Atmospheric Sciences 321

Science of Climate

Lecture 16: Extremes finish, then Chapter 6

Community Business

- **Mid Term is Wednesday May 7**
  - 4 multiple choice
  - Practice exams on assignment page
  - 4 multiple choice worth total of 20 pts
  - 4 problems worth a total of 80pts
  - 10 points for name – 110 points total
  - Content through Lecture today, chapters 1-5
- We’re now, almost, on Chapter 6: Atmosphere
- Questions?

Penman's Equation

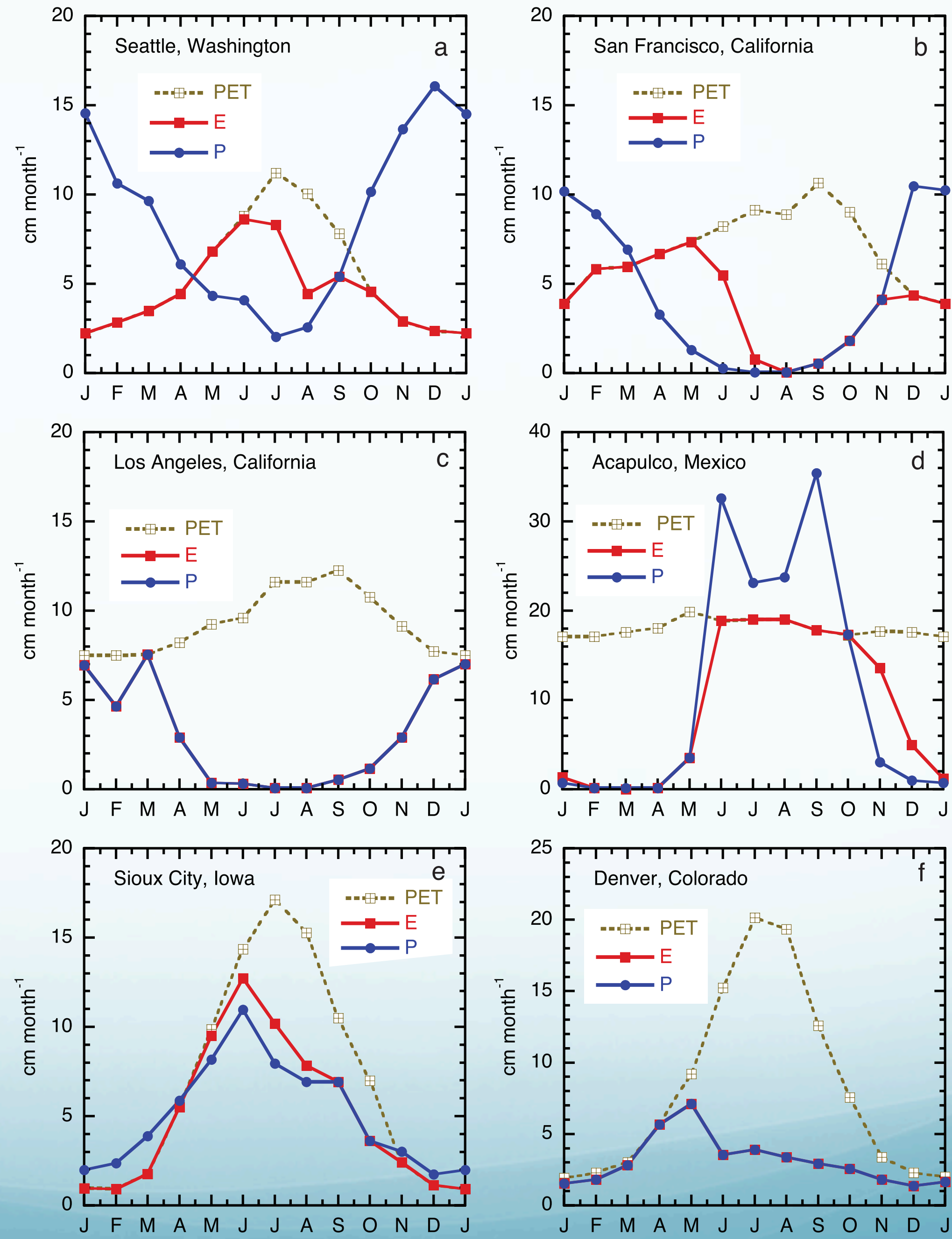
$$E = \frac{1}{(1+B_e)}\left(E_{\text{en}} + B_e\, E_{\text{air}}\right)$$

$$E_{\text{en}} = \frac{1}{L}(R_s - \Delta F_{\text{eo}} - G)$$

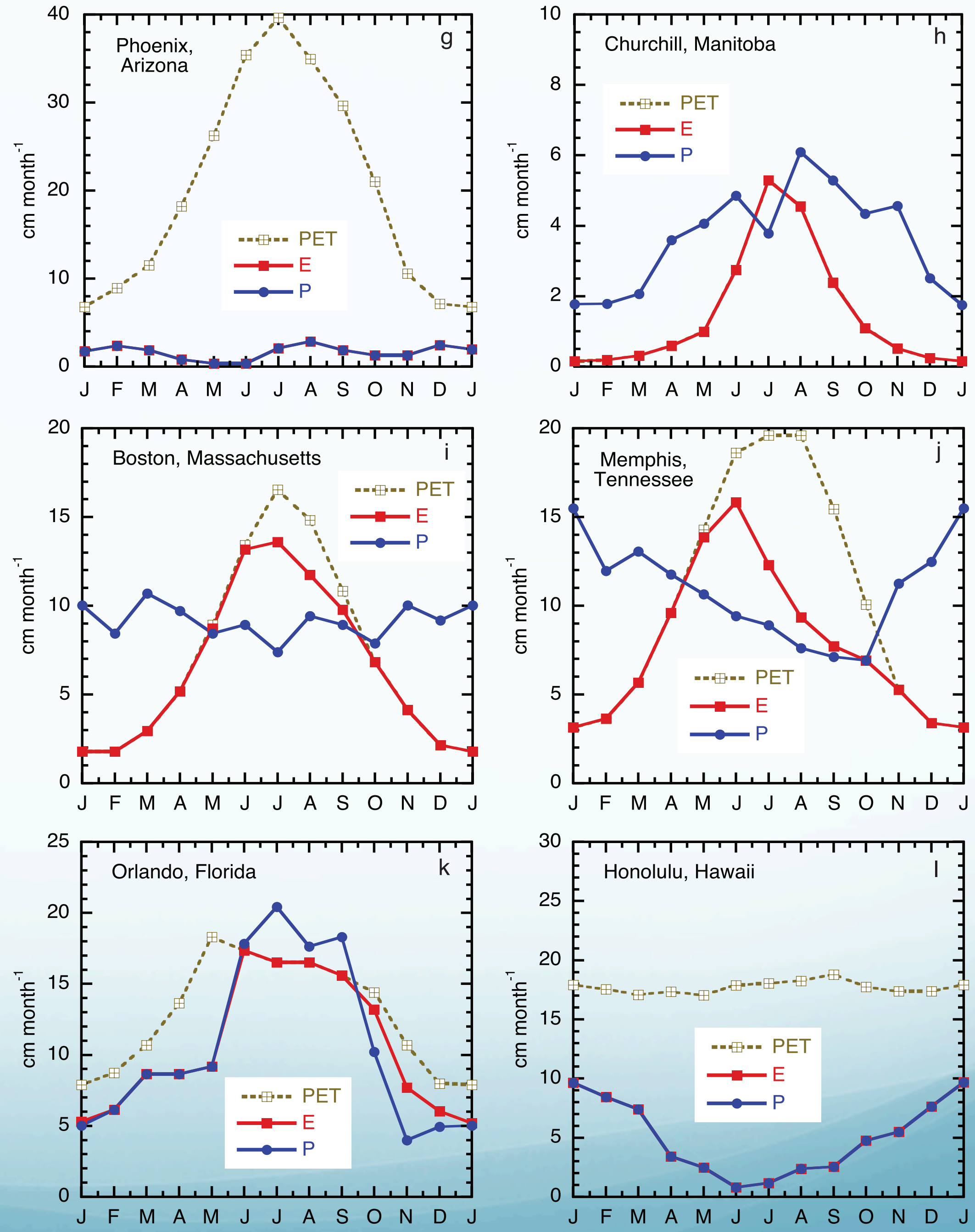
$$E_{\text{air}} = \rho\, C_{\text{DE}}\, U(q_a^* - q_a) = \rho\, C_{\text{DE}}\, U\, q_a^*(1 - \text{RH})$$

- So Evaporation gets smaller for large B_e – cold temperatures, as more of the heat goes into SH
- The relative importance of air dryness becomes less important at tropical temperatures where Be is small. (this is because as long as their is a temperature differences, Ts=Ta, there is a substantial moisture difference.

