Atmospheric circulation II

Reading: GPC Ch6

Outline:

- Zonal mean circulation: zonal wind; the mean meridional circulation (MMC)
- Hadley and Ferrel cells
- Stationary and transient eddies
- Atmospheric poleward energy transport by eddy circulation
- Energy in the atmosphere
- Angular momentum balance

The zonal mean circulation

Preliminaries:

Zonal mean =
Average over longitudes λ
at a particular ϕ and p

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

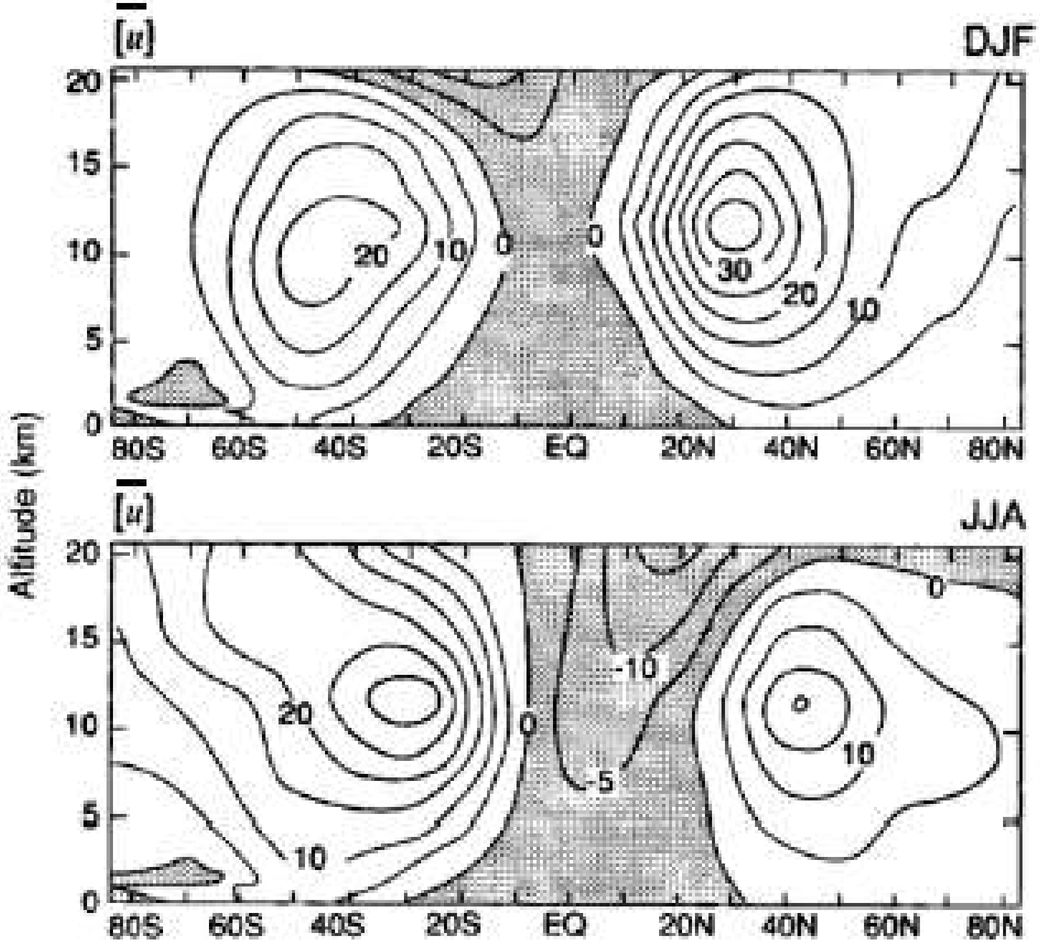
Time mean

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

For climatological purposes, we are normally interested in averages over a Δt long enough to average out most of weather variations:
a particular month or season, or year, or an ensemble of many months, seasons or years.
Climatological zonal averages are usually obtained by averaging over both λ and t.

Mean Zonal Wind

Easterly values are shaded



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

- Midlatitude westerly winds
- Deep tropical easterlies
- Well-defined winter wind max ~ 30° lat at ~ 12 km ("jet stream")
- Summer jet is weaker and further poleward

[v] and [w] are much weaker: $[v]_{max}$~1 m/s, [w] tipically ~0.01 [v]

The mean meridional circulation (MMC)

MMC is composed of the zonal-mean meridional and vertical velocities and can be described by a

mass mean meridional streamfunction

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

It is a measure of how much mass is transported north or south above a particular pressure level p.
The mass flow between any two streamlines of the streamfunction is equal to the difference in the streamfunction values (so the units of streamfunction are kg/s). Ψ_M is useful for understanding the flow in the y-z plane.

The conservation of mass for the zonal mean flow implies a relationship between Ψ_M and [v] and [ω]:

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

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

Atmospheric poleward energy transport in the tropics by the mean meridional circulation

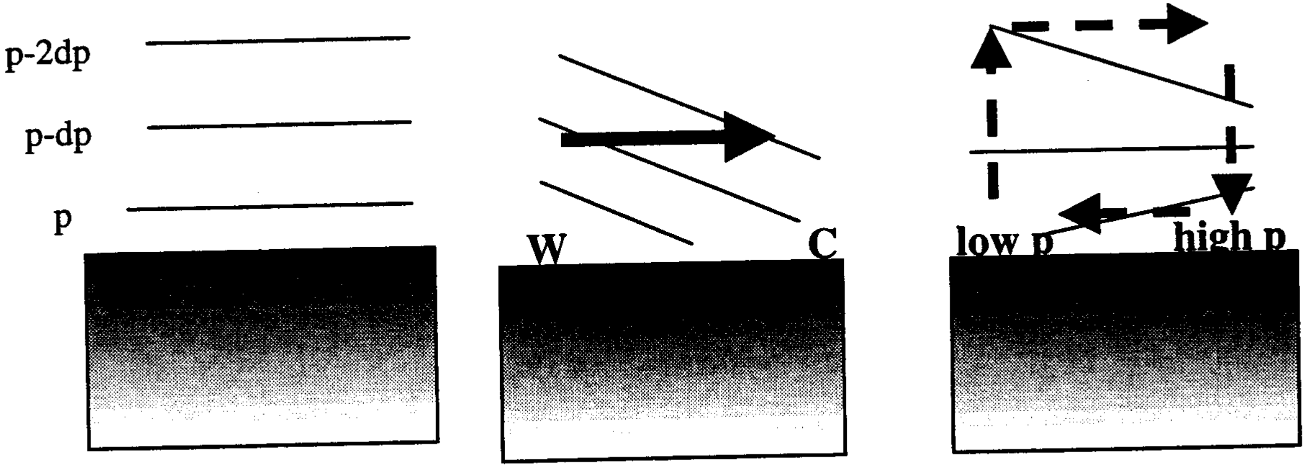
The MMC is dominated in the solstitial season by a single circulation cell in which air arises near the equator, flows toward the winter hemisphere at upper levels and sinks in the subtropical latitudes of the winter hemisphere. The MMC cell is called the **Hadley cell**.
The mean meridional winds near the surface bring air back toward the equator.

