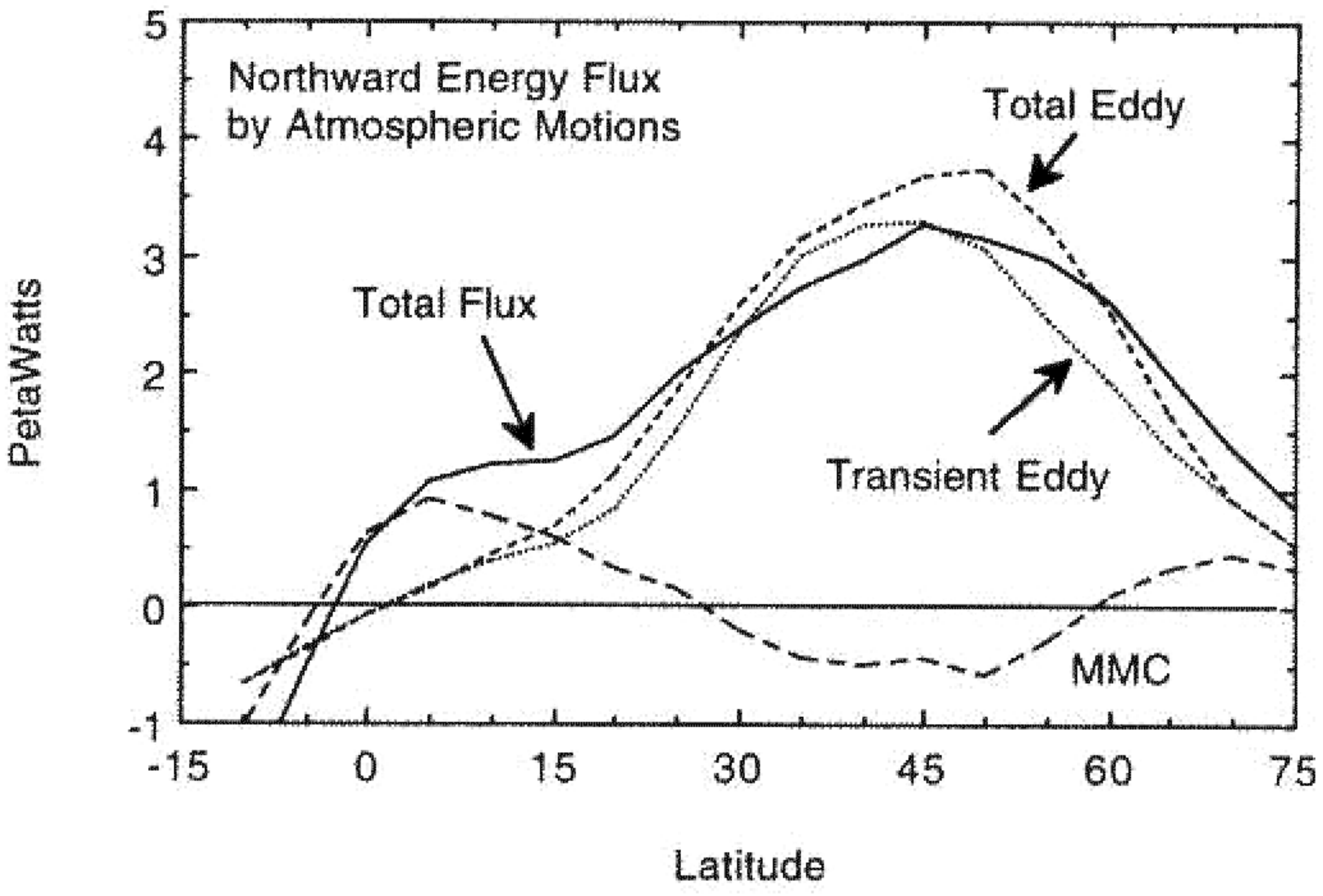
- Distribution of surface pressure is an important indicator of general circulation
- Midlatitude westerlies in both hemispheres
- Strong semipermanent high and low pressure areas (especially in NH) associated with stationary waves
- Tropical tradewind regime
- Seasonal migration of ITCZ (monsoon)

Northward Energy Fluxes by season and latitude



- Like a “bucket brigade” of energy
- MMC dominates in tropics
- Eddies dominate in midlatitudes, particularly in winter (large thermal gradient)
- LE peaks near 30° lat, while H peaks near 50°
- H + LE move into tropics in winter
- gz moves poleward into subtropics
- Eddy H carries energy to polar night