Annual Variation of Water Balance for Selected Regions



Annual Variation of Water Balance for Selected Regions - II



Potential Evapotranspiration

$$E = \frac{1}{(1+B_e)}\left(E_{\mathrm{en}} + B_e E_{\mathrm{air}}\right)$$

$$E_{\mathrm{en}} = \frac{1}{L}(R_s - \Delta F_{\mathrm{eo}} - G)$$

$$E_{\mathrm{air}} = \rho C_{\mathrm{DE}} U(q_a^* - q_a) = \rho C_{\mathrm{DE}} U q_a^*(1 - \mathrm{RH})$$

- Since Penman's equation assumes a wet surface, it is in a sense the maximum evaporation that could occur, which we can call the Potential Evapotranspiration or PET.
- $$\mathrm{PET} = \rho_a C_{\mathrm{DE}} U\left(q^*(T_s) - q_a\right)$$
- All else being equal, it increases rapidly with temperature

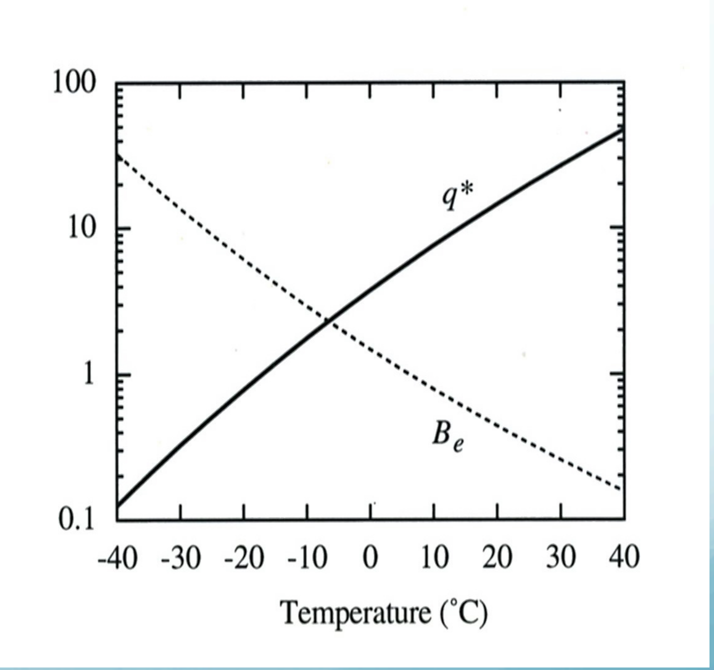
Potential Evapotranspiration and warming

- How does it change in a warmed climate??

$$\frac{\partial \mathrm{PET}}{\partial T_s} \cong \rho\, C_{\mathrm{DE}}\, U \left(\frac{\partial q_s^*}{\partial T_s}(1-\mathrm{RH}) + \mathrm{RH}\, \frac{\partial B_e^{-1}}{\partial T_s} \frac{c_p}{L} (T_s - T_a) \right)$$

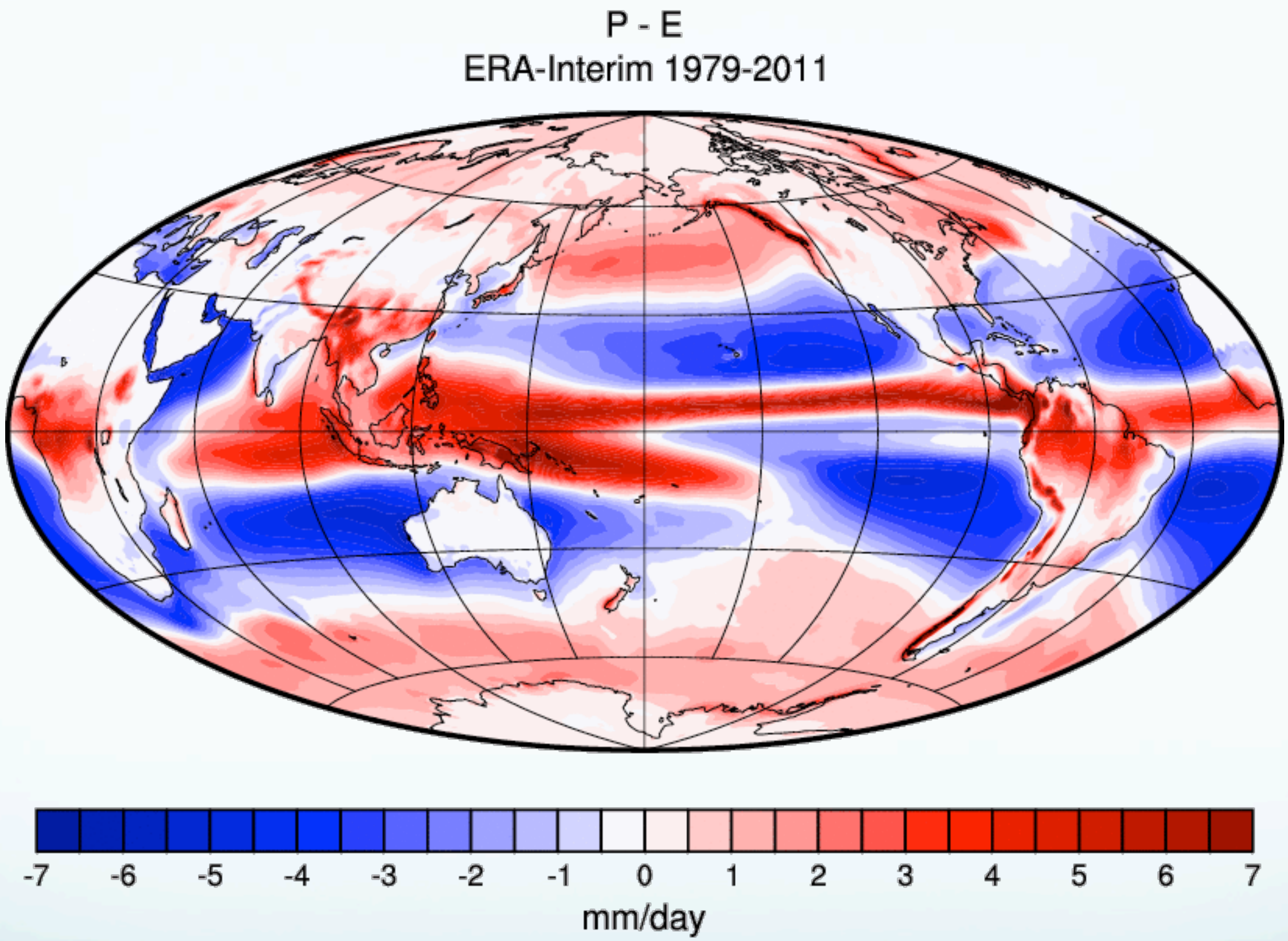
Both saturation mixing ratio and inverse equilibrium Bowen ratio increase rapidly with temperature, so we expect that potential evapotranspiration will increase as the planet warms, as long as wind speed, relative humidity and surface-air temperature difference don't change too drastically.

What will that mean for climate?