The MMC for the equinoctal season and for the annual average consists of two smaller cells of about equal strengths, located on opposite sides of the equator.

Hadley cells, in which warm air rises and cold air descends, are called **thermally direct** circulations.

Thermally direct circulation - rises in warm air, drops in cold air Transports energy from warm to cold regions. The Hadley circulation is an example of a thermally direct circulation.

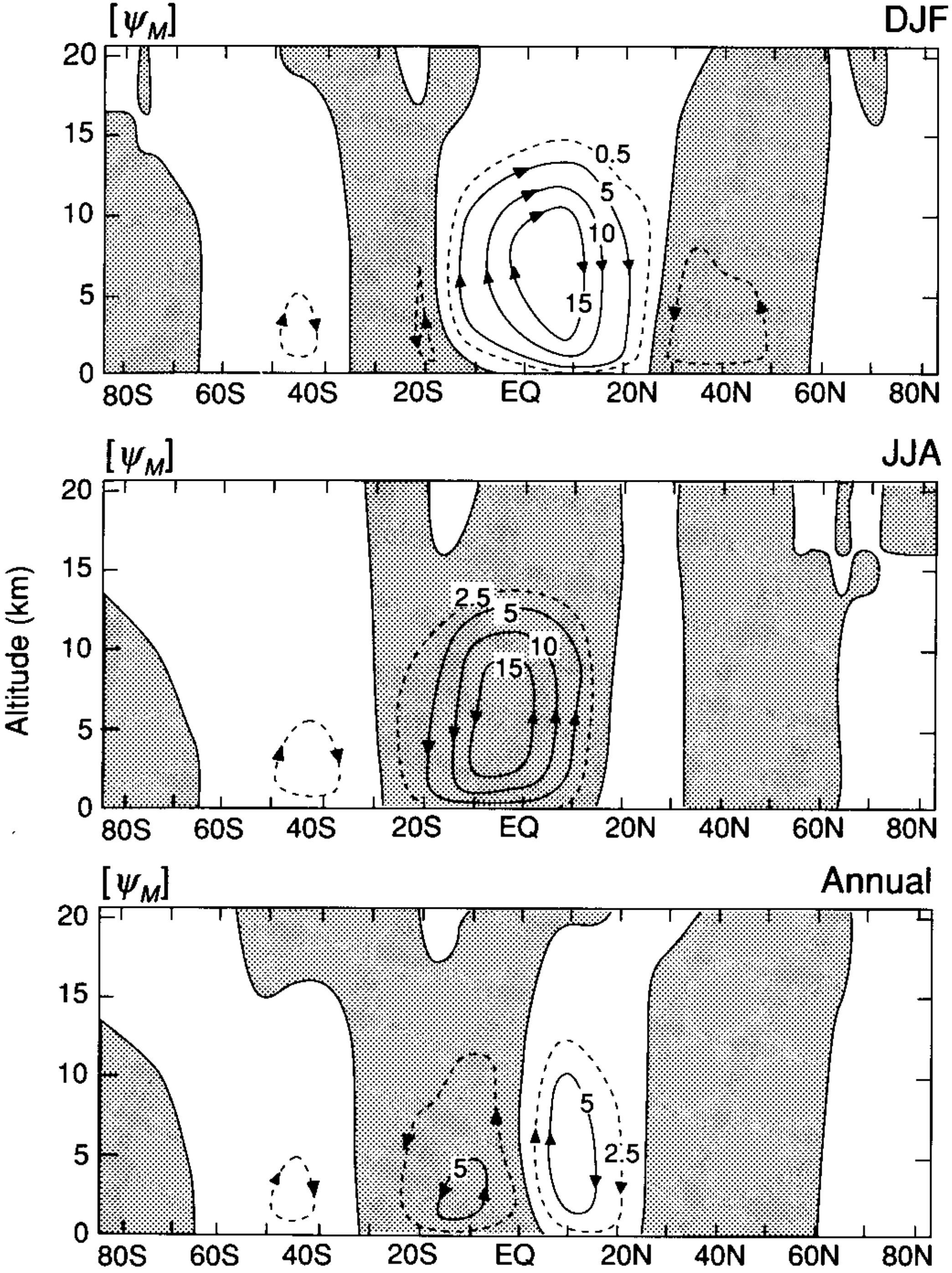
Development of a thermally-direct circulation:
Note: thin lines are isobars; thick arrow in middle frame is the pressure gradient force; dashed arrows in third frame indicate wind directions



initial motionless state

heat left side mass shifts right

thermally-direct circulation



The mean meridional circulation (MMC)

The stronger central cell (s) are the ***Hadley cell(s)*** and they are ***thermally direct***

In midlatitudes, weaker cells called **Ferrel cells** circulate in the opposite direction to the Hadley cell. Cold air rises and warm air sinks, so they are **thermally indirect** andso actually transport energy from cold to warm regions.

