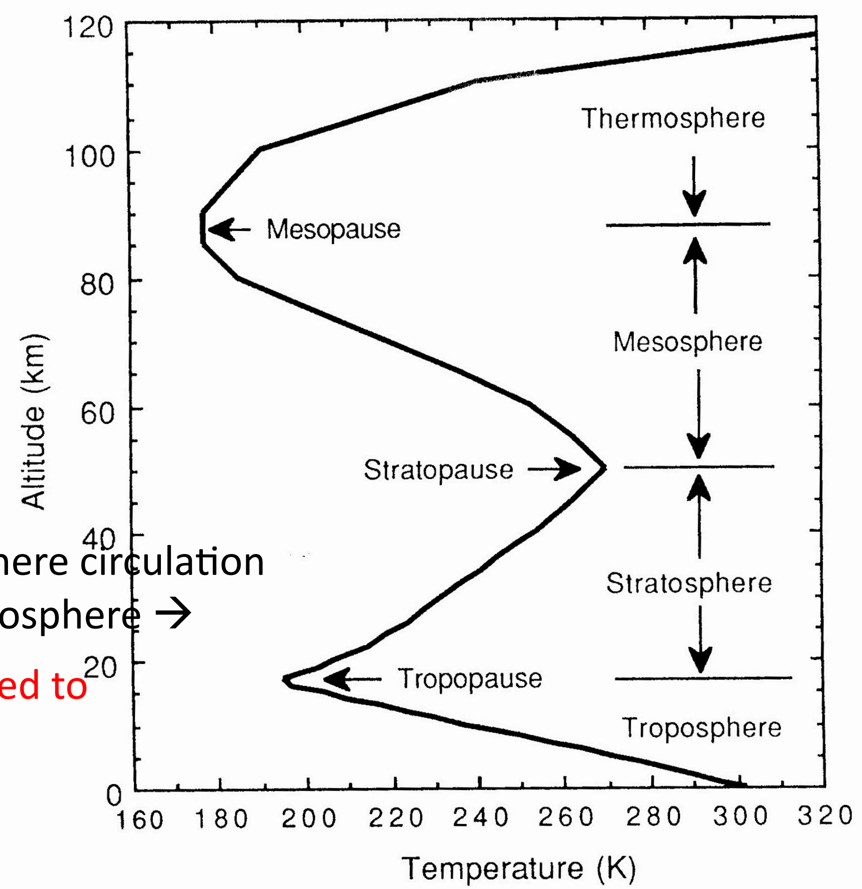
Lecture 1:

Framing the General Circulation

*(or: **What are the two jobs of the atmospheric general circulation ?**)*

-- The Basic State of the Atmosphere
-- Radiative forcing of the earth-atmosphere system
-- Necssity of upward energy transport from surface to atmos
-- Necessity of poleward energy transport (atmos & oceans)
-- Hadley and Ferrel Cells.

Mean Temperature Profile (15°N) (schematic)



2 The main zones of the atmosphere defined according to the temperature profile of tl sphere profile at 15°N for annual-mean conditions. [Data from U.S. Standard Atmosphe 1966).]

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Lower Stratosphere circulation affects the Troposphere →

Weather confined to troposphere →

Basic State of the Atmospheric Circulation

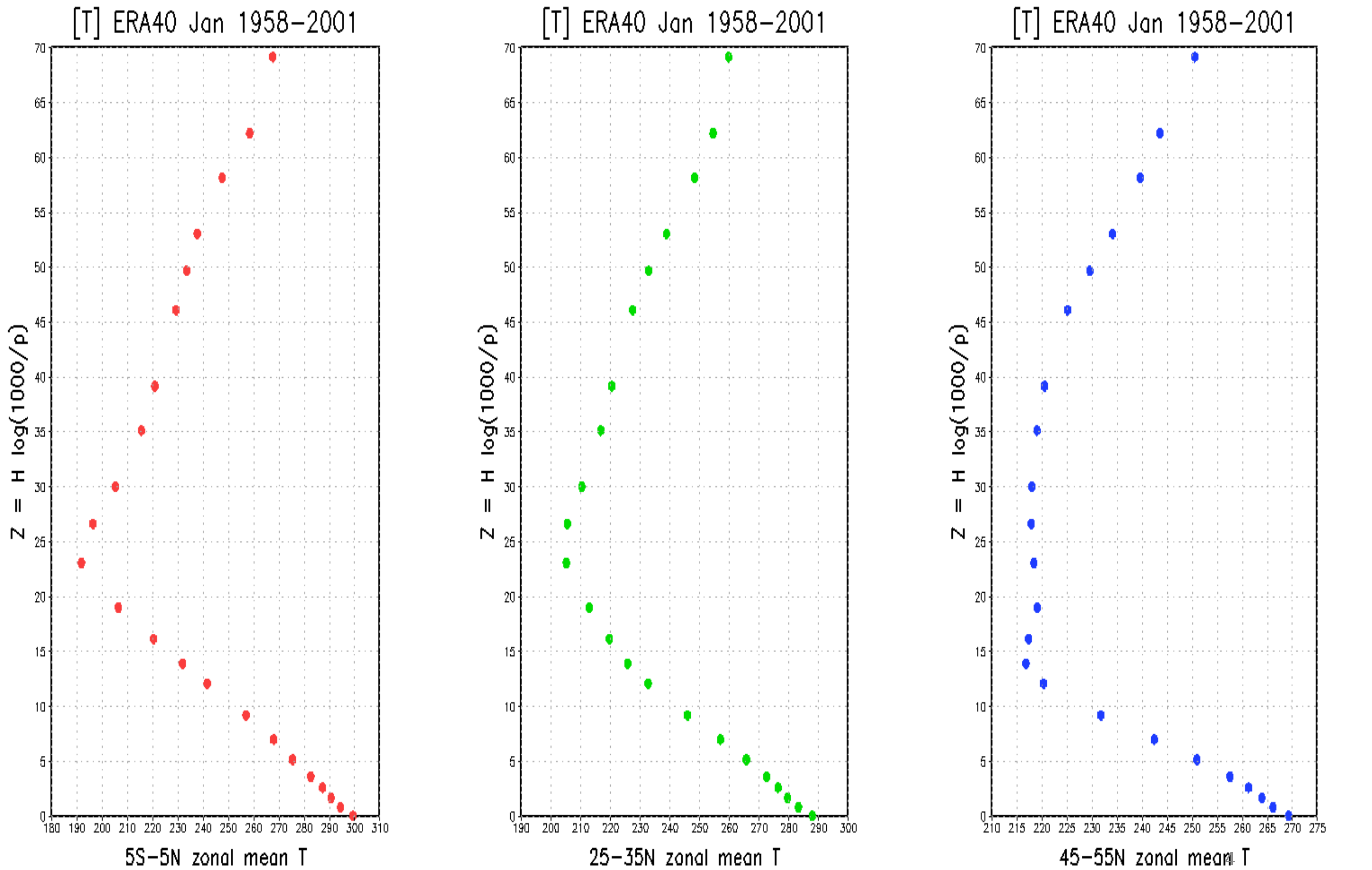
- Define time mean over any 3-month season (e.g. DJF) (denoted by an overbar)

$$\overline{T}$$

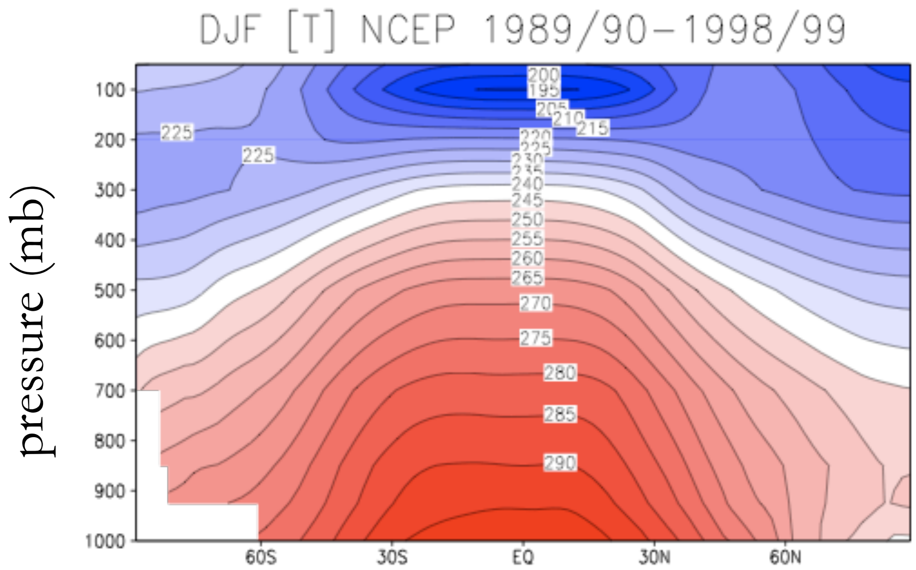
- Take the longitudinal average:
  (where a = radius of earth, dx = a dλ cos(φ))

$$\left[\overline{T}\right] = \frac{1}{2\pi}\int_0^{2\pi} d\lambda\,\overline{T} = \frac{1}{2\pi a\cos(\phi)}\int_0^{2\pi a\cos(\phi)} dx\,\overline{T}$$