Poleward Energy Transport

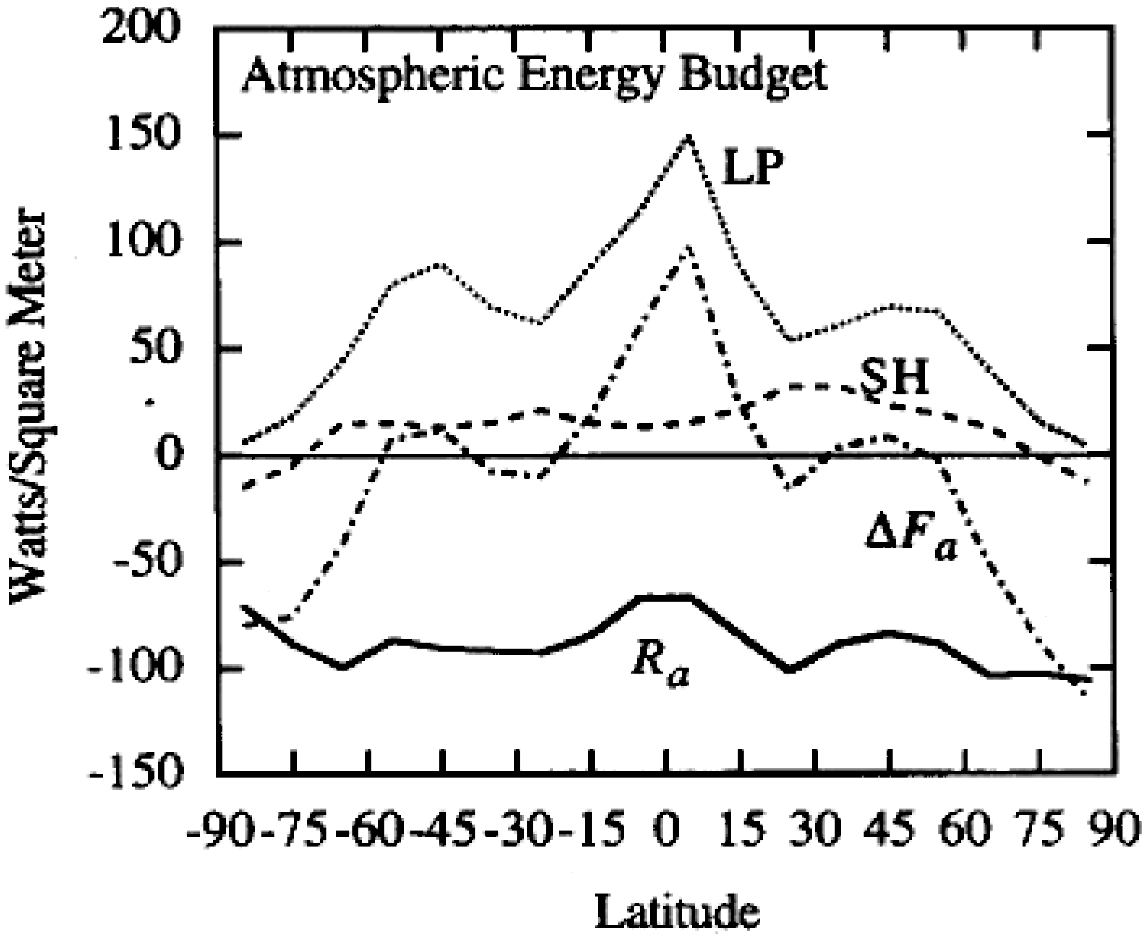


- MMC carries energy out of tropics (as gz)
- Eddy motions carry it the rest of the way (mostly as transients)
- Consider d/dφ of energy flux (divergence)
- Thermally indirect MMC in midlatitudes is response to strong eddy flux divergences

Atmospheric Energy Budget

R_a=net radiation, E_a=atmospheric energy content, LP=latent heat, SH=sensible heat, ΔF_a=horizontal divergence

$$\frac{\partial E_a}{\partial t} = R_a + \mathrm{LP} + \mathrm{SH} - \Delta F_a$$