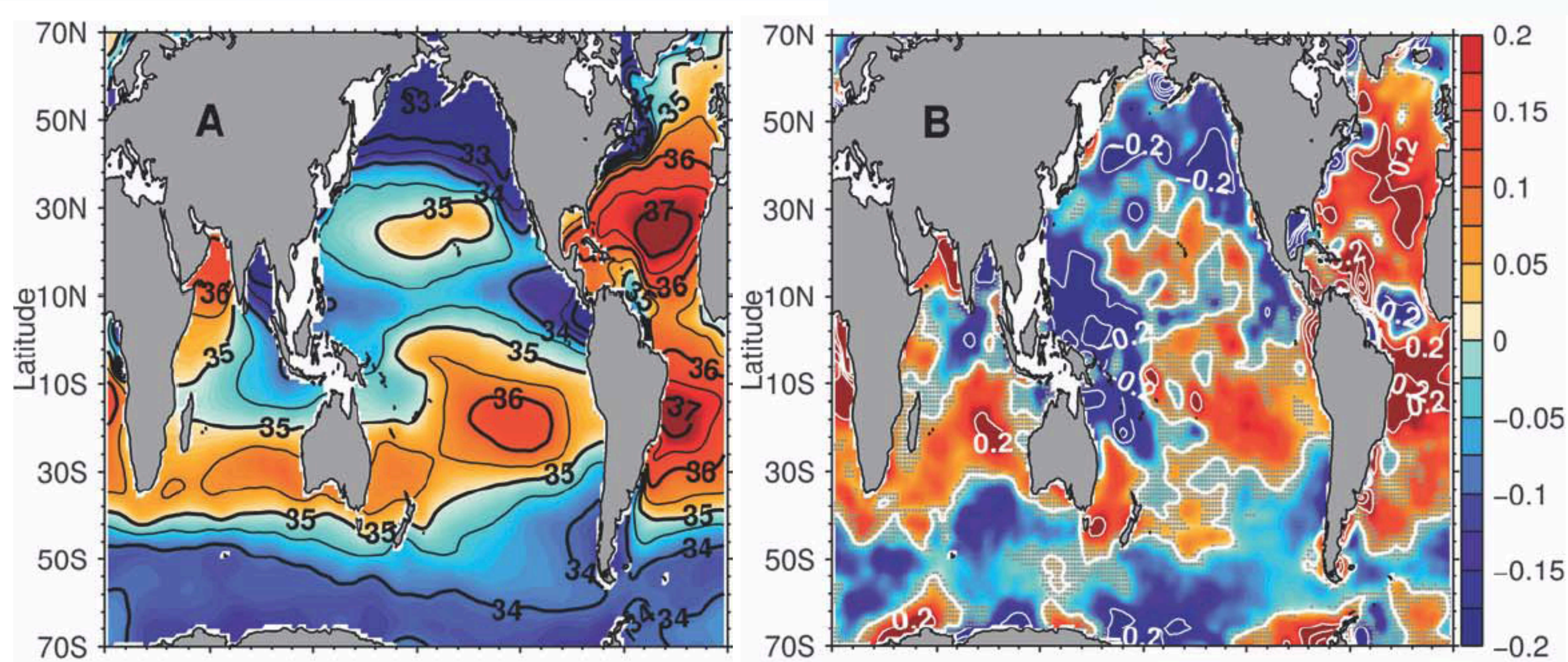
Hydrologic Cycle Change

- As we'll see in the chapter 6, the global mean rate at which it can rain is constrained by the atmospheric energy balance to be at the rate at which the atmosphere can radiate energy away.
- So precipitation increases much more slowly than at the Clausius Clapeyron rate of 7% per degree C.
- But PET and atmospheric water vapor do increase at the CC rate.
- So what has to give?



The pattern of the salinity trend looks like the climatological (long-term mean) pattern of Salinity, which looks like the climatological pattern of E – P . Suggests things are getting more contrasty. Wet gets wetter, dry gets drier, which is what models of global warming do

Ocean Salinity –
Integrator of Hydrologic Cycle Change

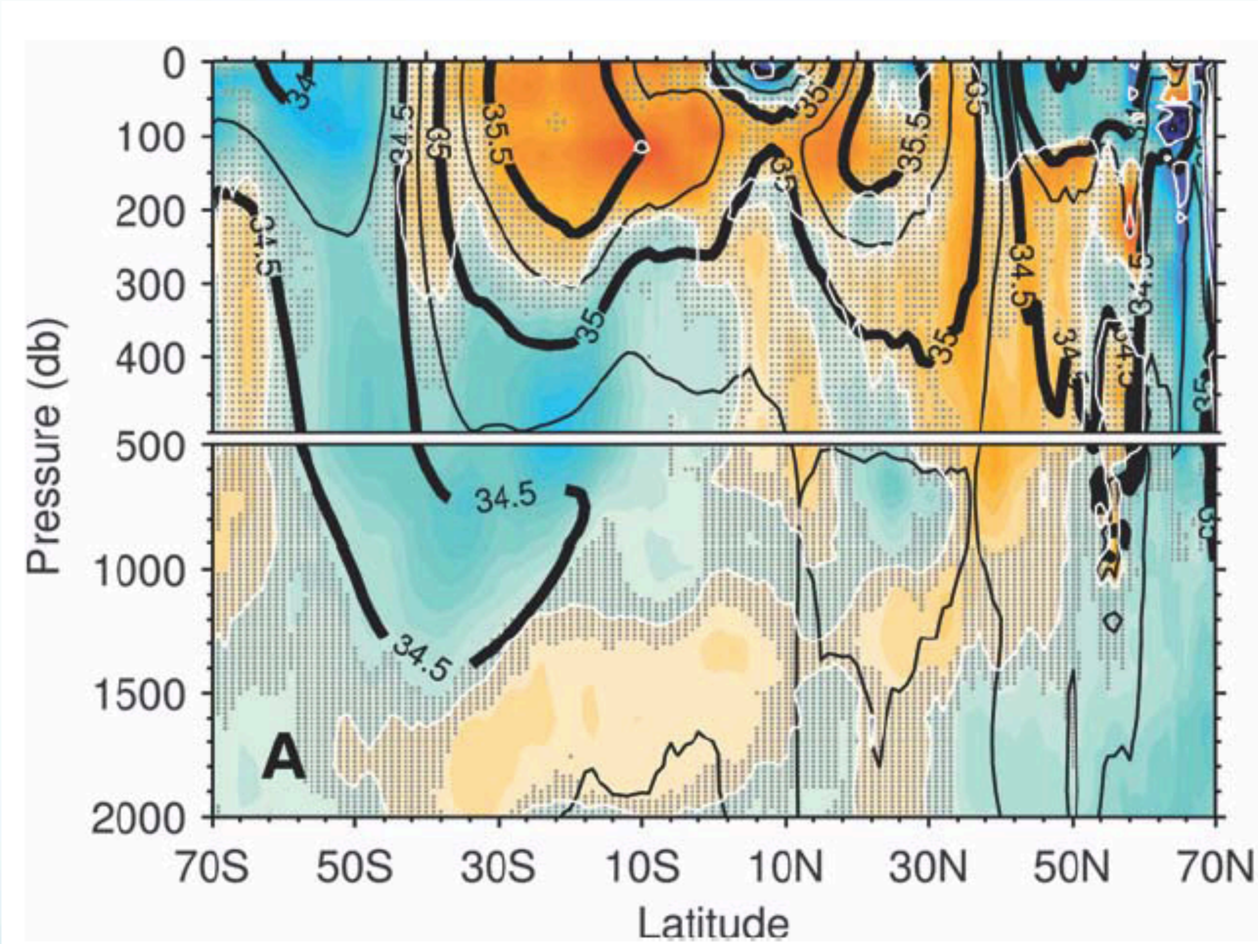


Salinity Climatology, 1950-2000
Durack & Wijffels, 2010
parts per thousand

50-year linear trend difference,
< 99% significance gray stippling

Durack & Wijffels 2010

Salinity change with depth



Color shading is change, black contours are climatology, grey hatching is not significant at 90%.

Salinity Trends

- They are astonishingly big. Mean value is 34, but contrast in tropics in subtropics is 36-34 ~ 2.0, Trends over 50 years are ±0.2 10-20% of contrast.
- The trends have a similar shape as the climatological distributions, which are driven at the surface by freshwater flux (E-P),
- It is argued that the trends, are driven by increasing intensity of the hydrologic cycle –mean P and E don't change, but contrast in E – P increases.
- The surface changes penetrate to depth by mixing along surfaces of constant density.