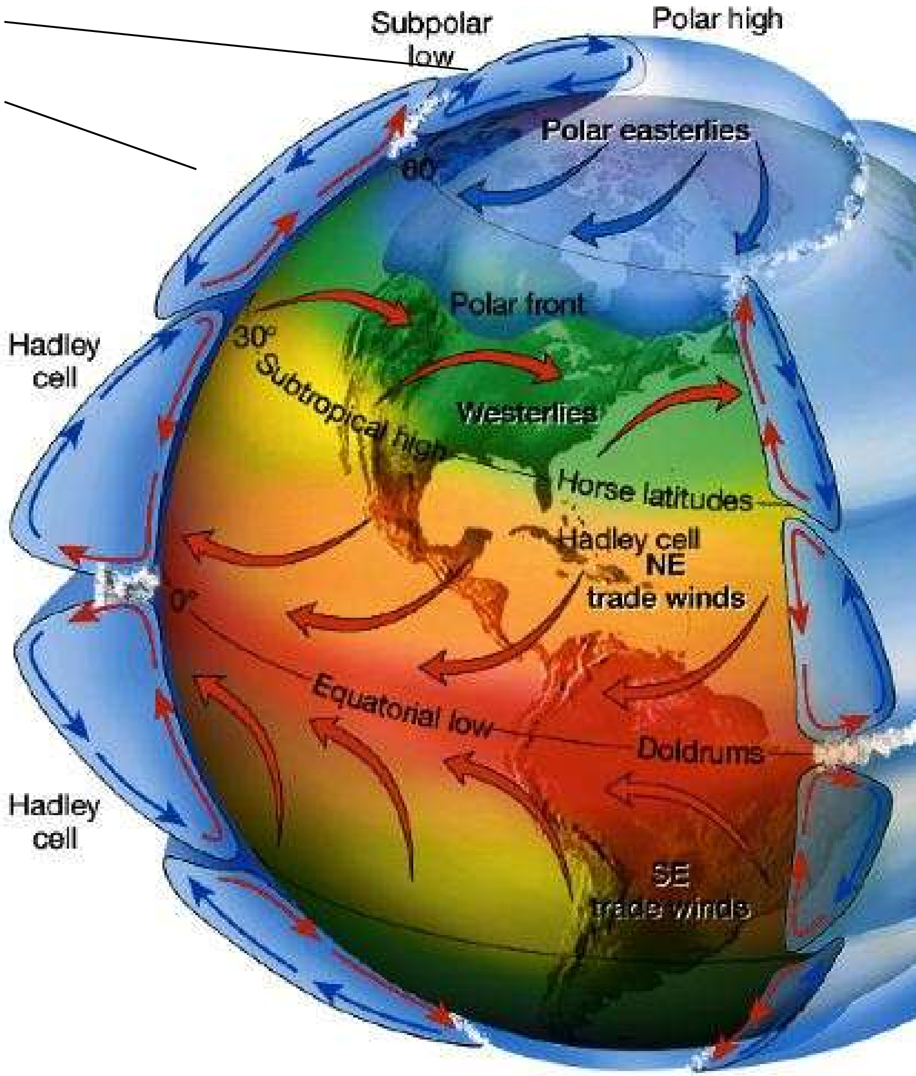
The MMC is a small component of the total flow in midlatitudes, and the Ferrel cells are a byproduct of the very strong poleward transport of energy by **eddy circulation**.
Eddies are deviations from the time or zonal average, and are a key component of the AGC.

In summary:

- **energy absorbed by the atmosphere in the tropics is delivered to the subtropics by the Hadley circulation.**
- **From the subtropics to the mid and high latitudes, the energy transfer is performed by the midlatitude eddy circulations, both transient and stationary.**

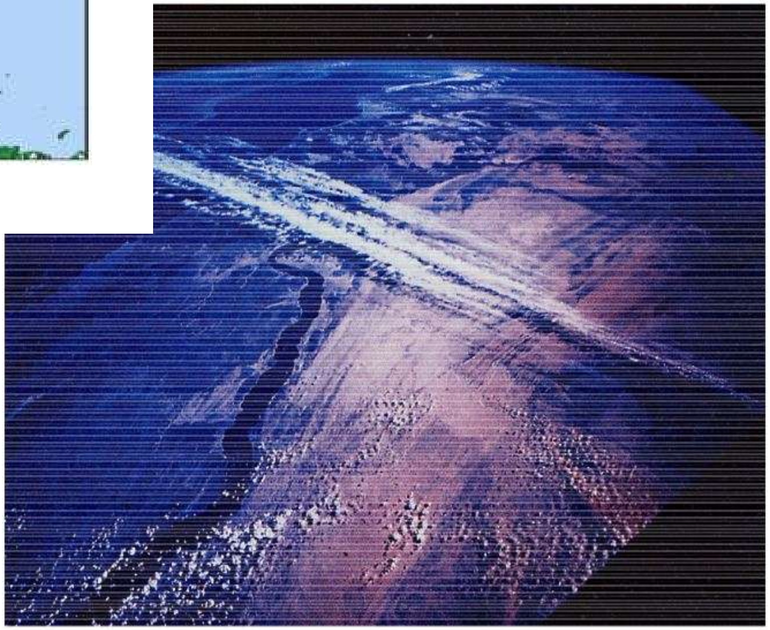
Polar Cell

Ferrel Cell



The ***Ferrel cell*** is a 'residual' circulation - it comes as a consequence of the stationary and transient eddy circulations in the midlatitudes. The warmer midlatitude Ferrel cell meets the colder polar cell at the ***polar front***, where it 'lifts' over the denser polar air.

The ***Polar cell*** subsides over the poles where it acts to warm the atmosphere there (to balance the radiative cooling). Hence: dry, high pressure conditions (polar high). The air moves back to the midlatitudes in lower troposphere (as polar easterlies).



The polar front creates pressure gradients that give rise to the ***midlatitude jet*** (aka polar jet).
It can be 100 km/h or faster

Transient and stationary eddies

The cyclones and anticyclones that are responsible for most of the weather variations in midlatitudes produce large meridional transports of momentum, heat and moisture. These disturbances have large wind and T variations on scales of several thousands of km, which do not appear in a zonal average but have a profound effect on the zonal-mean climate.
The fluctuations associated with weather appear as deviations from time average (***transient eddies)***.

In addition to temporal variations associated with midlatitude cyclones, the atmosphere exhibits variations around latitude circles associated with the position of continents and oceans, that are quasistationary and appear clearly in time averages. These are characterized by deviations of the time mean from its zonal average (***stationary eddies***).

Atmospheric poleward energy transport by eddy circulation

Deviations from time average: $x' = x - \overline{x}$

They show fluctuations associated with travelling weather disturbances (transient).

Deviation of time mean from its zonal average: $\overline{x}^* = \overline{x} - [\overline{x}]$

They show variations around latitude circles, associated with the presence of continents and oceans (stationary).

So: ***zonal and time mean northward transport of temperature*** can be broken into:

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

Zonal and time mean northward transport of temperature

Contribution by the ***mean meridional circulation (Hadley, Ferrel)***

Contribution by ***stationary eddies***

Contribution by ***transient eddies***

Northward eddy fluxes of T are produced when northward flowing air is warmer than southward flowing air, so that, when zonally averaged, the product of meridional velocity and T is greater than zero, even when $[\overline{v}] = 0$.

Transient eddy fluxes are associated with the rapidly developing and decaying weather disturbances of midlatitudes, which generally move eastward with the prevailing flow and contribute much of the variations of wind and T, expecially in winter. These disturbances are very apparent on weather maps.