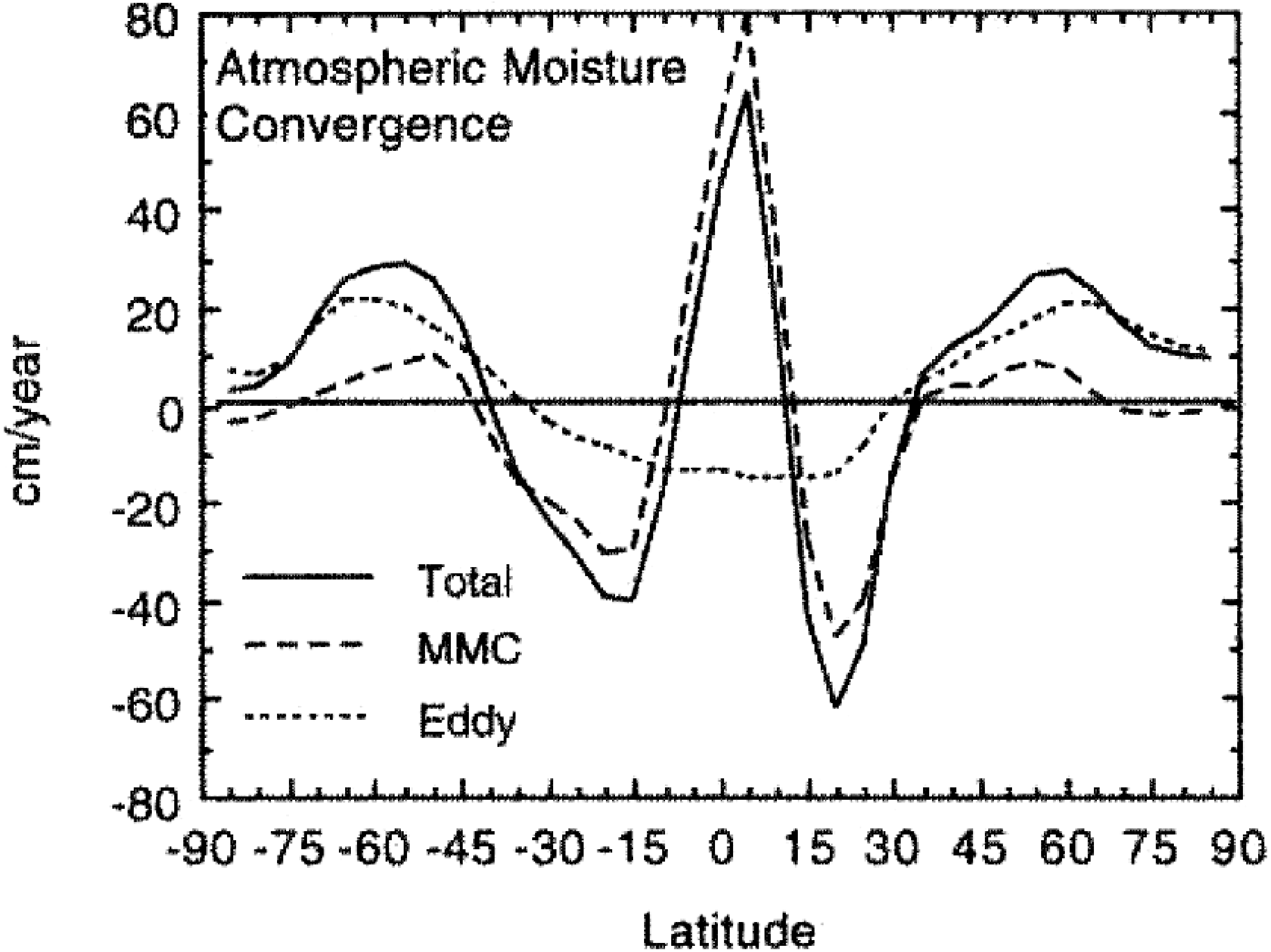
$$R_a = R_{\mathrm{TOA}} - R_s \qquad R_a + \mathrm{LP} + \mathrm{SH} = \Delta F_a$$

- Storage of energy $\Delta E_a/\Delta t$) in the atmosphere is everywhere negligible in long-term averages
- Radiative cooling R_a~-90W/m^2~-1.5ºC/day not dependent on latitude ($R_a=R_{TOA}-R_s$)
- SH is weak everywhere
- Latent heating strong in tropics (150 W/m^2) and middle latitudes (80 W/m^2)→precipitation
- Energy transport out of tropics, into high latitudes (flat in 20°-60°)

Atmospheric Hydrology

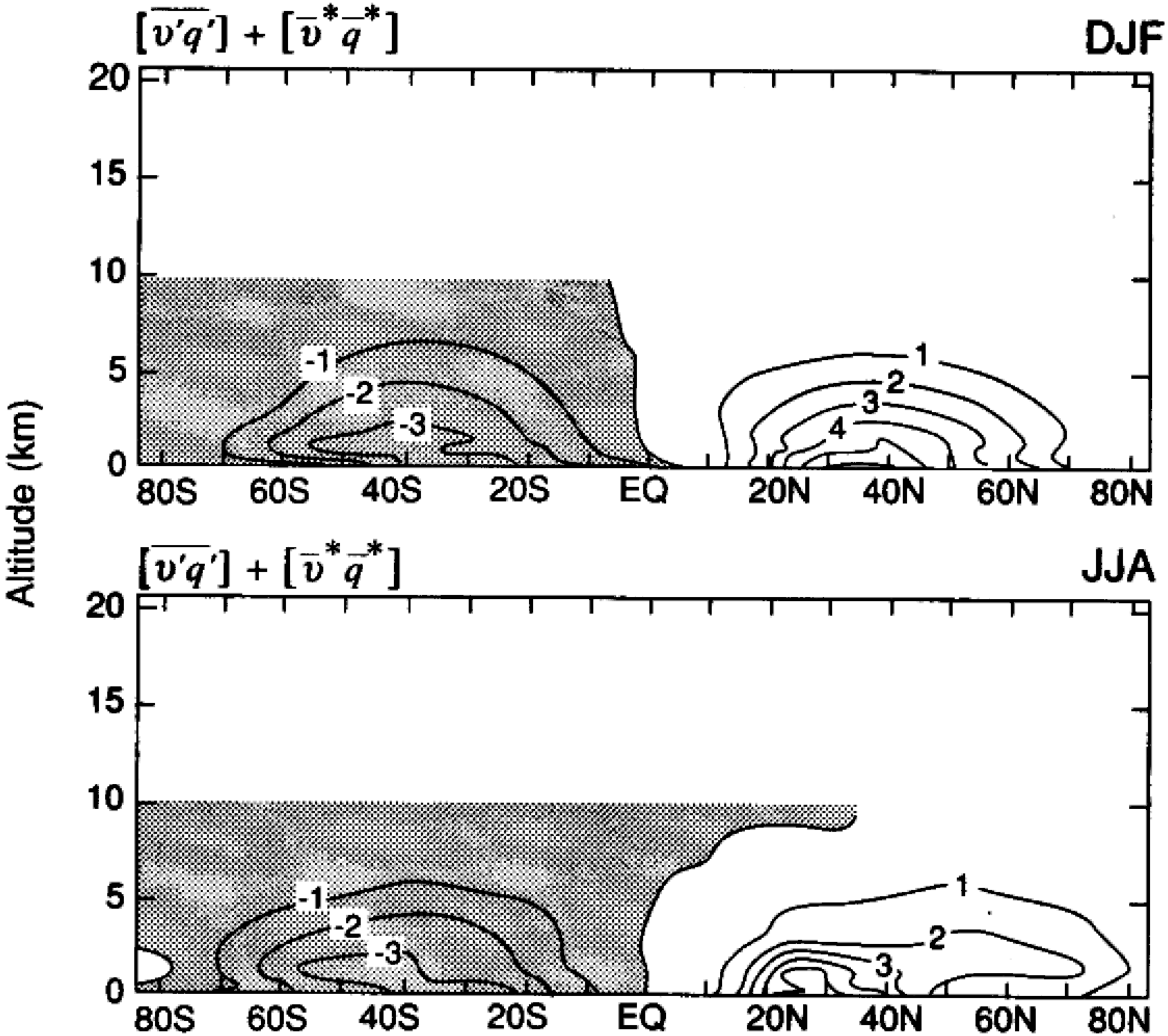
$$\frac{\partial[\overline{vq}]}{\partial y} = \frac{\partial[\overline{vq}]}{a\partial\phi}$$