- Average over many years



201 GrADS: COLA/IGES 2011-06-19-22:37 2011-06-19-



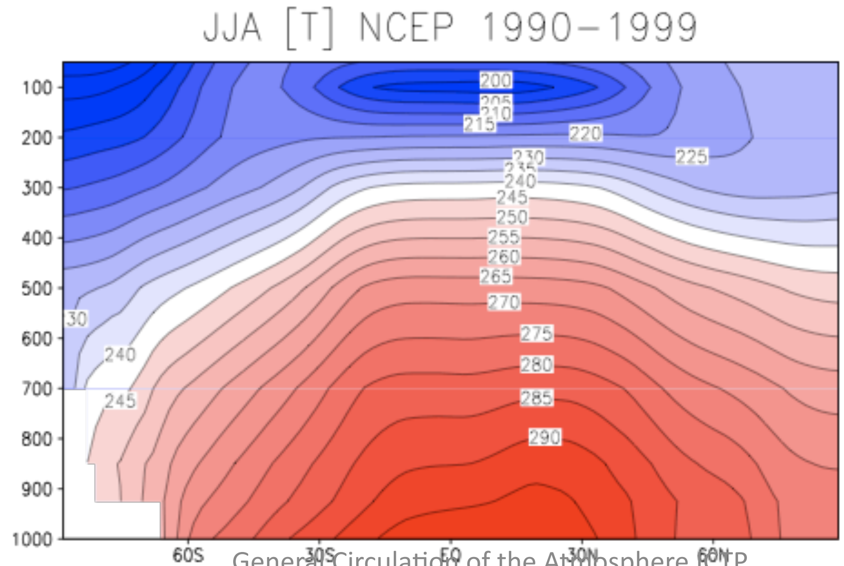
<u>Troposphere:</u> [T] decreases with height (increases with p).

<u>Stratosphere</u>: [T] increases with height, or at least does not decrease.

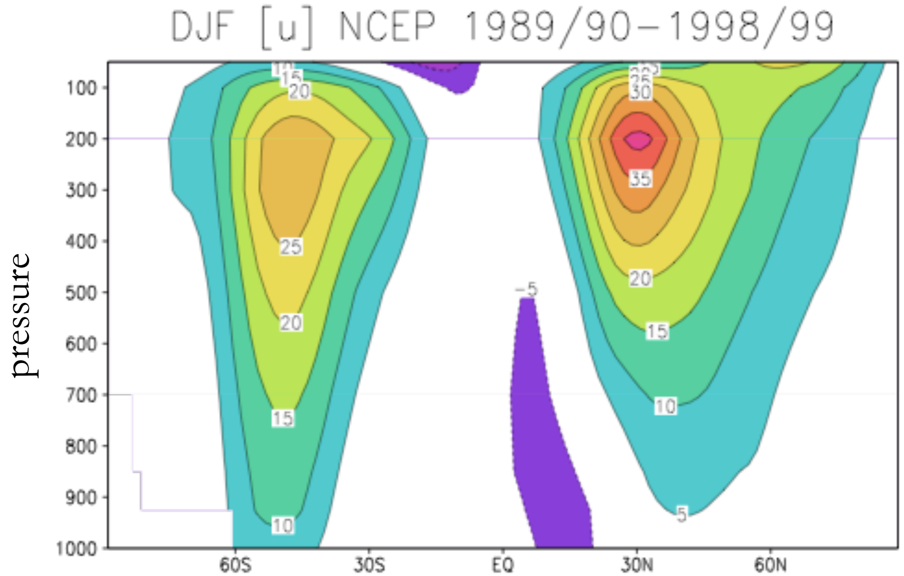
Tropopause: The separation between troposphere and stratosphere. It is much higher in the tropics (14 - 17 km) than in midlatitudes (8 - 10 km).

[T] vs. p from NCEP reanalysis. 10 winters DJF mean; 10 summers JJA mean

Note the strong meridional gradient of [T] (d[T]/dy) in mid-latitudes



Lowest T is found at high latitudes in winter, AND at the equatorial tropopause



Sub-tropical jets are present in both hemispheres.

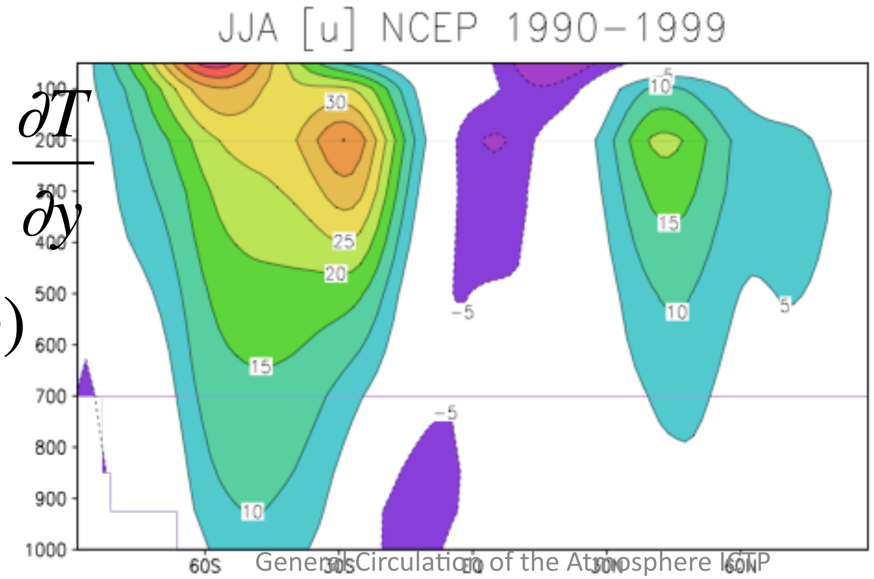
The vertical wind shear is maximum at those latitudes where d[T]/dy is most negative (thermal wind relationship)

The jets shift poleward in summer, equatorward in winter

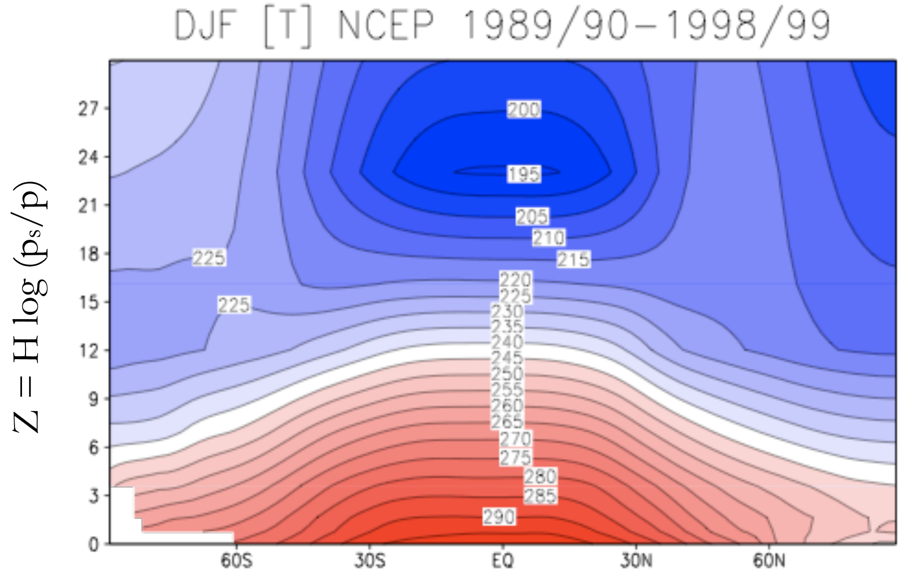
[u] vs. p from NCEP reanalysis: DJF mean, JJA mean