Stationary eddy fluxes are associated with **stationary planetary waves** = Departures of the time average from zonal symmetry, well visible in monthly mean tropospheric pressure patterns. They result from the east-west variations in surface elevation and surface T associated with continents and oceans. Stationary eddy fluxes are largest in the NH where the Himalaya and the Rocky Mountains provide mechanical forcing of east-west variations in the time mean winds and T. The thermal contrast between the warm waters of the Kuroshio and Gulf Stream currents (see later) and the cold T in the interior of the continents also provides strong thermal forcing of stationary planetary waves during winter.

Stationary Eddies (Waves)

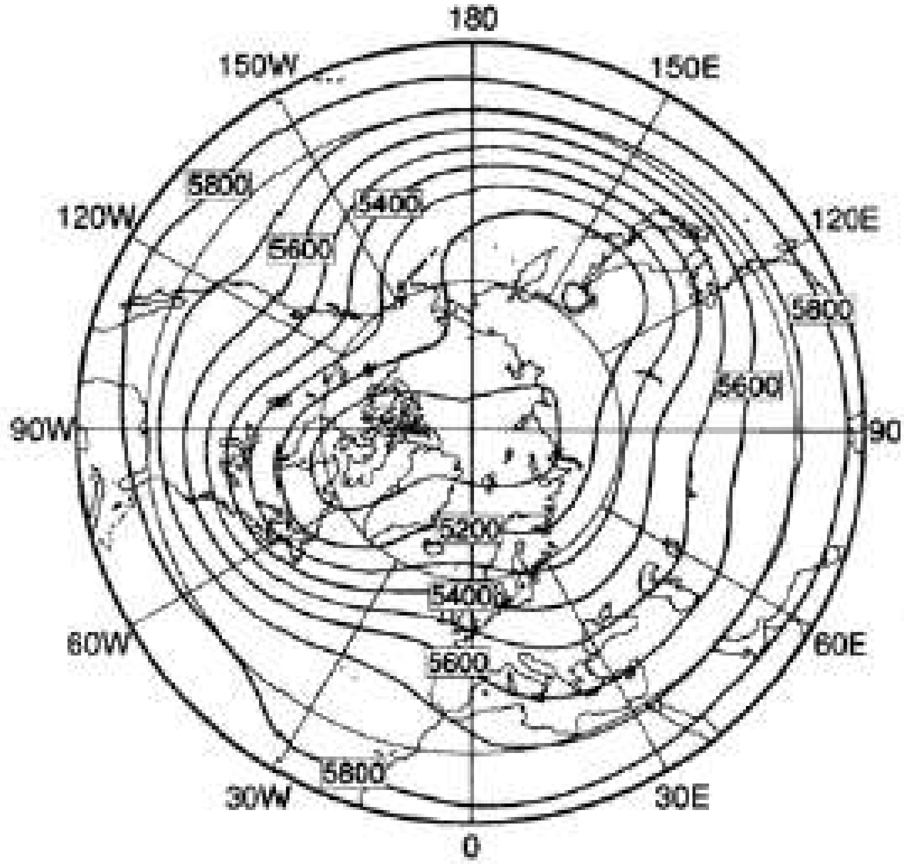
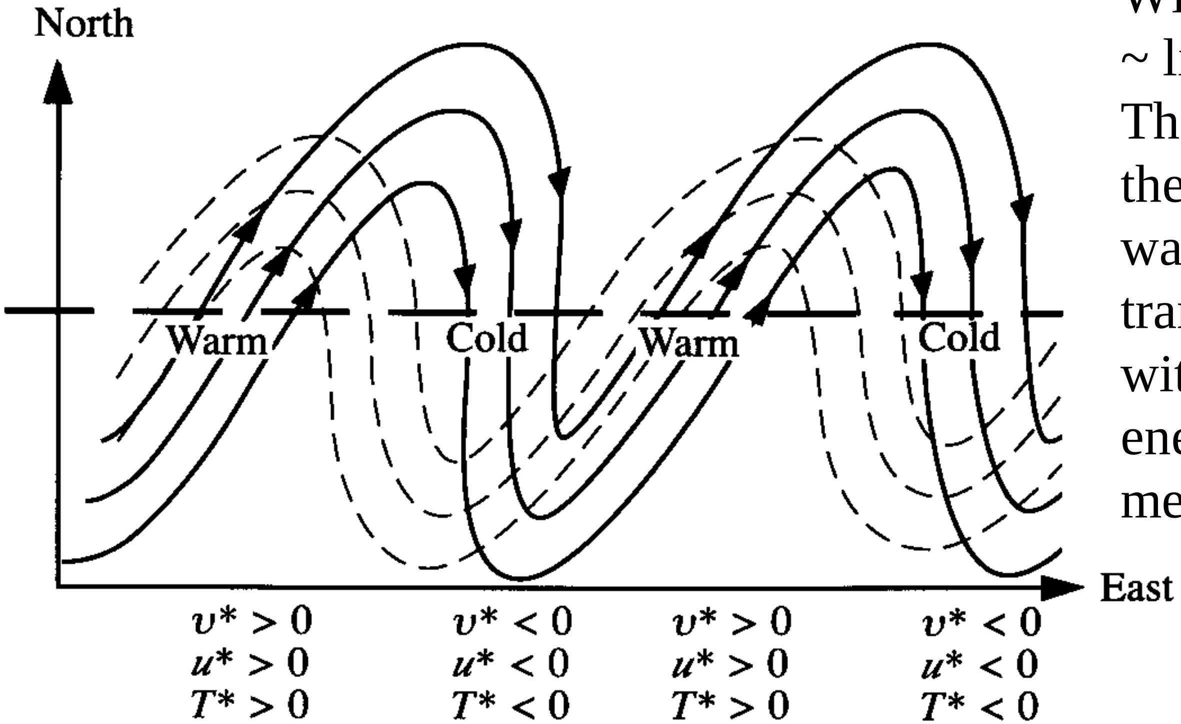


Fig. 6.7 Average height of the 500-mb pressure surface during January in the Northern Hemisphere. Contour interval is 100 m.