MMC and eddies transport water and play an important role in determining the nature of hydrologic cycle



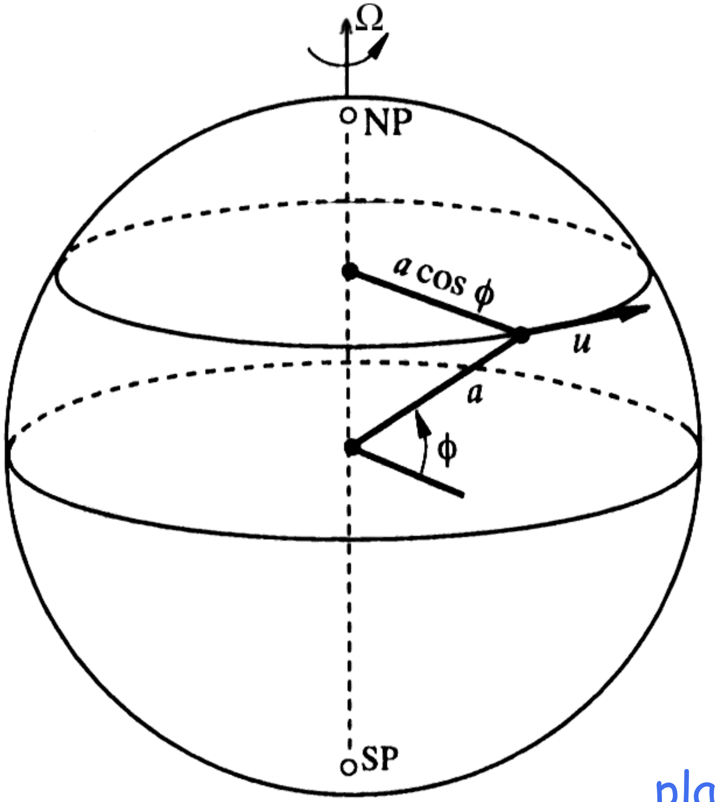
- **MMC** (dominant in tropics) transports q out of subtropics, into tropics
- **Eddies** (dominant in high latitudes) carry q out of tropics and subtropics into midlatitudes

Eddy Water Vapor Flux



- Eddy moisture flux is confined to the lower troposphere
- Stronger in NH then SH
- Peaks are largest in NH than in SH

Angular Momentum on the Sphere



- The speed of a parcel times the distance ("lever arm") from the axis of rotation is its angular momentum
- This quantity is conserved following the motion
- Combination of two components: planetary angular momentum and that associated with the motion of the parcel relative to the solid Earth

planetary → M_Ω; relative → M_r

$$M = M_\Omega + M_r$$

$$= \{\Omega\, a \cos\phi + u)\, a \cos\phi$$

speed of Earth's surface → $\Omega a \cos\phi$; zonal wind → u; lever arm → $a \cos\phi$

Conservation of Angular Momentum

$$M = (\Omega a \cos\phi + u)\, a \cos\phi = (u_{\text{earth}} + u)\, a \cos\phi$$

$$u_{\text{earth}} = \Omega a \cos\phi = 7.292 \times 10^{-5}\ \text{rad s}^{-1} \bullet 6.37 \times 10^{6}\ \text{m} \bullet \cos\phi$$

$$= 465\ \text{m s}^{-1} \bullet \cos\phi$$

much faster than the one associated with every wind!!