$$\frac{\partial U}{\partial z} = -\left(\frac{R}{Hf}\right)\frac{\partial T}{\partial y}$$

$$f = 2\Omega \sin(\phi)$$



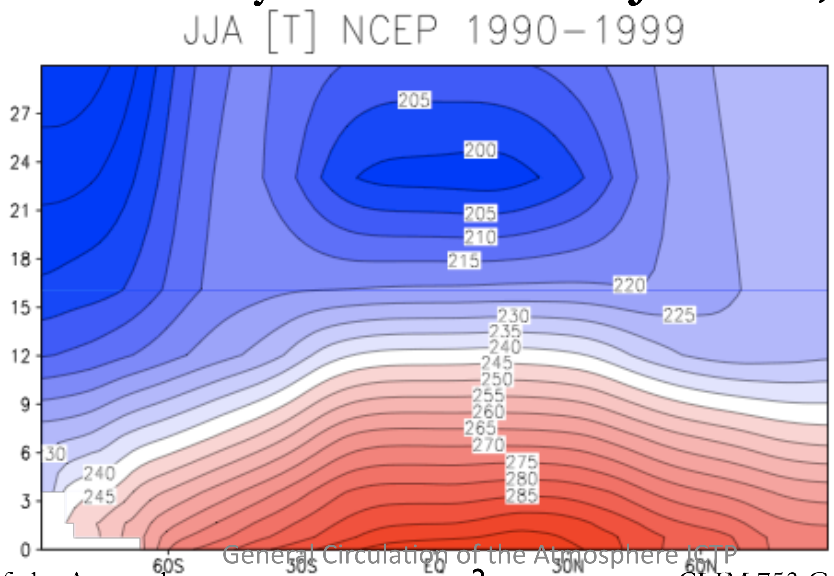
Note the easterlies in the tropics. Since the surface wind acts as a stress on the surface, the distribution of surface easterlies and westerlies is connected to the angular momentum budget of the earth-atmosphere system.

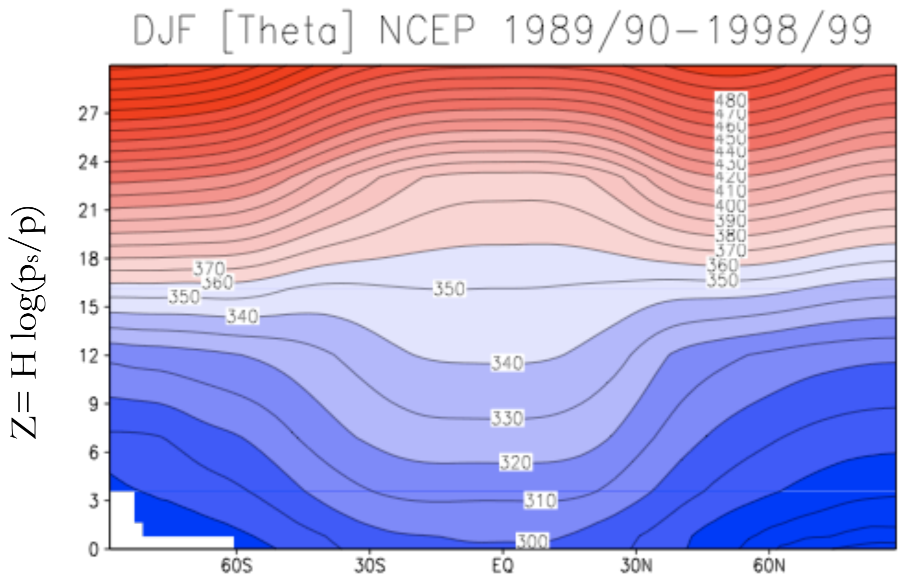


$$Z = H \log(p_s/p)$$

$$H = 10 \text{ km}$$
$$p_s = 1000 \text{ mb}$$

[T] vs. Z from NCEP reanalysis. 10 winters DJF mean; 10 summers JJA mean





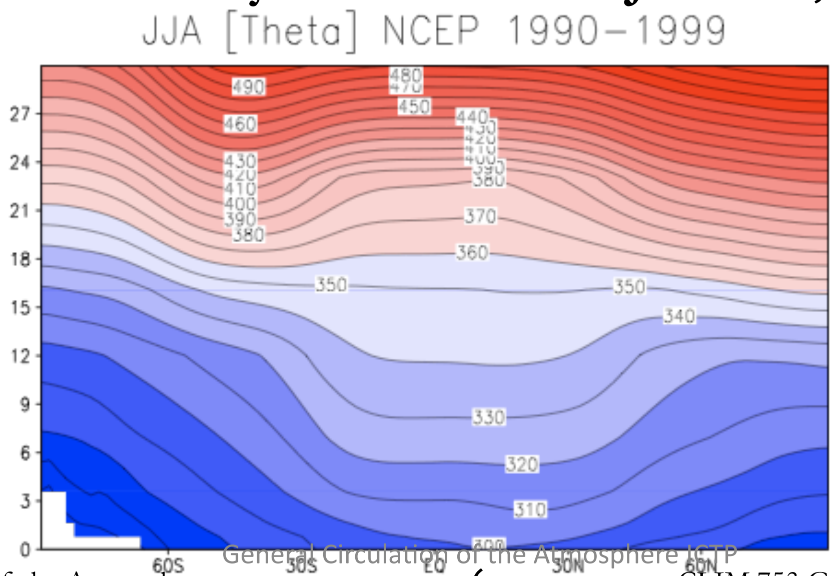
Potential Temperature Q
Entropy (per unit mass) s

$$s = C_p \log \ \theta$$

$$\theta = T \log\left(\frac{p_0}{p}\right)^{\kappa}$$

C_p = specific heat at constant pressure
P_0 = 1000 hPa

[θ] vs. Z from NCEP reanalysis. 10 winters DJF mean; 10 summers JJA mean



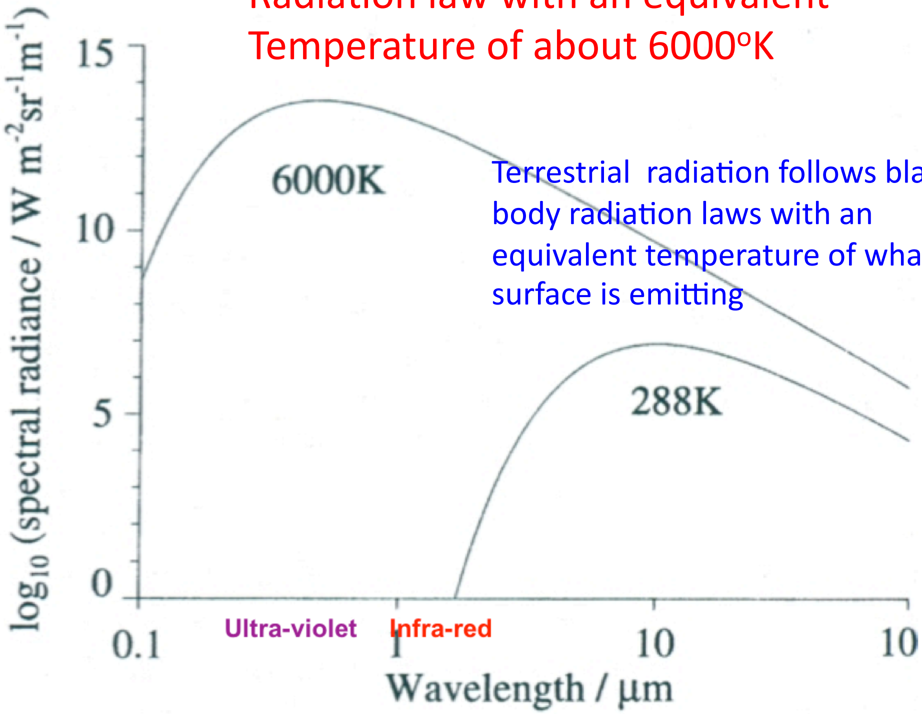
s must increase upward for static stability.
ds/dz > 0

From Andrews

3 ATMOSPHERIC RADIATION

Solar radiation follows black body
Radiation law with an equivalent
Temperature of about 6000^{o}K

Figure 3.1 Logarithm of the black-body spectral radiance $B_\lambda(T)$, plotted against the logarithm of wavelength λ, for $T = 6000$ K, a typical temperature of the solar photosphere, and 288 K, the Earth's mean surface temperature.