- Like a big spinning bowl
- Ridges and creases in bowl are caused by temperature contrasts (land vs ocean) and by mountain ranges
- 3 or 4 waves are typical

Northward heat flux by eddies

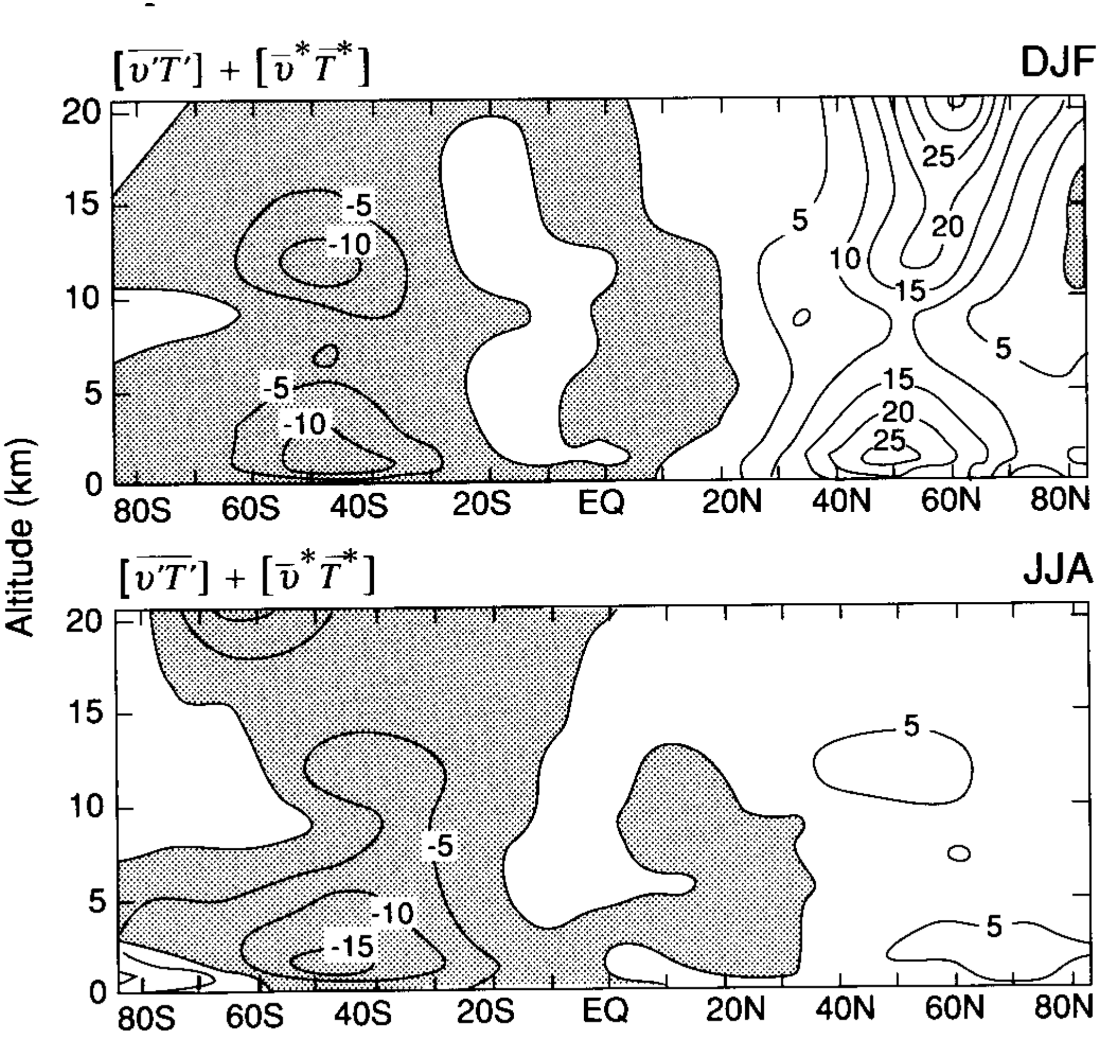
Schematic of streamlines (solid) and isotherms (dashed) associated with a large-scale atmospheric wave in the NH midlatitudes



Wind nearly geostrophic →
~ lines of constant p.
The westward phase shift of the T wave relative to pressure wave, that gives a northward transport of heat, is associated with the conversion from energy available in the mean meridional T gradient to the energy of waves.

Note that $v^*T^* > 0$ in all instances, so that energy is transported northwards by these eddies

Zonal mean northward flux of temperature by stationary and transient eddies



Note that while the flux in the NH changes dramatically from NH winter to summer, the SH flux remains roughly the same magnitude both summer and winter. Transient eddy fluxes dominate the meridional flux of heat except in the NH during winter, where stationary eddies contribute up to half of the flux.

Energy in the atmosphere

Total energy in the atmosphere =
Internal (or sensible) + Potential + Latent + Kinetic

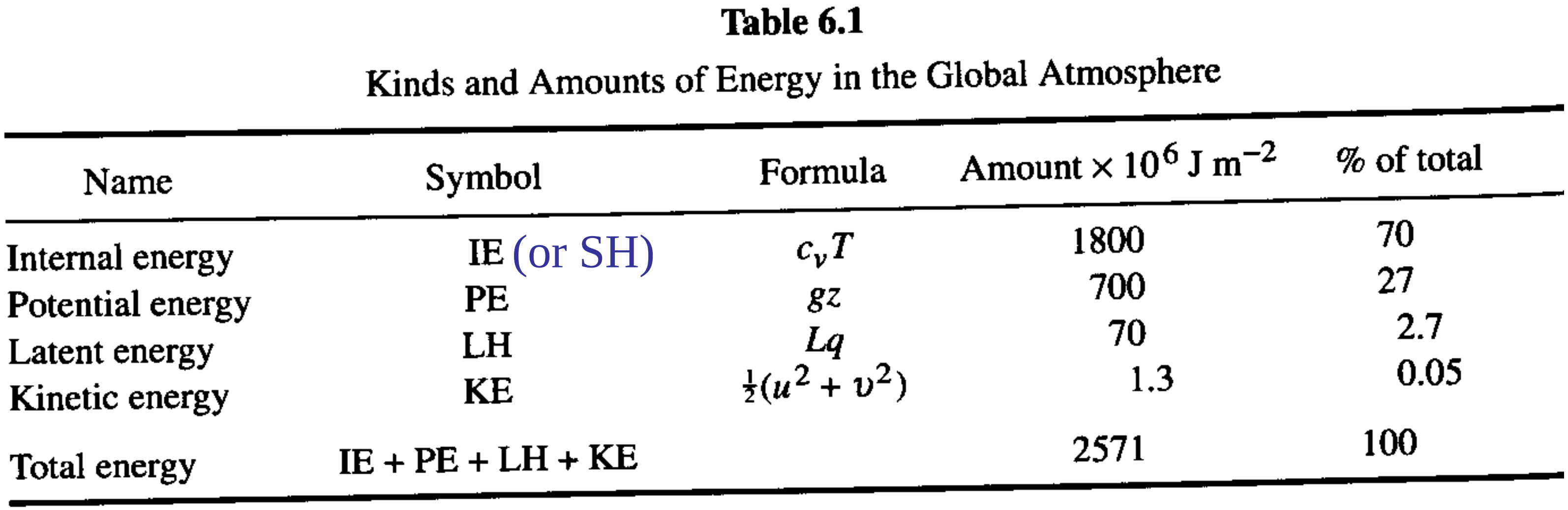


Table 6.1

Kinds and Amounts of Energy in the Global Atmosphere

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

Kinetic energy is generally negligible (but is important in setting up circulation that transports energy)
While latent energy is a small fraction of the total energy in the atmosphere, it is an important component of horizontal energy transport