Consider a parcel changing latitude from φ_1 to φ_2 while conserving angular momentum. What is the wind speed at new position?

$$M = (\Omega a \cos\phi_1 + u_1)\, a \cos\phi_1 = (\Omega a \cos\phi_2 + u_2)\, a \cos\phi_2$$

Suppose a parcel starts at the Equator, at rest relative to the sfc, then moves poleward to latitude φ?

$$M = \Omega a^2 = (\Omega a \cos\phi + u_\phi)\, a \cos\phi \qquad u_\phi = \Omega a \frac{\sin^2\phi}{\cos\phi}$$

Why jet max is only about 30 m s^{-1}?

- According to previous calculations, a parcel will acquire a velocity of **134 m/s at 30° latitude!**
- Observed subtropical jet max is only about 30 m s^{-1}.
- Why?
- A parcel traveling at a mean meridional velocity of 1 m/s would require about 30 days to travel from Equator to 30°N
- During this time there is sufficient time for small-scale turbulence or some other slow processes (i.e. large-scale eddies) to reduce its angular momentum

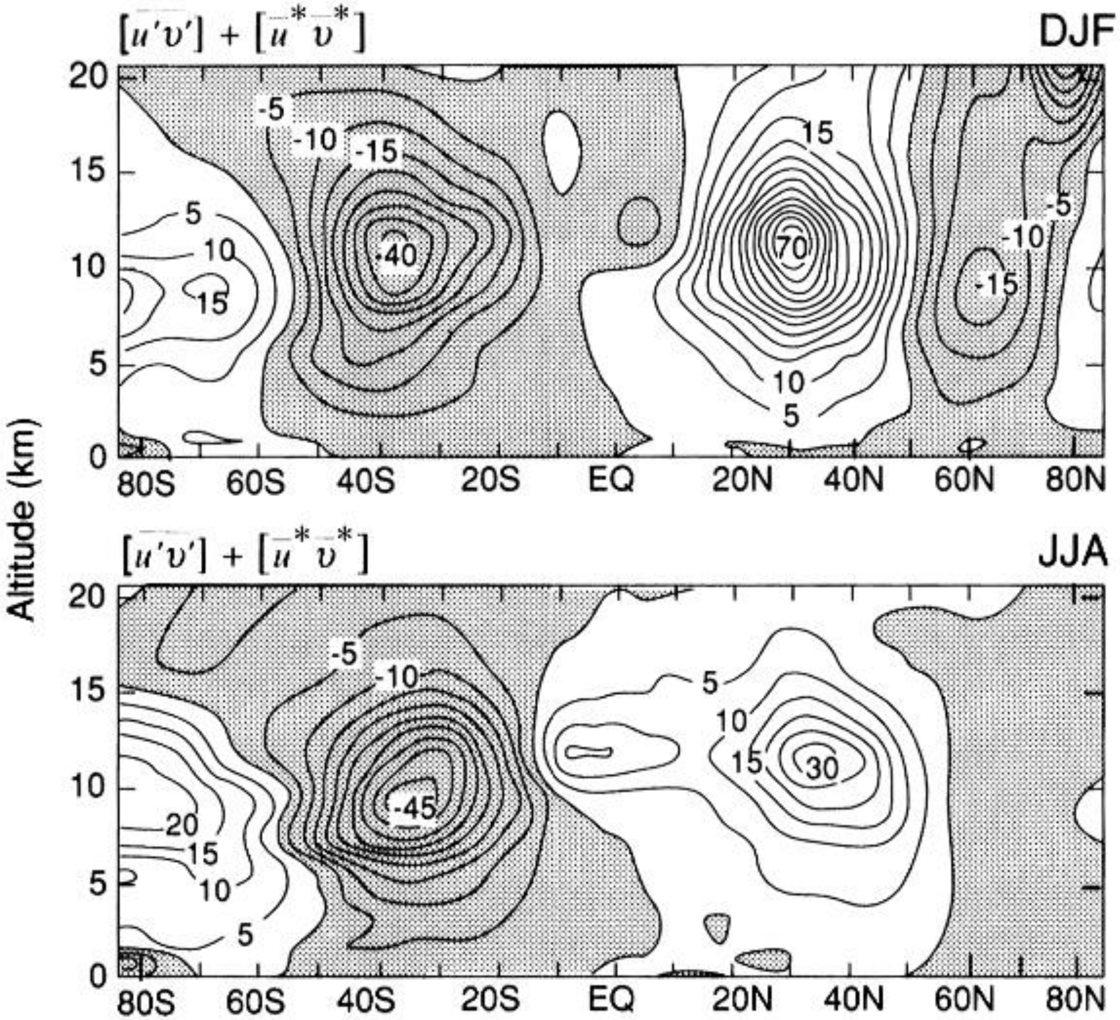
Eddy Angular Momentum Transport

Zonally averaged meridional flux of angular momentum is:

$$[\overline{vM}] = [\bar{v}]\left(\Omega a \cos\phi + [\bar{u}]\right) a \cos\phi + \left\{[\overline{u'v'}] + [\bar{u}^* \bar{v}^*]\right\} a \cos\phi$$