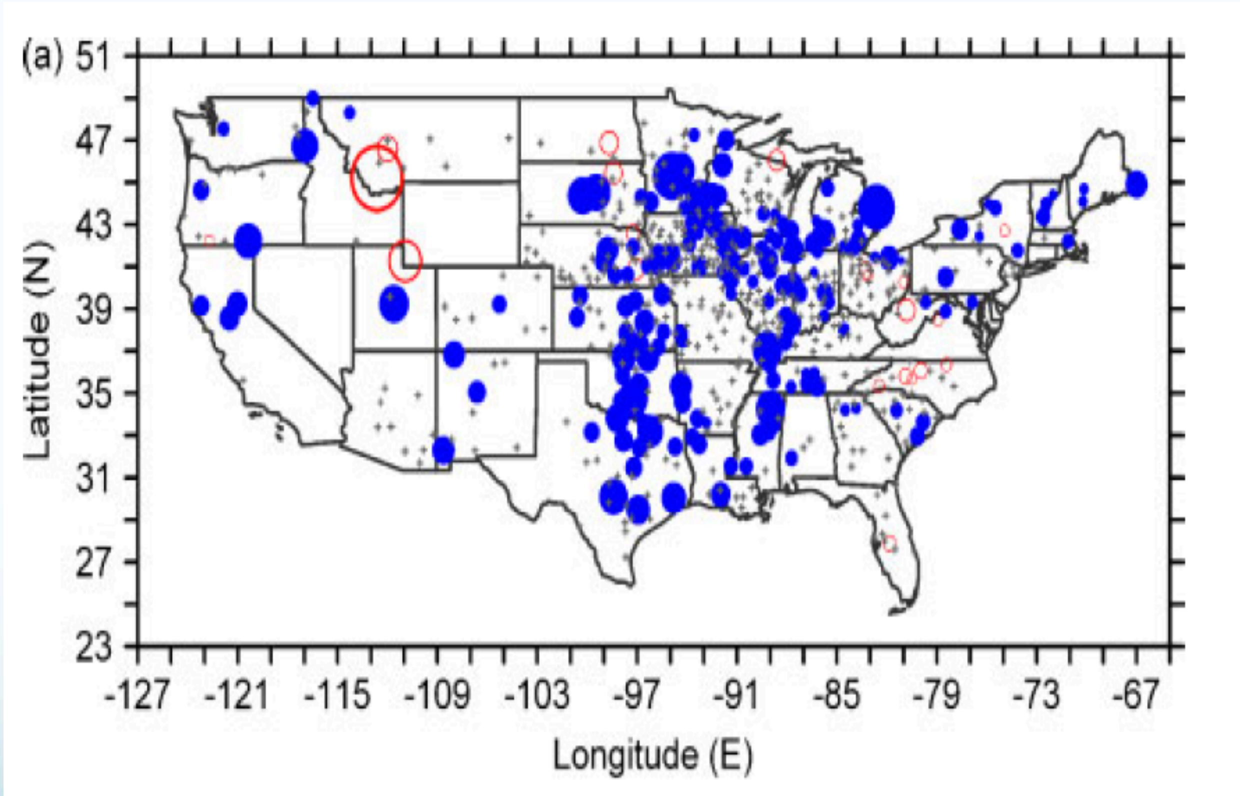
Extreme Events

- Theory: Although mean precipitation changes may be too small to measure yet, the latent energy in surface air is increasing, so maybe the precipitation will come in fewer, more intense bursts – models kinda do this.
- Observational evidence of more intense precipitation extremes, more drought, more floods, etc. is spotty. Some medium confidence indications of more intense precipitation events, especially for North America, conflicting evidence for Europe and many other regions.

Extreme Precipitation

Trends over the USA in the period from 643 stations with substantial data in the 20TH Century 1895-2002 or at least 1905-1995.

Trends in mean precip.



Pryor et al., 2009, Int. J. Climatol.

Extreme Precipitation

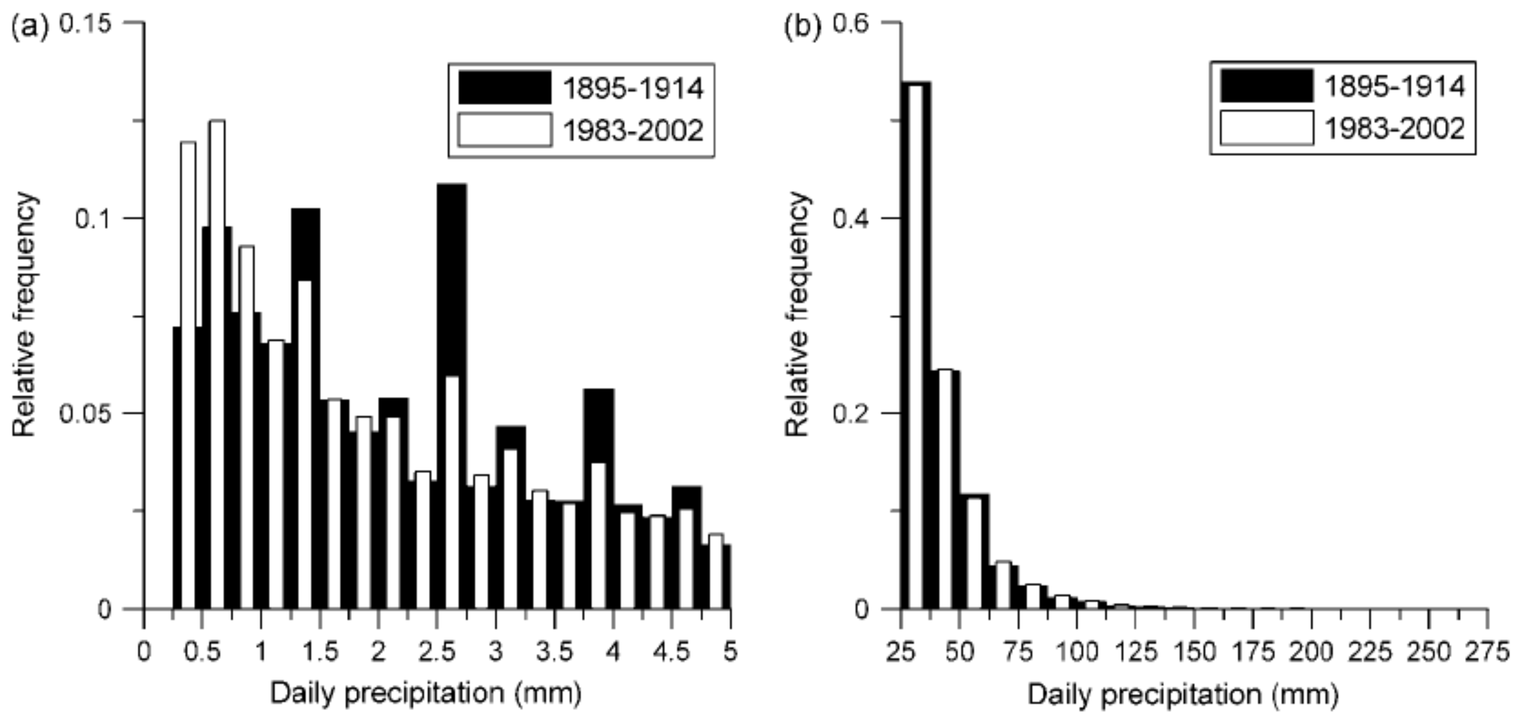
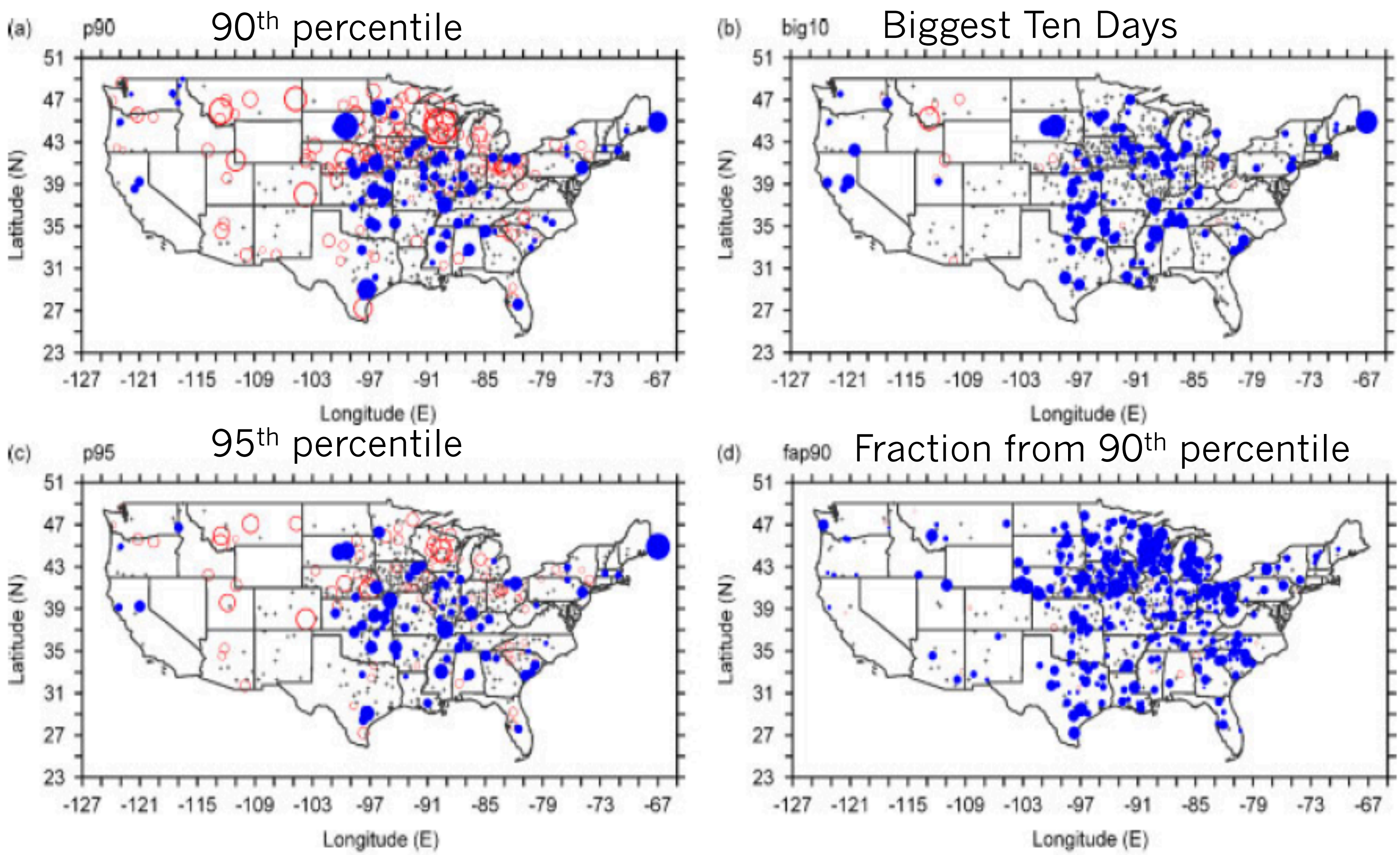