B_λ for T = 6000 K (characteristic of the sun) and for T = 288 K (characteristic of the Earth). Note the use of log scale on both axes. Note also that the "sun" curve lies above the "earth curve" for all wavelengths

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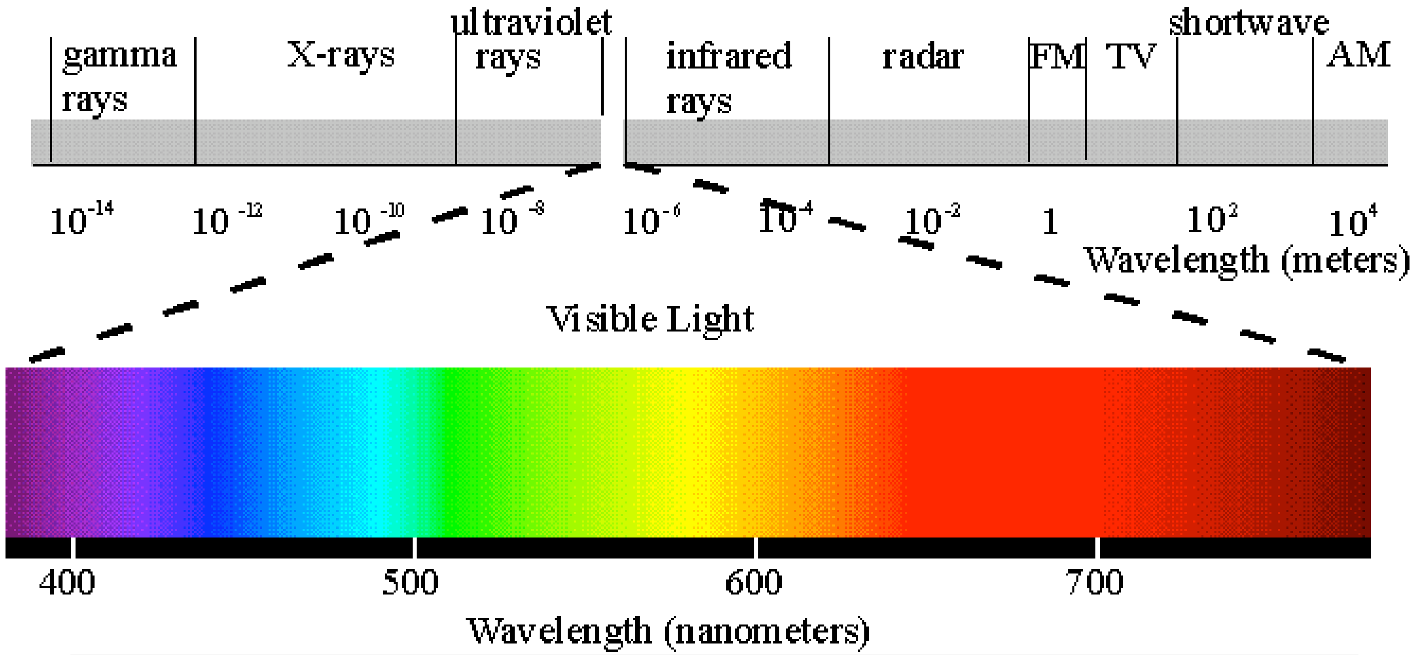
http://www.yorku.ca/eye/spectrum.gif



1 nanometer = 1 nm = 1.0 x 10^{-9} meters

1 micrometer = 1 μm = 1.0 x 10^{-6} meters

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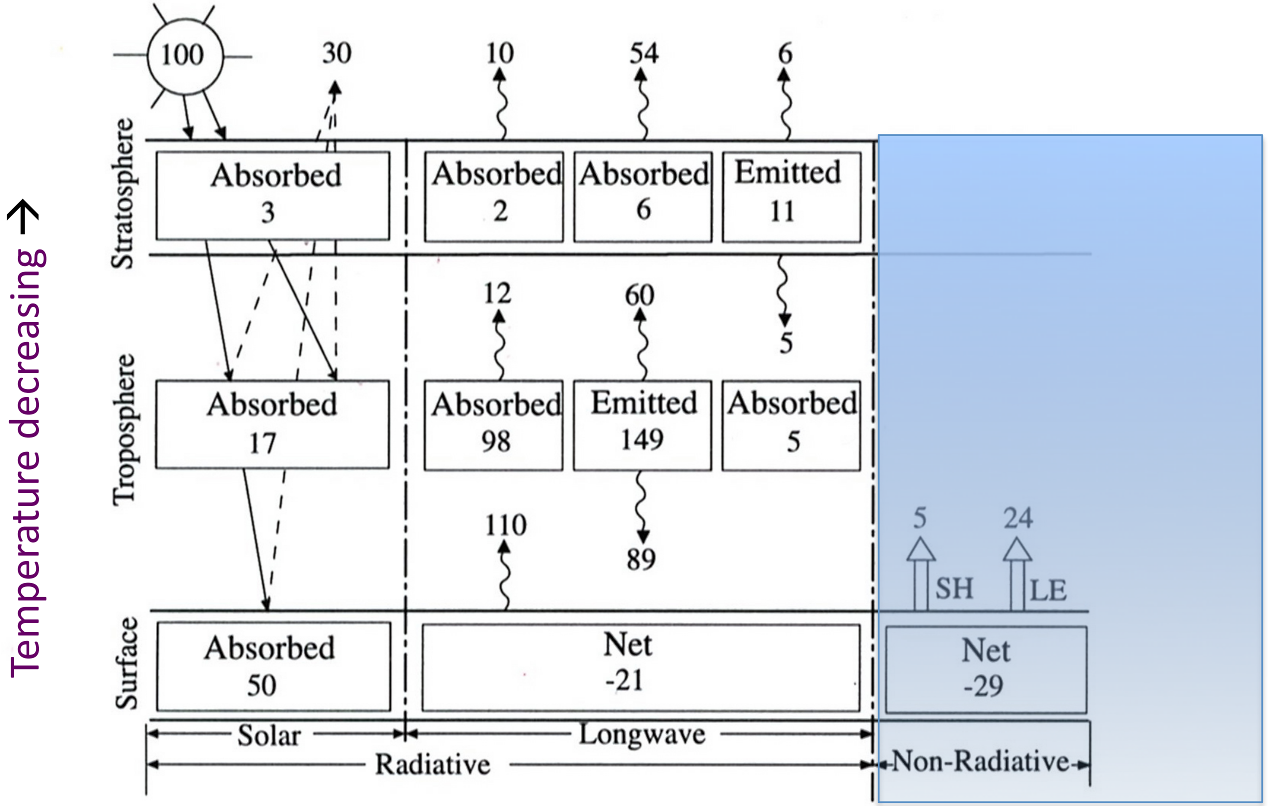
Earth's surface, atmospheric molecules of water vapor, carbon dioxide, and clouds emit terrestrial radiation, *both upward and downward, and also absorb radiation*:



Global Mean Energy Flow – Vertical Dependence

Units are percentages of the global-mean insolation (100 units = 342 Watts/m^2)

From "Global Physical Climatology" by Dennis Hartmann. Academic Press

Time Mean, Global Mean Radiation Balance in the vertical (simple summary):