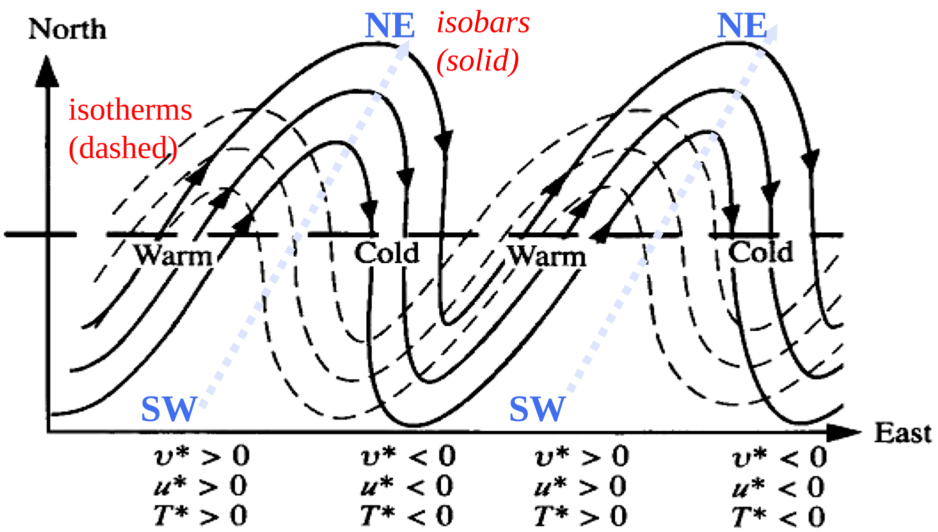
Transport by MMC

Transport by eddies



- Huge poleward flux of angular momentum by the eddies in midlatitude upper troposphere
- Dominant at 30°, where Mmvelocity is small
- Consider d/dφ of this flux
  - Divergence in tropics
  - Convergence from 30º to 70 º in winter

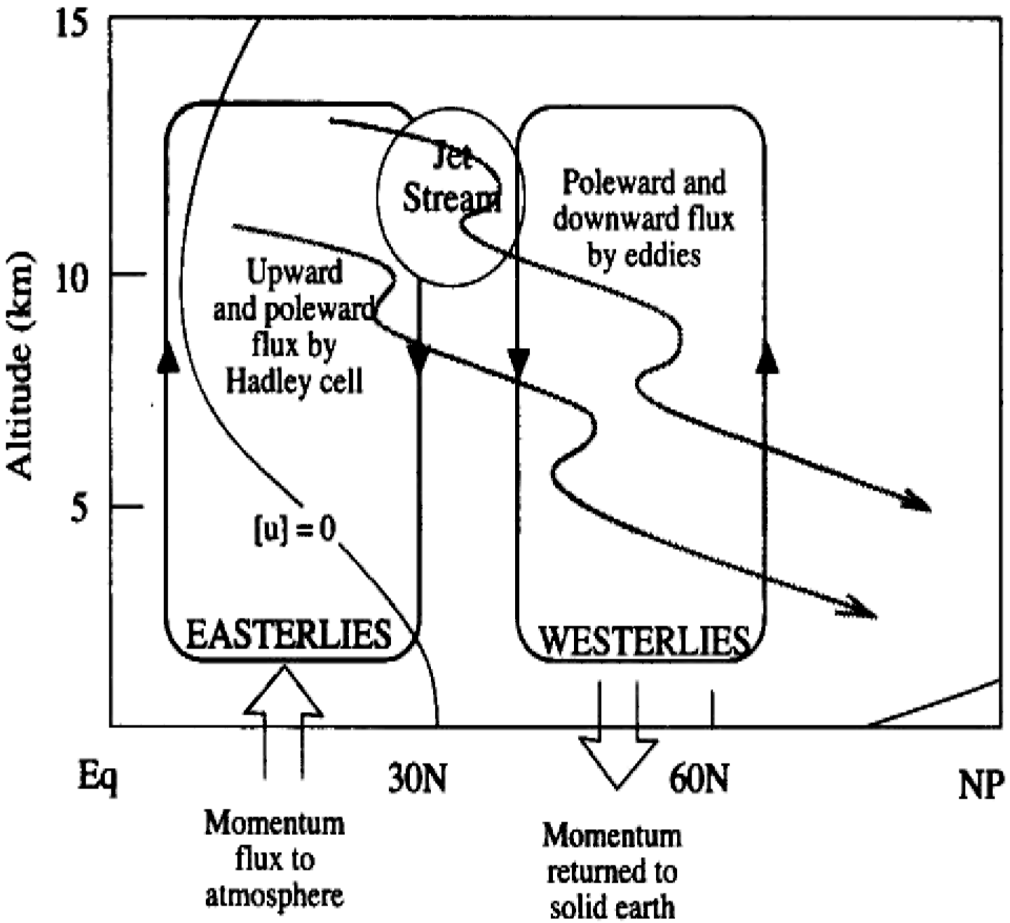
Eddy Angular Momentum Transport (cont)