Figure 2. The relative frequency with which precipitation amounts (a) below 0.2 in (5 mm) and (b) above 1 in (25 mm) was observed at all stations during the first 20 years of the data record (1895–1914) and the last 20 years of the record (1983–2002).

Pryor et al., 2009, Int. J. Climatol.

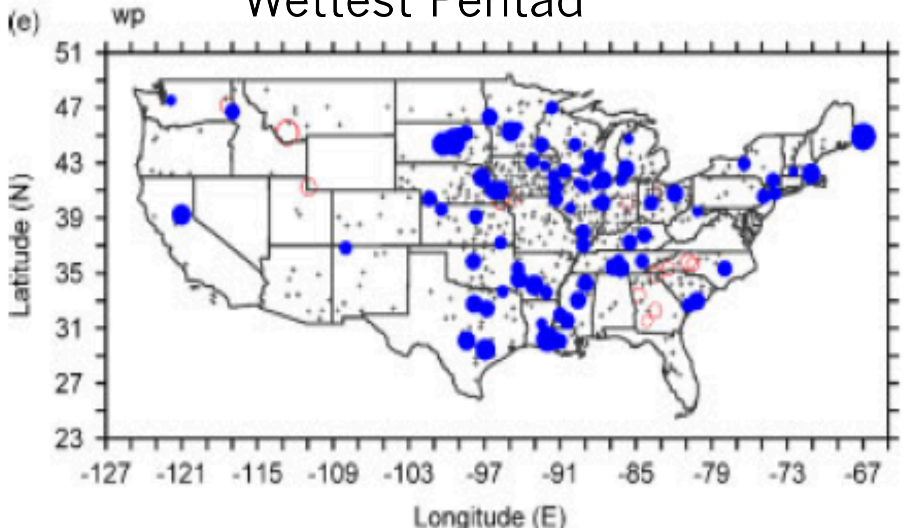
Extreme Precipitation Trends



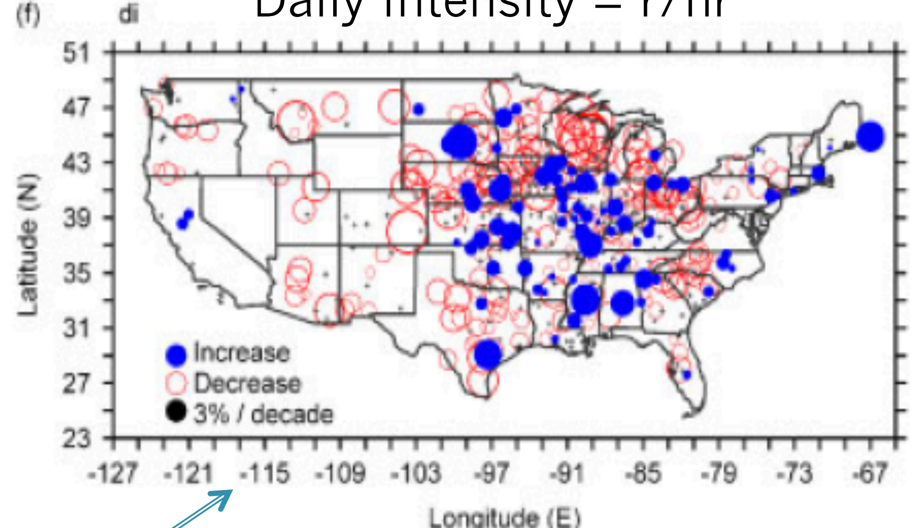
Pryor et al., 2009, Int. J. Climatol.

Extreme Precipitation Trends

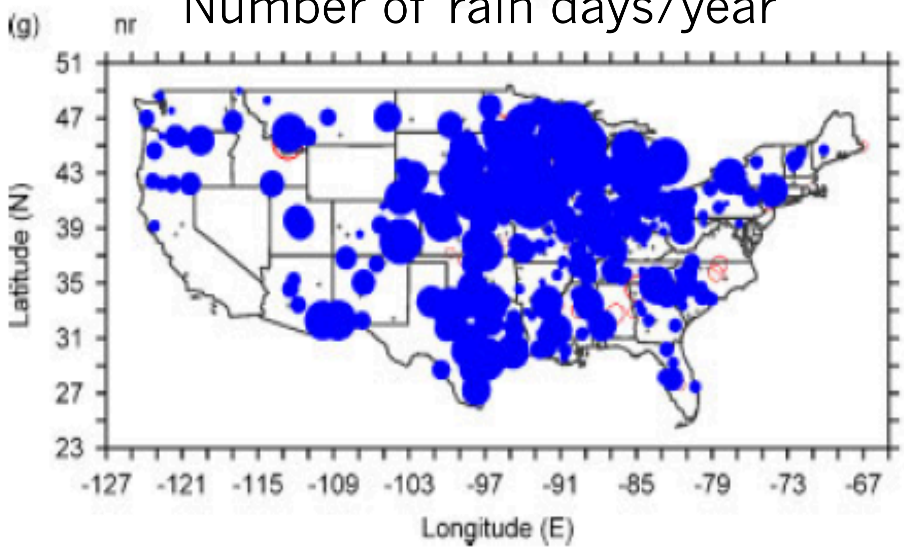
Wettest Pentad



Daily Intensity = r/nr



Number of rain days/year



Trend in reporting of light rain.