- Troposphere loses 29 units = 99 Watts / m^2 throughout the layer

- Stratosphere is nearly in balance

- Surface gains 29 units = 99 Watts / m^2

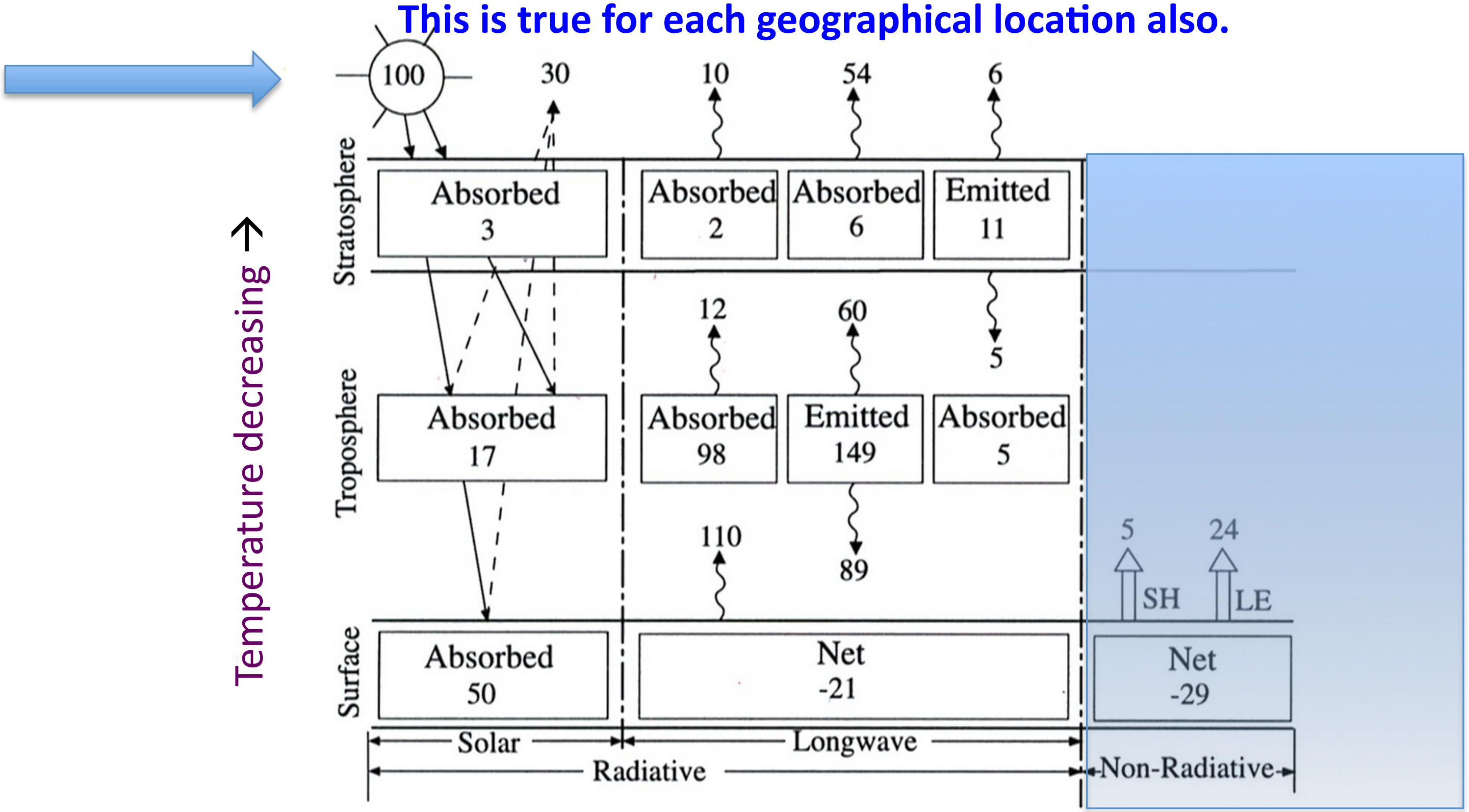
- Balance requires transfer from surface (oceans and land) to atmosphere:

  (a) "Sensible Heat" direct warming of air by surface (oceans in winter)

  (b) "Latent Heat" – evaporation of water from the surface requires energy – which is released when the water vapor condenses (rain)

JOB 1: In order to balance entire tropospheric loss, atmosphere must transport latent heat and sensible heat up from the surface (oceans and land) to the depth of the troposphere.

The total earth – atmosphere system energy balance can be viewed from space: Net energy = Absorbed solar radiation minus outgoing long wave (OLR). This is true for each geographical location also.

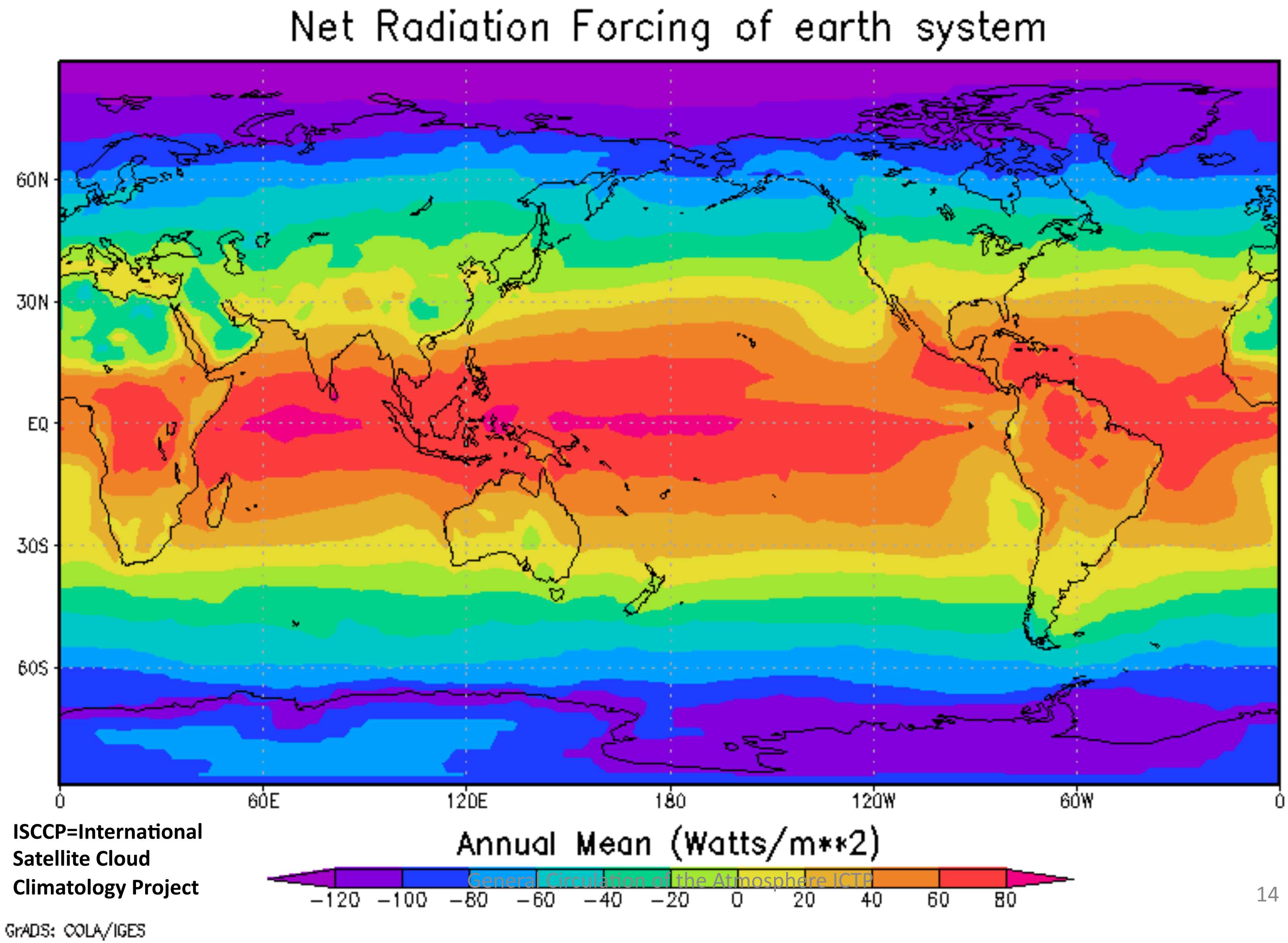


Global Mean Energy Flow – Vertical Dependence

Units are percentages of the global-mean insolation (100 units = 342 Watts/m^2)