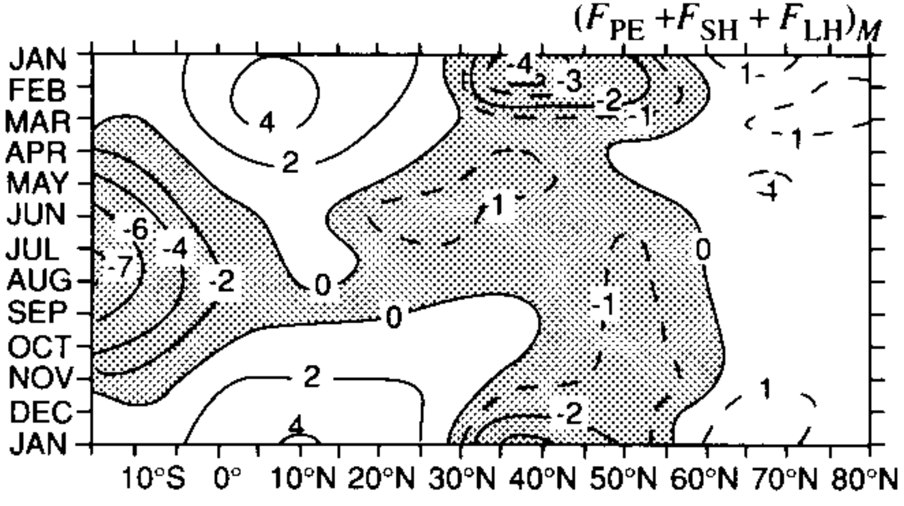
DEFN: ***Moist static energy*** = sensible + latent + potential energy

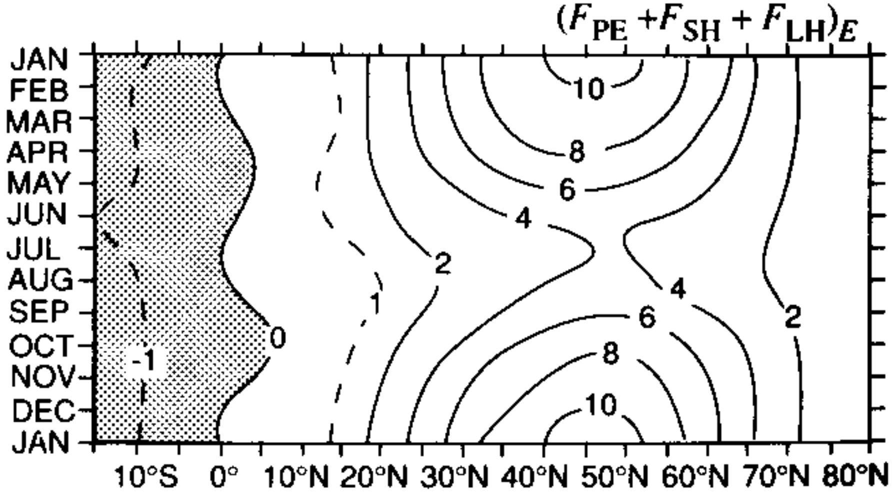
Vertically averaged meridional energy flux of moist static energy, obtained integrating the fluxes through the mass of the atmospheric column, so that z disappears.

Breakdown by season and by the mean meridional and eddy circulations

Northward transport by **mean meridional circulation -** dominates in the tropics, where the mass flux associated with the Hadley cell is large