Pryor et al., 2009, Int. J. Climatol.

New Topic
Chapter 6: The Atmosphere

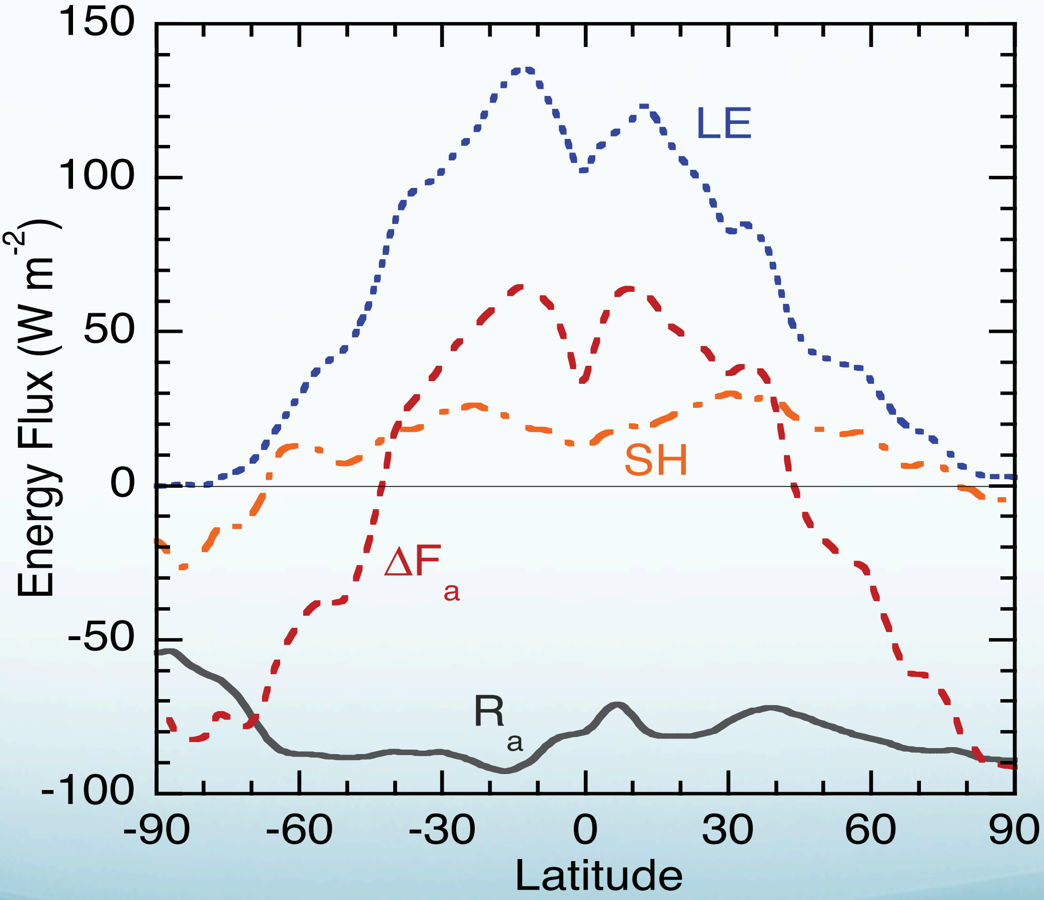
- The atmosphere is the fastest responder and the fastest communicator of information from region to region.
- The Energy Balance

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

- In the global mean P=E.

Atmospheric Energy Budget

- Versus Latitude



Atmospheric Energy Balance and Precipitation

- In the global mean, P=E, so the atmospheric energy balance can be written,

$$P = E = -\left(R_a + SH\right)/L$$

- Since SH is generally positive, we need Ra to be negative and to be larger than SH for it to rain. The rate at which P and E can increase in a warmed climate is constrained by the energy balance, which is primarily constrained by the rate at which the atmosphere can cool radiatively.

LP = 80, SH = 20, Ra = –100Wm^{-2}

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LP = 80, SH = 20, Ra = –100$\mathrm{Wm^{-2}}$

The Radiative Constraint

- The radiative cooling of the atmosphere is the difference between the flux at the top and bottom

$$R_a = R_{TOA} - R_s$$

- In equilibrium in the global mean $R_{TOA} = 0.0$
- So how much the global precipitation changes in a warmed climate is all about how surface radiative flux changes in a warmed climate

$$R_s = S^{\downarrow}(0) - S^{\uparrow}(0) + F^{\downarrow}(0) - F^{\uparrow}(0)$$

The Radiative Constraint

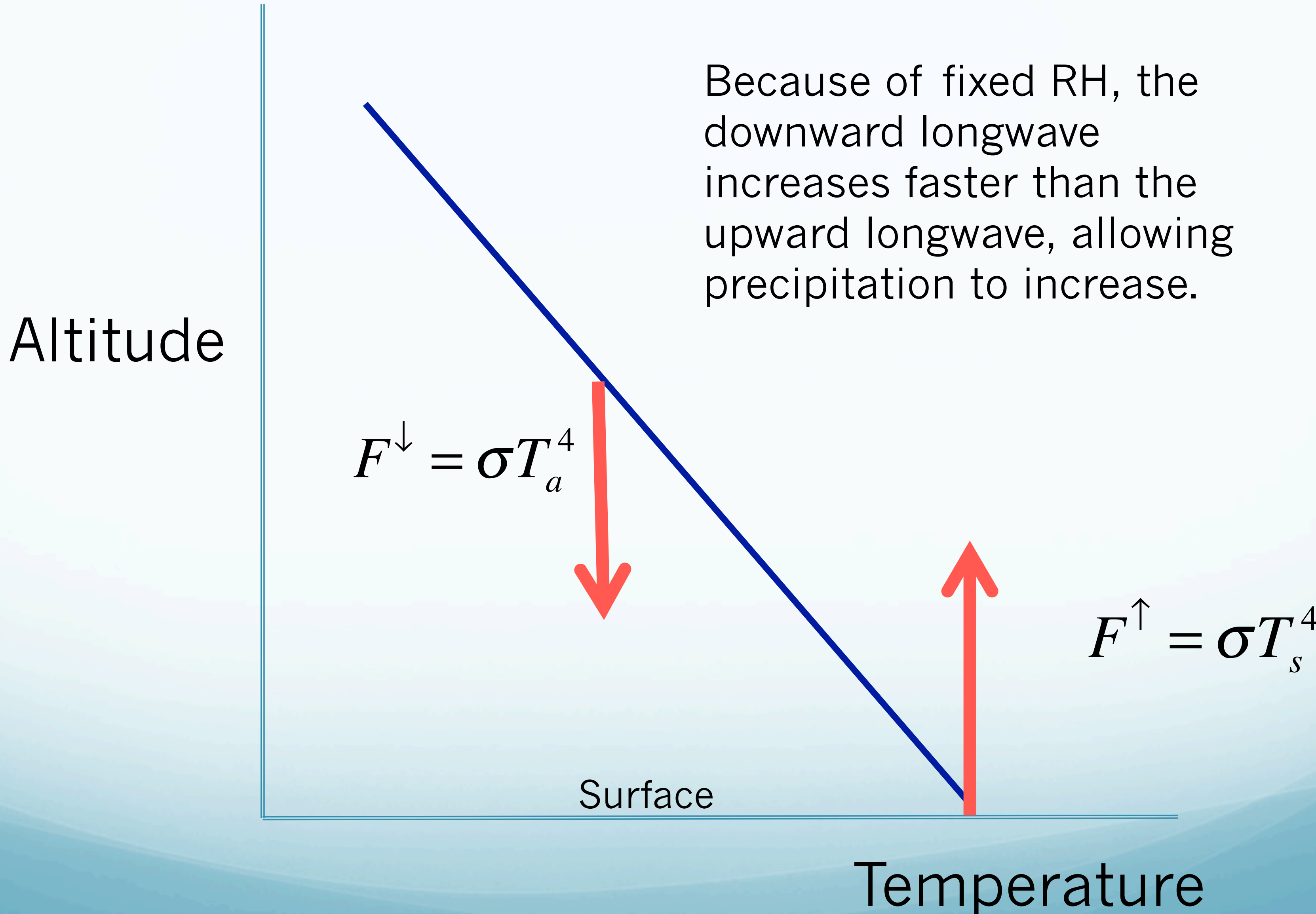
- The change in radiative cooling of the atmosphere in equilibrium is related to the increase in net downward at the ground.