- Northward zonal momentum flux by large-scale atmospheric disturbances is product when flow streamlines are oriented such that high and low anomalies tilt from southwest to northeast in NH

- When streamlines are tilted in this manner, eastward component of wind is greater when the meridional component of wind is poleward, and eastward component of wind is weaker when the meridional component of wind is equatorward
- Therefore, a longitudinal average of the product of deviations of zonal and meridional components of wind will be positive → northward flux of zonal angular momentum

Angular Momentum Transport



- In the tropical easterlies (or trade winds, where atmosphere rotates slower than Earth surface), eastward angular momentum is transferred from Earth to atmosphere (friction)
- Westerly angular momentum is transported upward and poleward by Hadley cell
- Atmospheric eddies transport angular momentum poleward and downward into midlatitude westerlies
- Planetary angular momentum transferred back to solid Earth in midlatitudes (westerlies)
- Surface zonal winds cannot be of same sign everywhere: eastward angular momentum must flow into atmosphere where surface winds are easterly, and return to the Earth where surface winds are westerly

Planetary Waves and Poleward Energy Transport

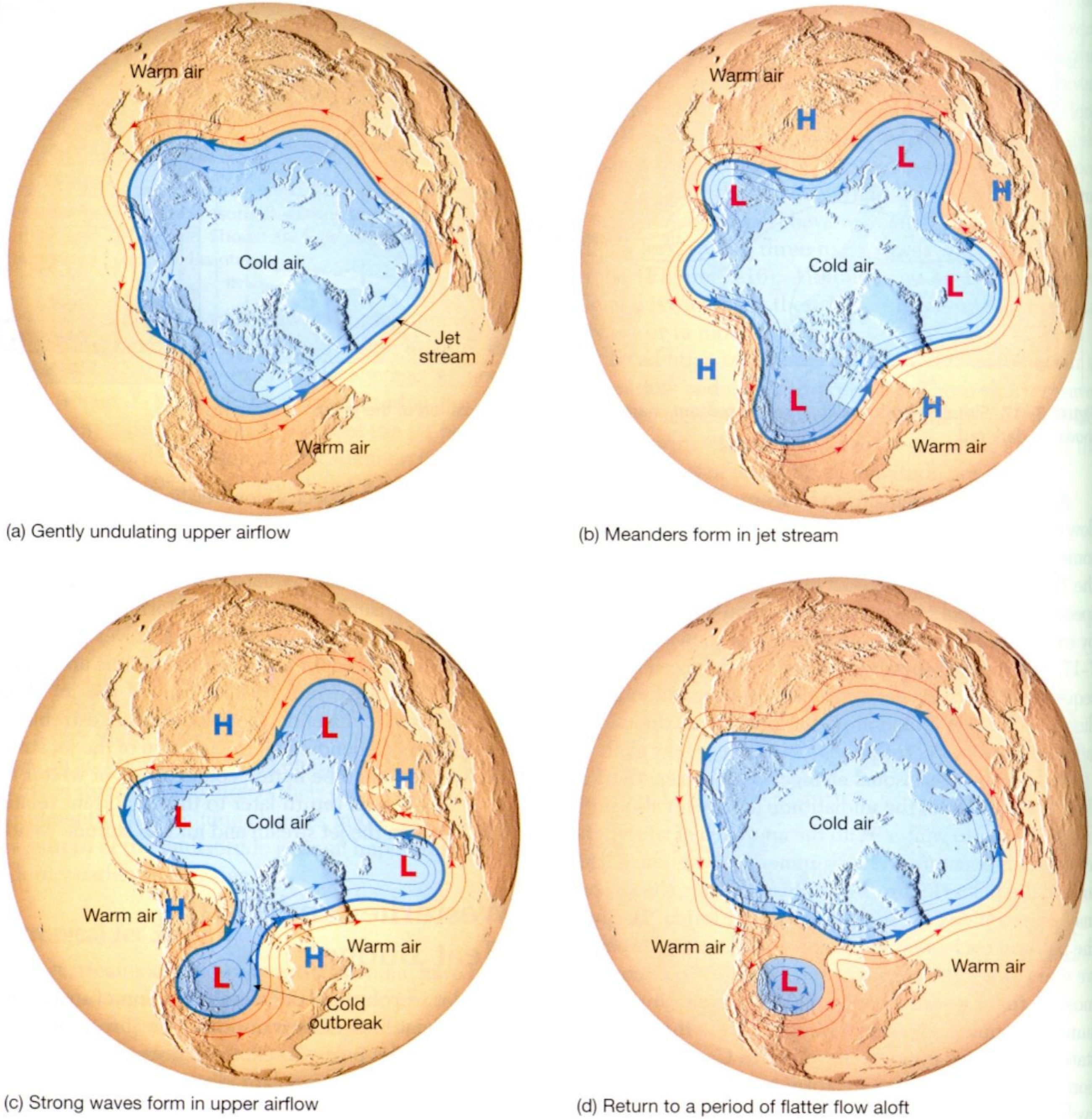