Northward transport by **eddy circulation -** dominates in the midlatitudes

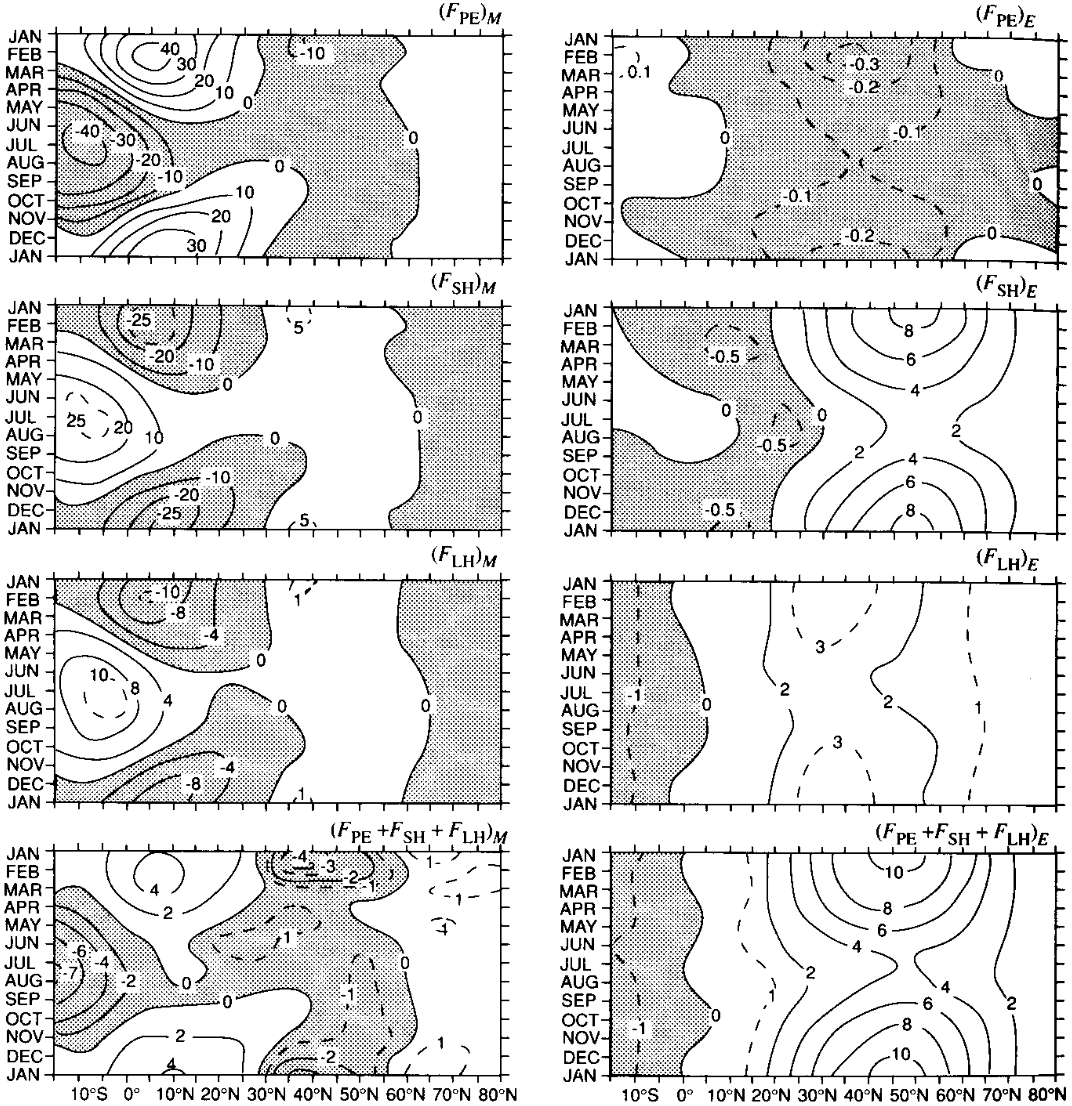




Breakdown into potential, sensible, and latent energies (+ve northward)

Mean meridional circulation   Eddy circulation

the transport of potential energy dominates the total transport of energy by the MMC, whereas the transport of sensible energy dominates the total transport of energy by the eddies