$$R_s = S^{\downarrow}(0) - S^{\uparrow}(0) + F^{\downarrow}(0) - F^{\uparrow}(0)$$

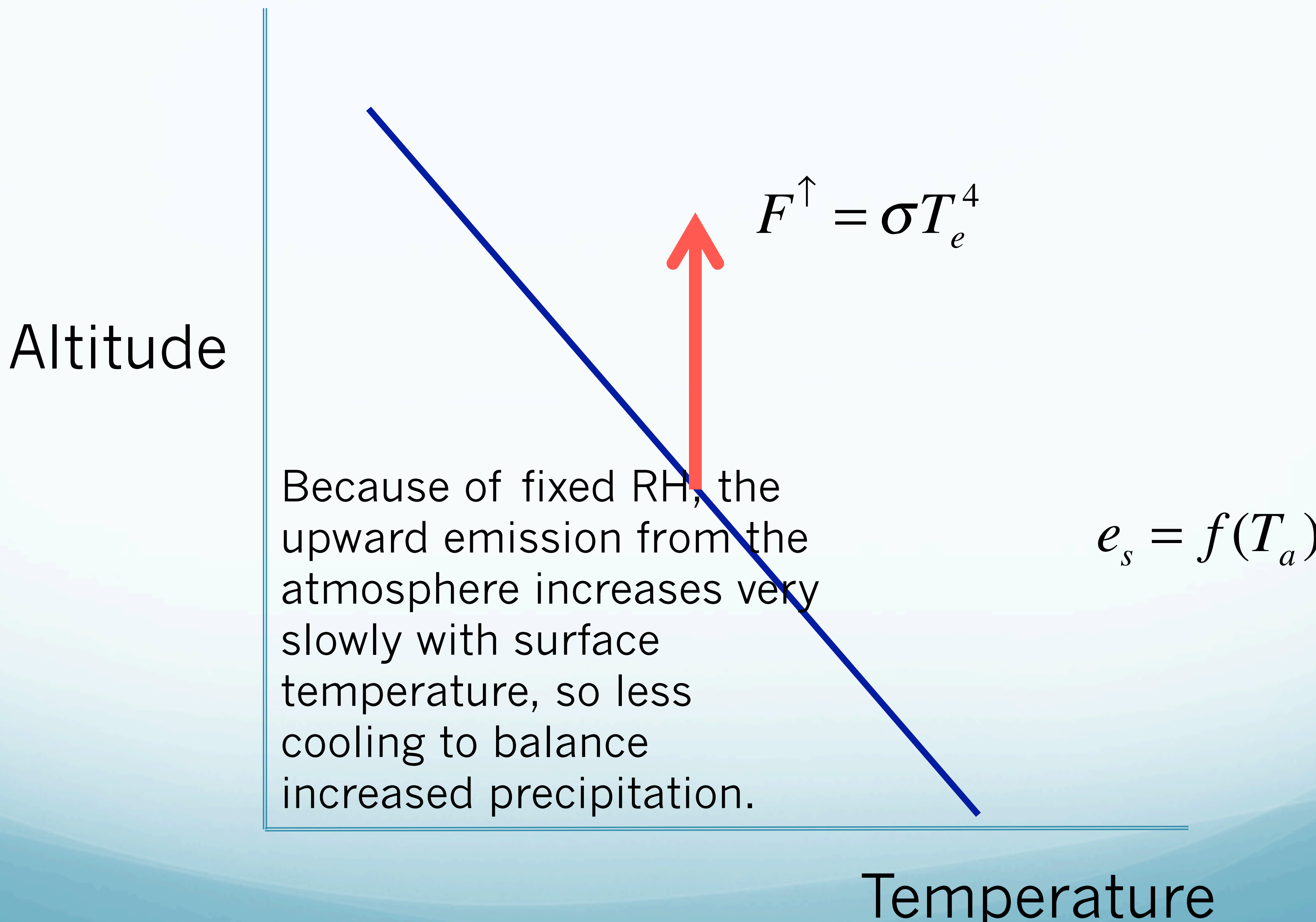
- Most important effect turns out to be increased downward longwave at ground, caused by increase in water vapor in the atmosphere.
- Because of water vapor increase with temperature, longwave downward increases faster than longwave upward. Otherwise precipitation would decrease.

Atmospheric Radiative Cooling - Surface

Because of fixed RH, the downward longwave increases faster than the upward longwave, allowing precipitation to increase.



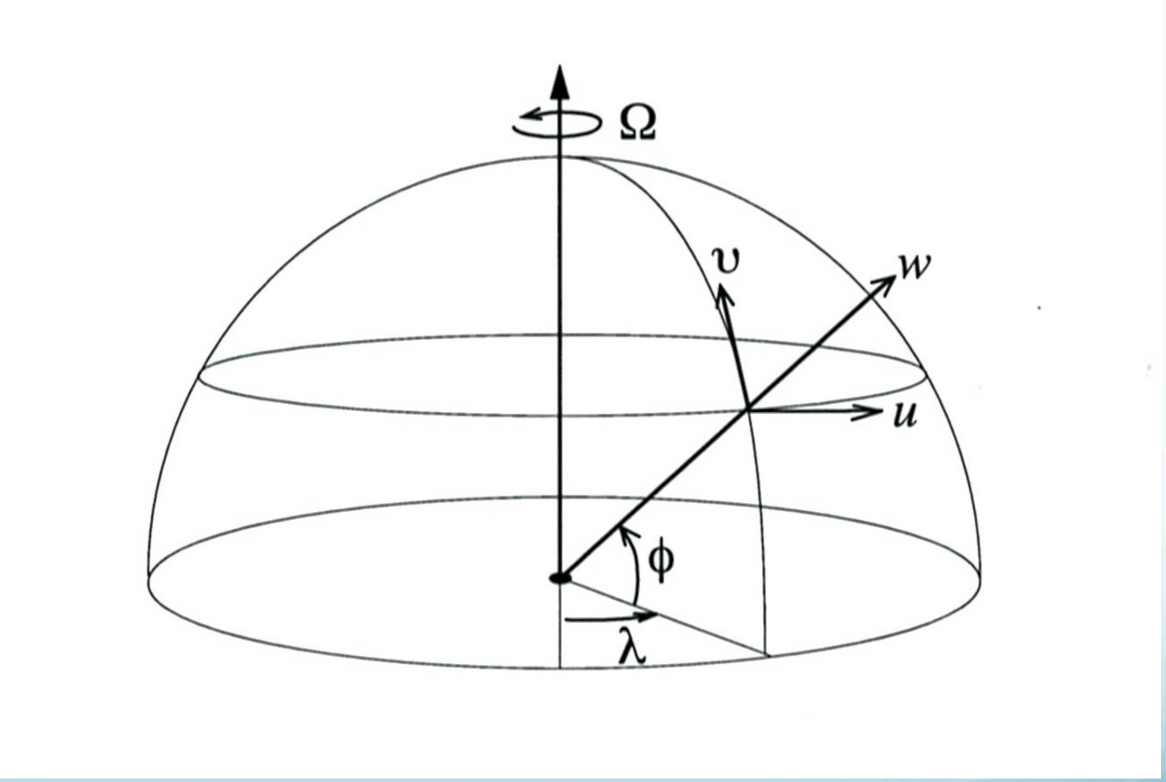
Atmospheric Radiative Cooling - Top



Because of fixed RH, the upward emission from the atmosphere increases very slowly with surface temperature, so less cooling to balance increased precipitation.