From "Global Physical Climatology" by Dennis Hartmann. Academic Press

Time Mean, Global Mean Radiation Balance in the Horizontal



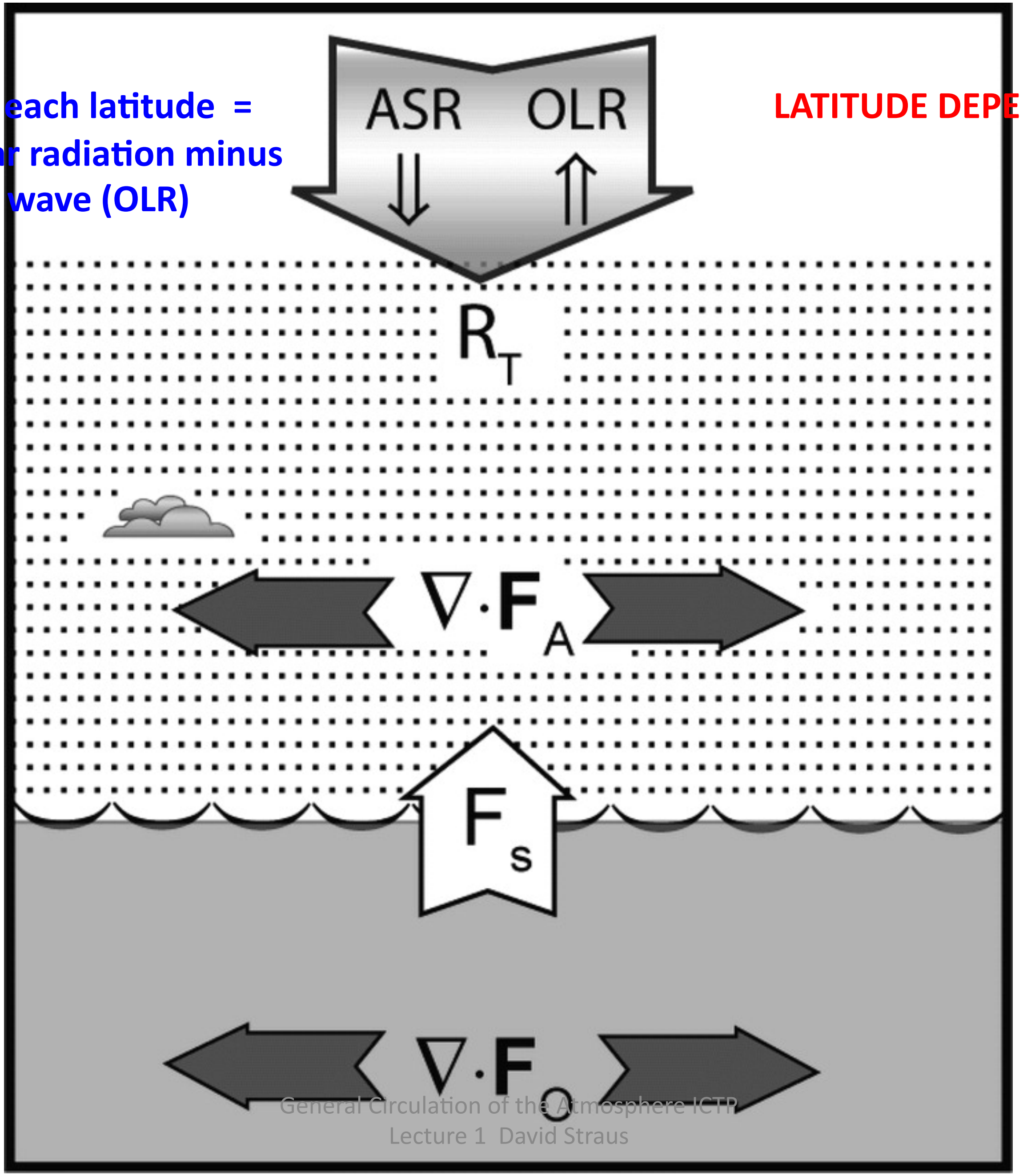
ISCCP=International Satellite Cloud Climatology Project

JOB 2: In order to balance the net radiatiave loss at high latitudes and net radiative gain at low latitudes, earth - atmosphere system must transport latent heat and sensible towards the poles.

The atmosphere and ocean participate in this!

Net energy at each latitude = Absorbed solar radiation minus outgoing long wave (OLR)

LATITUDE DEPENDENCE



The Line "Radiative Forcing" below gives the Total Northward Transport J_ϕ required by the top of atmosphere radiative balance F. (Taken from Hartmann)

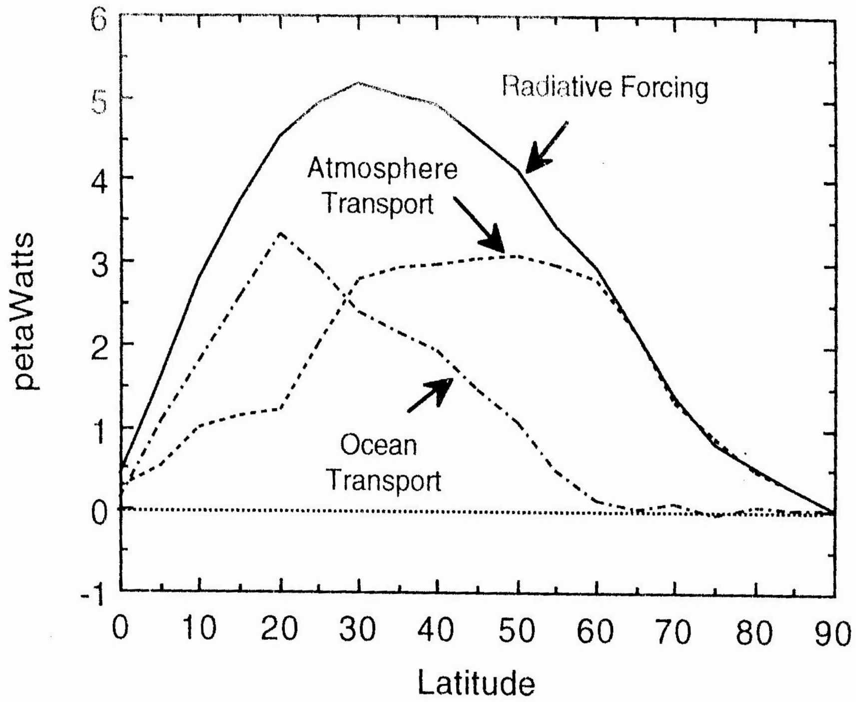


Fig. 2.14 Meridional transport of energy for annual-mean conditions. Net radiation and atmospheric transport are estimated from observations; ocean transport is calculated as a residual in the energy balance. [Adapted from Vonder Haar and Oort (1973). Used with permission from the American Meteorological Society.]

Mean Meridional Overturning Circulations
Hadley and Ferrel Cells

Pressure Coordinate Point of View

June 24, 2011

1 Continuity Equation

The mass continuity equation in pressure coordinates is a diagnostic equation:

$$\vec{\nabla} \cdot \vec{v} + \frac{\partial \omega}{\partial p} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \tag{1}$$

in Cartesian coordinates. (u, v) are the components of the horizontal wind $\vec{v}$, $\omega = \frac{dp}{dt}$ gives the Lagrangian rate of change of pressure of a parcel.

In spherical coordinates, this becomes:

$$\frac{1}{a\cos\phi}\frac{\partial u}{\partial \lambda} + \frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(v\cos\phi) + \frac{\partial \omega}{\partial p} = 0 \tag{2}$$

where λ is longitude, ϕ is latitude, and a is the earth's radius.

2 Defining the Streamfunction

Averaging over longitude (and remembering that $[F]$ is defined as longitudinal *average*) we obtain:

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left([v]\cos\phi\right) + \frac{\partial[\omega]}{\partial p} = 0 \tag{3}$$

We can define the *mass streamfunction* Ψ as the *total northward mass flux* above a given latitude and height, integrated also over all x, where $dx = (a\cos\phi)d\lambda$. This gives:

$$\Psi = 2\pi a \int_z^\infty dz\ \rho[v]\cos\phi = 2\pi a \int_0^p \frac{dp}{g}[v]\cos\phi \tag{4}$$

Note that the units of the streamfunction are kg/sec.