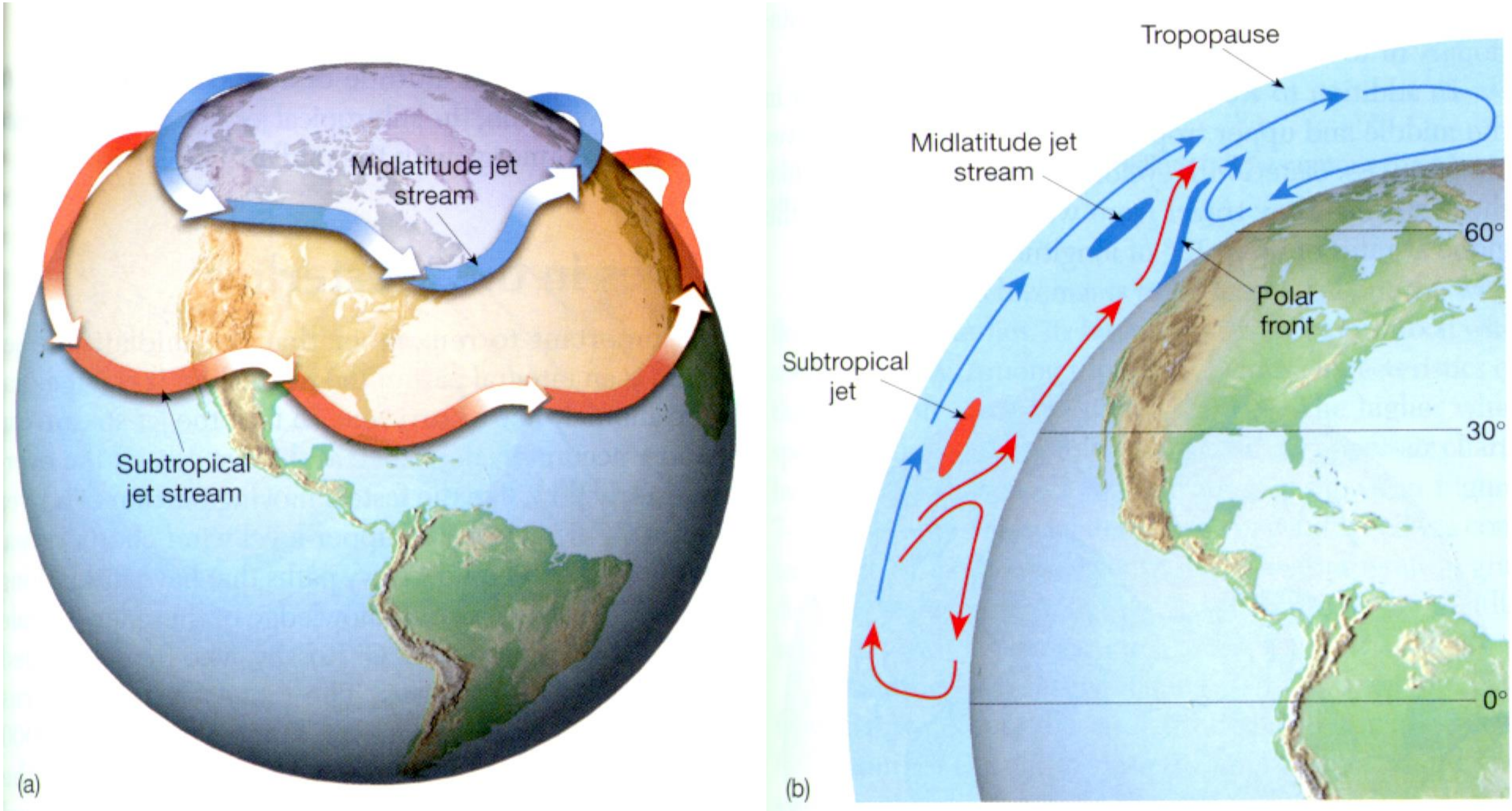


Figure 7–18 Cyclic changes that occur in the upper-level airflow of the westerlies. The flow, which has the jet stream as its axis, starts out nearly straight and then develops meanders and cyclonic activity that dominates the weather.

Jet Streams



- Subtropical Jet is zonal mean response to poleward flow in upper branch of Hadley Cell
- Polar front jet is response to meridional temperature gradients

Large-scale circulation patterns and climate

- The distribution of climate systems on the troposphere and their spatial and temporal variation determine the climate
- The seasonal variations in sea-level pressure are most apparent in the NH, due to the higher distribution of land
- During winter, the high-latitude oceans are characterized by low-pressure centers, while a net high-pressure center lies over Asia
- During summer, the land-sea pressure contrast is reversed in mid-latitudes, with highest pressures over oceans and lowest pressure over land
- Dramatic shifts in land-sea pressure distribution are driven by seasonal changes in insolation and different responses of land and ocean to heating: land surfaces warm up dramatically in summer and cool in winter
- Low pressure generally occupy warm regions, where atmosphere is heated, while high pressures occur when temperature is low and is being cooled