Potential

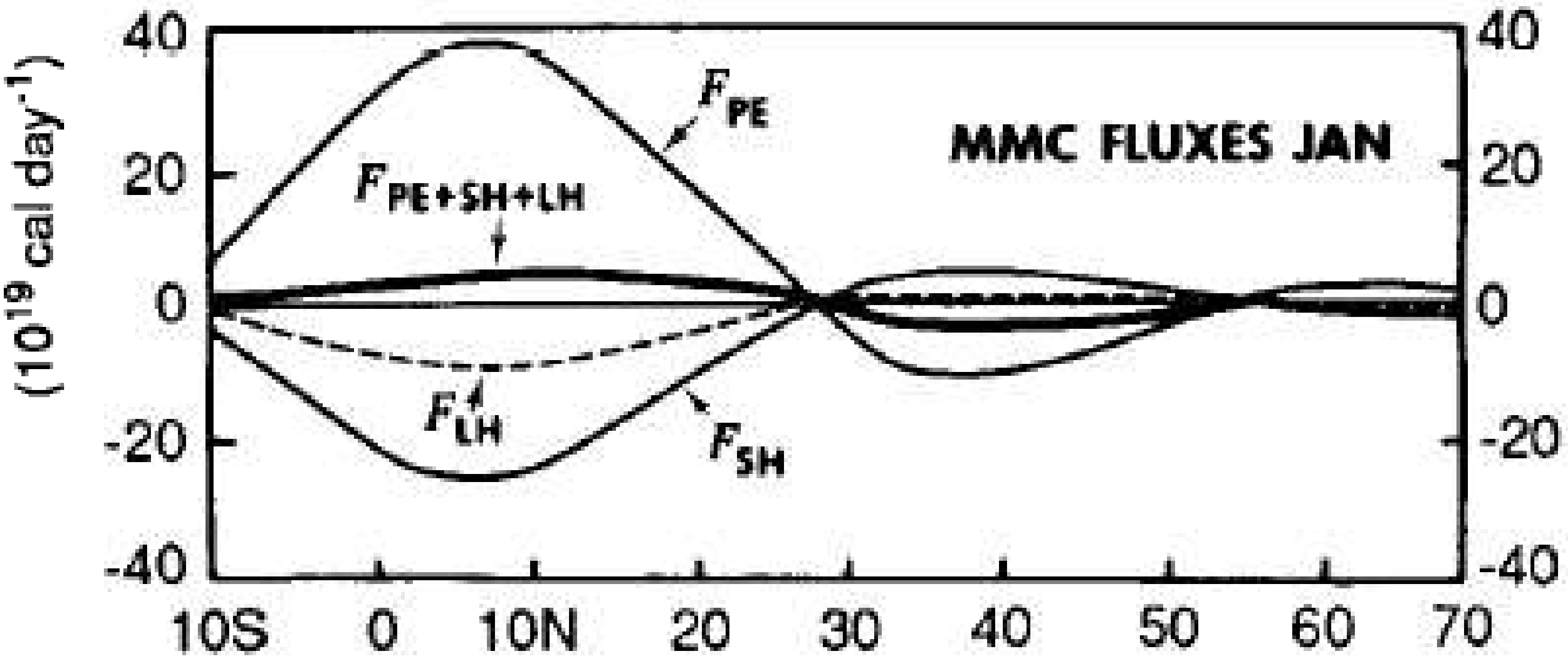
Sensible

Latent

Total

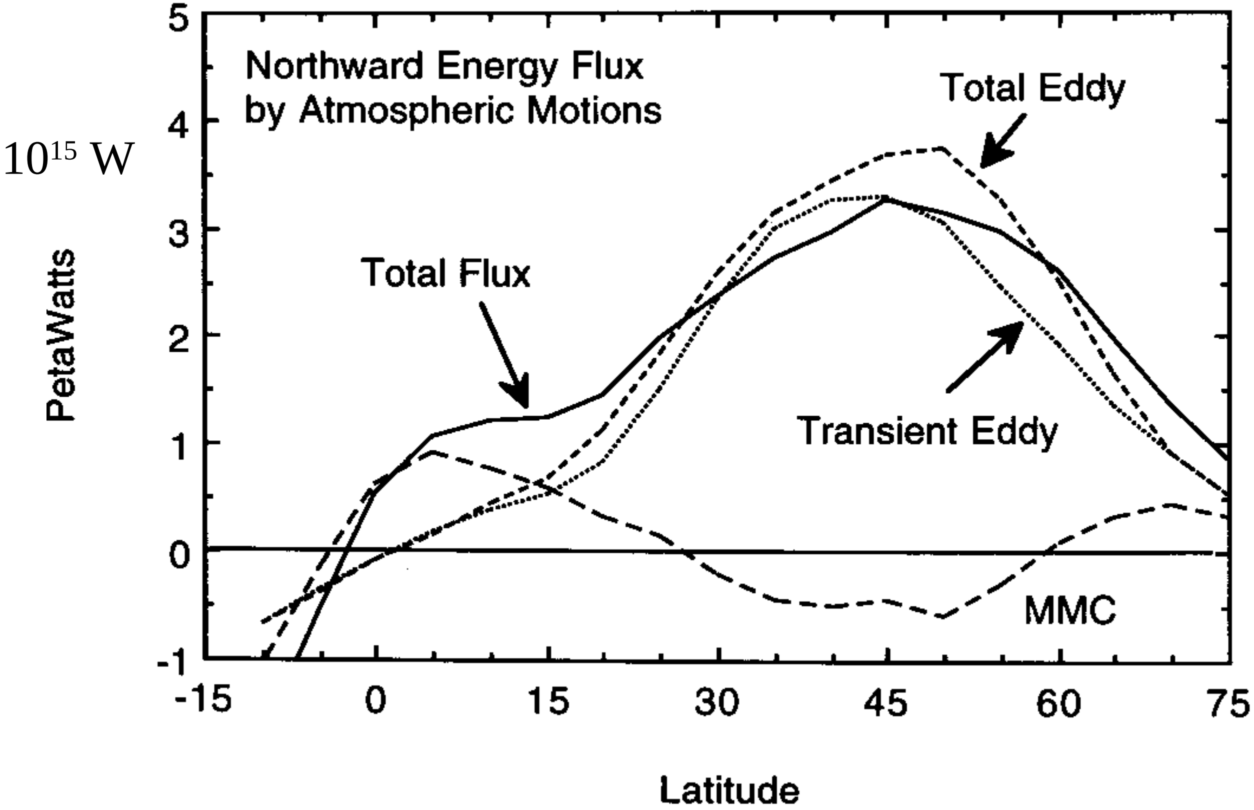
How does the mean meridional circulation transport energy?

Northward transport of energy by MMC as a function of latitude: example using the month of January.



Total is much less than individual contributions! MMC cells are not a particularly efficient mechanism of poleward energy transport.

Breakdown of the annual and zonal mean northward energy flux into the mean meridional circulation, total eddy and transient eddy



10^{15} W

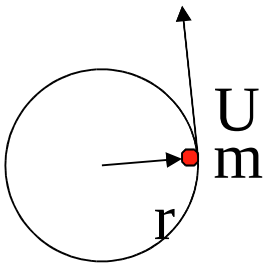
The meridional flux *in midlatitudes* is dominated by the transient eddy flux, associated with travelling disturbances.

In the tropics, MMC dominates.

Note: equatorward transport for MMC in the midlatitudes (Ferrel cell) and relative contribution of transients to the total eddy transport

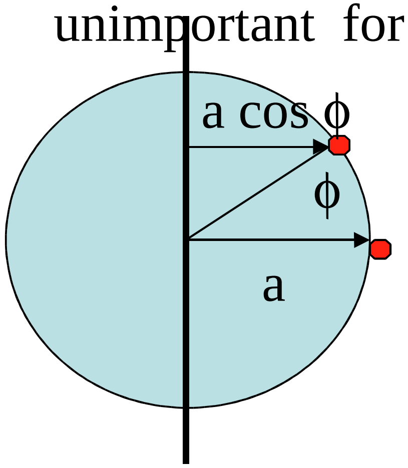
Zonal-mean zonal winds and the angular momentum balance

Def: the *angular momentum* M of a mass m rotating in a circle with radius r and tangential speed U is given by **M = mvr**
In the absence of any torques (force acting over a lever arm), the angular momentum of the mass must remain the same – *conservation of angular momentum*



$\mathbf{M=M_{earth\_rotation}+M_{zonal\_air\_motion\_relative\_to\_the\_earth\_surface}}$

The atmosphere is thin compared with the earth radius a. Therefore z is unimportant for M_{air} and a constant radius a can be assumed.



Per unit mass, $M=(u_{earth}+u)\ a \cos\phi$

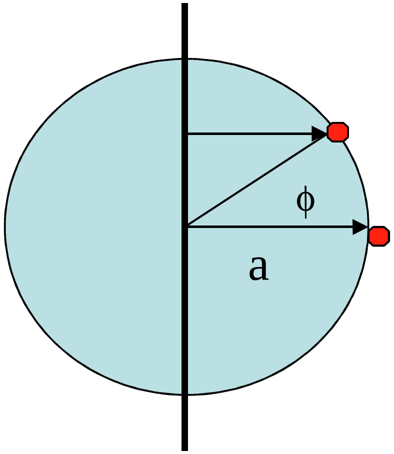
$u_{earth}=\Omega\ a \cos\phi = 7.292 \times 10^{-5}(\mathrm{rad/s}) \times 6.37 \times 10^{6}\ \mathrm{m} \times \cos\phi =$

$465\ \mathrm{m/s} \cos\phi \gg$ typical $u \quad \rightarrow$

$\mathbf{M_{earth\_rotation} \gg M_{zonal\_air\_motion\_relative\_to\_the\_earth\_surface}}$

$\mathbf{M \sim M_{earth\_rotation}}$

Atmospheric motions are generally heavily constrained by this conservation rule. Suppose a parcel at the equator is stationary relative to the ground. According to an observer in space, the parcel has a tangential speed $U_1 = \Omega a$ (rotation rate of earth x radius of earth). If the Hadley circulation transports this air parcel northwards (to latitude ϕ, say) and angular momentum is conserved, then the new tangential speed U_2 must increase since the radius about which the air parcel is rotating shrinks to ($a \cos\phi$). In fact:



M(at equator) = M(at latitude ϕ)

$$\Rightarrow \quad mU_1 a = m\, U_2\, a \cos\phi$$

$$\Rightarrow \quad U_2 = U_1/\cos\phi = \Omega\, a / \cos\phi$$

So poleward moving particles experience an eastward acceleration relative to the Earth surface (recall u = westerly-eastward zonal velocity).

The velocity U_2 computed in this way is faster than the tangential speed at the ground at latitude ϕ; in fact, at $\phi = 30^o$N, U_2 corresponds to westerlies (i.e. speed as measured from earth) of 134m/s!

In reality the subtropical jets are more like ~30m/s. We don’t see such large speeds partly because large-scale atmospheric motions also transport angular momentum out of the Hadley cell into the midlatitudes, and down to the surface .