From this we easily get:

$$[v] = \left(\frac{g}{2\pi a\cos\phi}\right)\frac{\partial\Psi}{\partial p} \tag{5}$$

2

Using this in the continuity equation gives:

$$\frac{\partial[\omega]}{\partial p} = -\left(\frac{g}{2\pi a^2 \cos\phi}\right)\frac{\partial^2 \Psi}{\partial p\,\partial \phi} \tag{6}$$

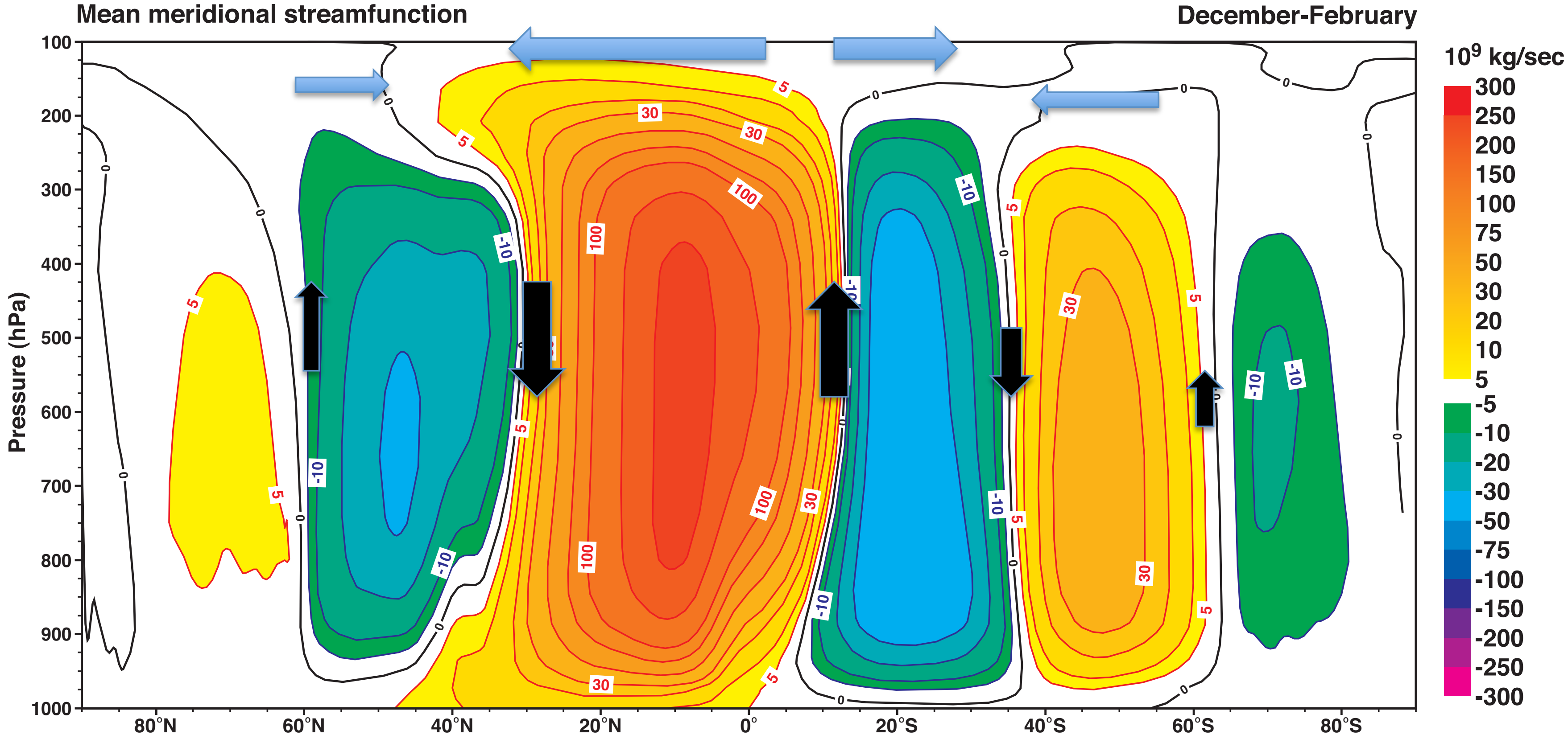
from which:

$$[\omega] = -\left(\frac{g}{2\pi a \cos\phi}\right)\frac{\partial \Psi}{\partial \phi} \tag{7}$$

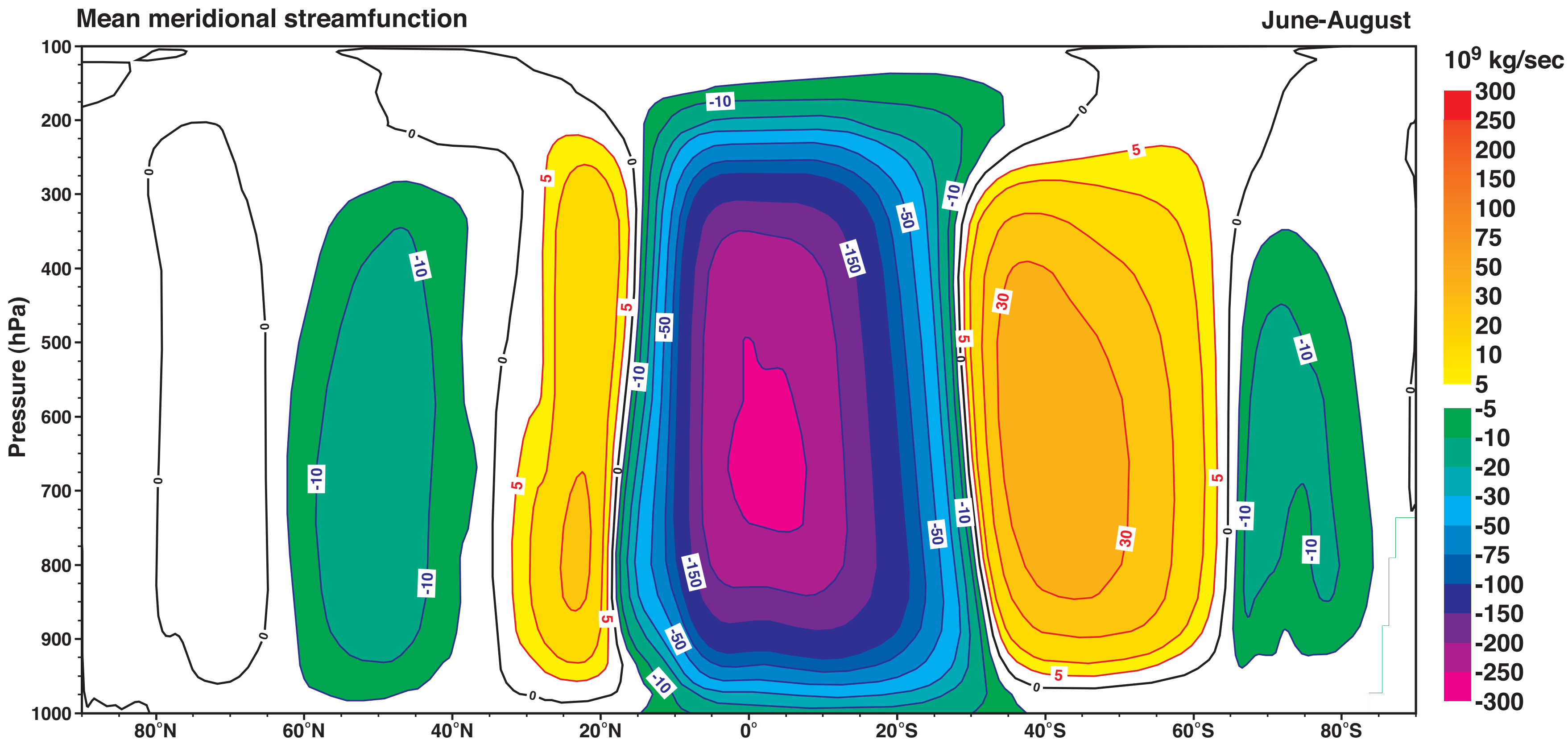
3 Calculating the Streamfunction

From the previous section we know how to calculate the streamfunction and compute the associated zonal mean ω and v. This can be applied instantaneously. What is more usual, however, is to compute the streamfunction from seasonally averaged time mean fields, and then further average over all years.

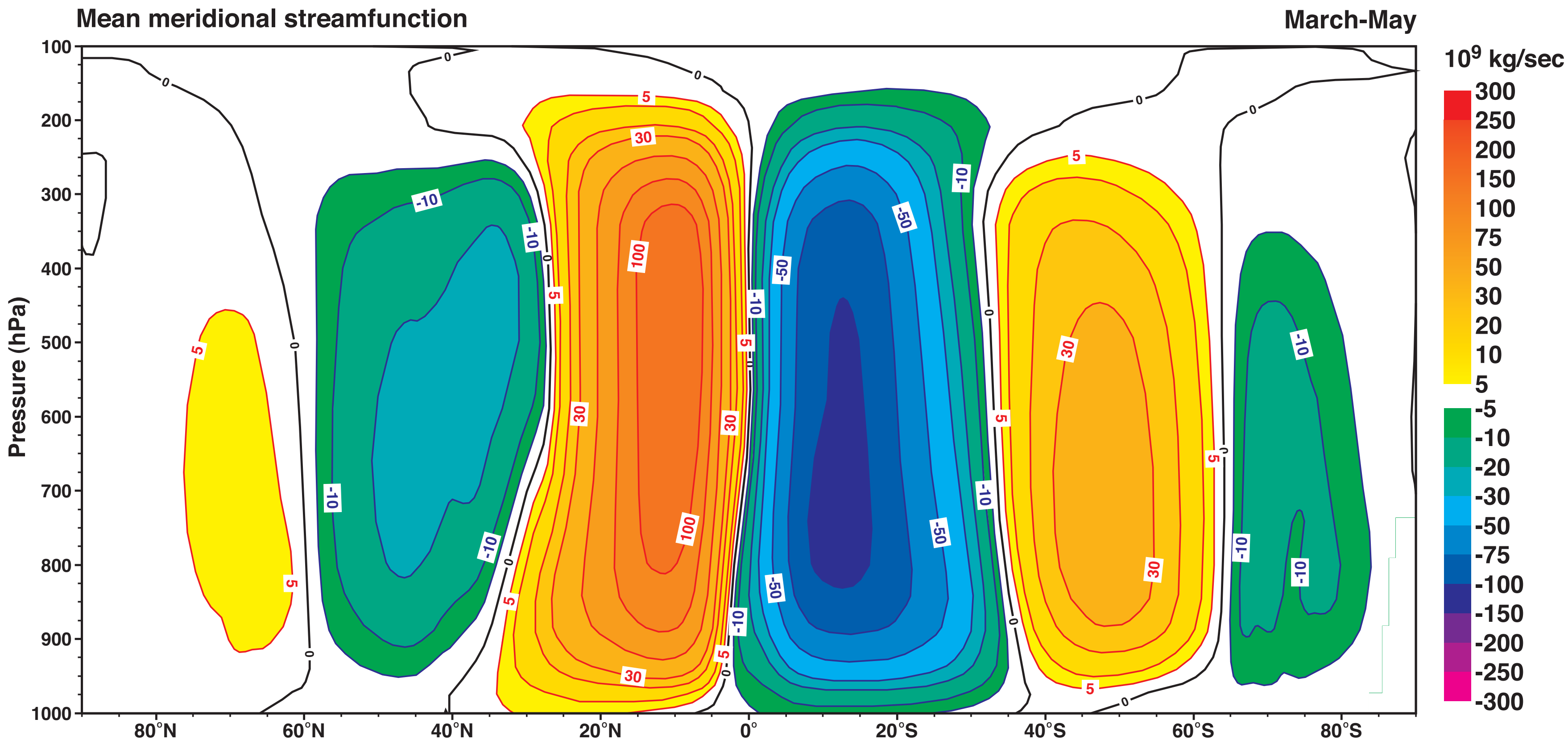
Ferrel Cell **Hadley Cells** Ferrel Cell



← Northern Hemisphere DJF(Northern winter) Southern Hemisphere →



← Northern Hemisphere JJA(Southern winter) Southern Hemisphere →



← Northern Hemisphere MAM(Northern Spring) Southern Hemisphere →

Summary of Configuration and Seasonal Dependence

Hadley cells asymmetric about equator during solsticial seasons:
-- Latitude of strong rising motion moves with the sun.
-- Very strong upper level return flow into the winter hemisphere
-- Weak upper level return flow into the summer hemisphere

Hadley cells more symmetric about the equator during equinox seasons

Hadley cells consist of warm air rising and cool air sinking (“direct”)

Ferrel cells ***seem*** to have cool air rising and warm air sinking (“indirect”)

Summary of Hadley and Ferrel Cell Energy Transports:

-- Hadley: Low level transport of warm moist air towards the equator

-- Hadley: High level transport of cool dry air towards the pole

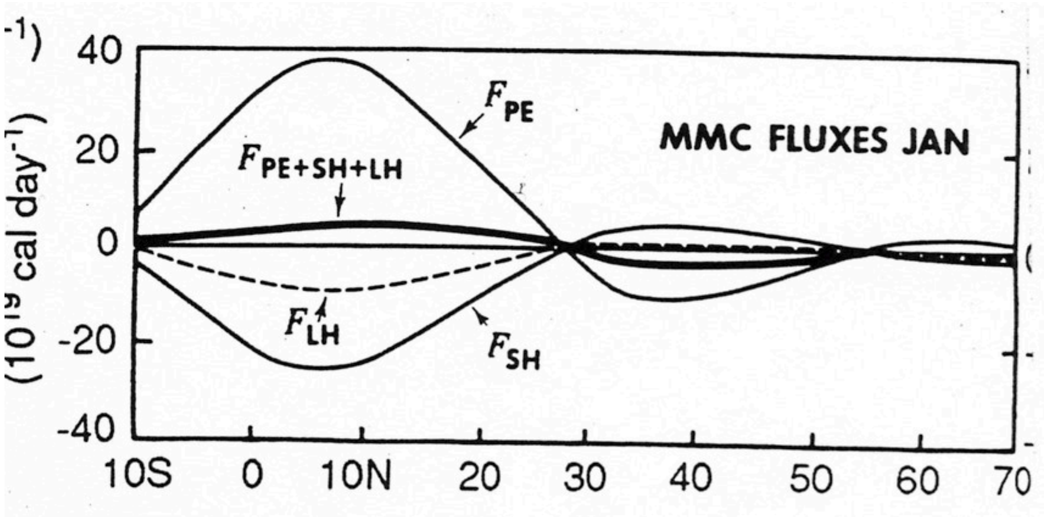
SO

-- Thermal and latent energy transported *the wrong way* (toward the equator)!

BUT

-- Potential energy transported toward the poles (outweighs the other two so total energy is transported toward the poles!)

-- Ferrel: Completely opposite transport (total energy transported away from poles)



From Fig 6.10
Hartmann

REFERENCES:

Hartmann, Dennis, “Global Physical Climatology”, 1994 Academic Press, ISBN 0-12-328530-5

ISCCP MPF Monthly Mean FLUX Data 7/1983-12/2006
Zhang, Y., W. B. Rossow, A. A. Lacis, V. Oinas, and M. I. Mishchenko (2004), Calculation of radiative fluxes from the surface to top of atmosphere based on ISCCP and other global data sets: Refinements of the radiative transfer model and the input data, J. Geophys. Res., 109, D19105, doi:10.1029/2003JD004457.

APPENDIX

Atmospheric General Circulation and Climate

The Meridional Flux of Total Energy Flux

Four types of energy are important in the atmosphere:

Type	Symbol	Formula	Amount ($\times 10^6$ J m^{-2})	% of total
Internal	IE (SH)	$C_V T$	1800	70
Potential	PE	Gz	700	27
Latent	LH	Lq	70	2.7
Kinetic	KE	$\frac{1}{2}(u^2+v^2)$	1.3	0.05

David Straus
George Mason University / COLA