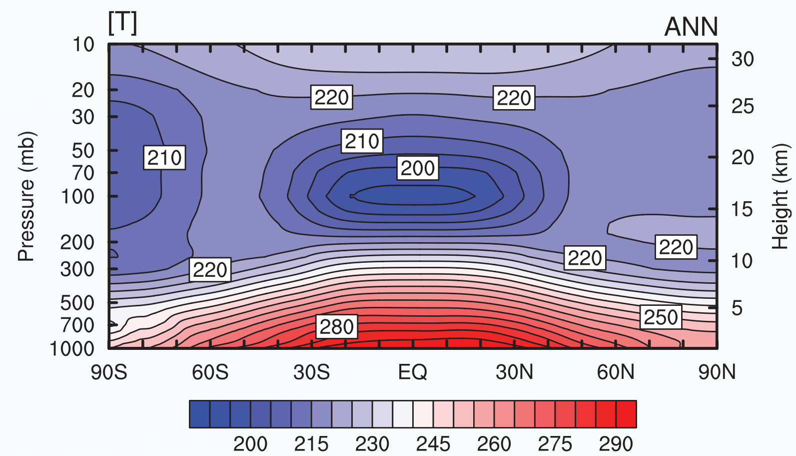
Coordinate System Spherical

- We need to define local zonal, meridional and vertical velocity on a sphere.



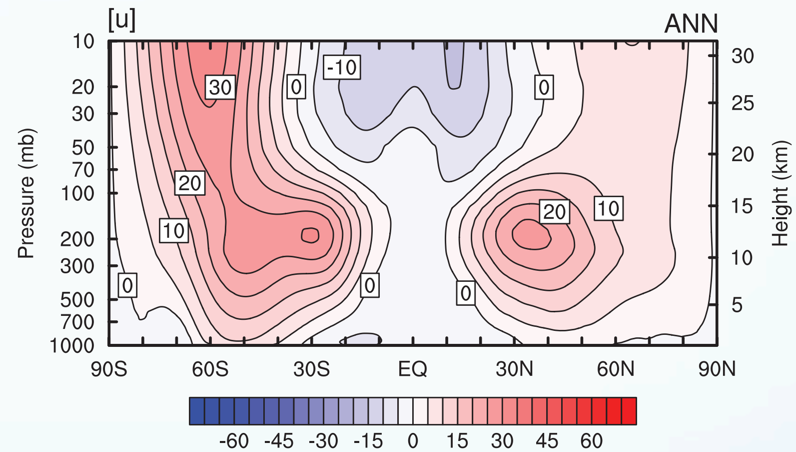
Zonal Averages, and time averages

- Zonal, annual mean T

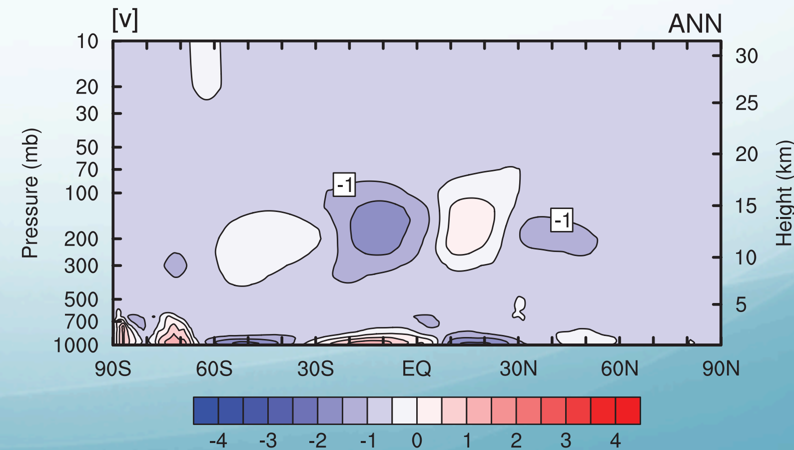


$$\overline{x} = \frac{1}{\Delta t}\int_0^{\Delta t} x\,dt$$

- Zonal, annual mean u



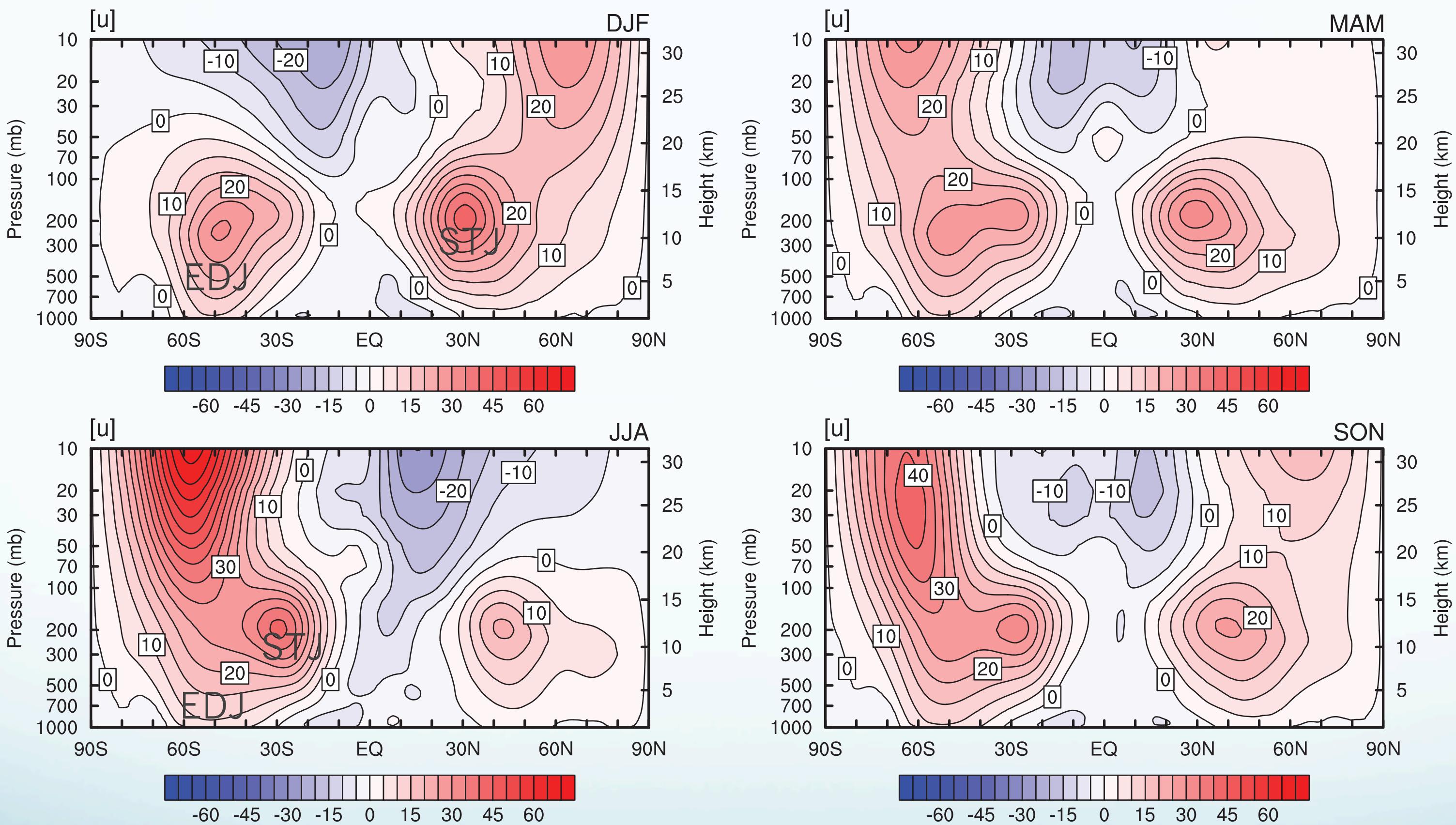
- Zonal, annual mean v



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

Seasonal and Zonal averages

- Zonal Mean Wind



30 N/S Subtropical, Hadley Cell-driven Jet in Winter

50 N/S Extra-tropical, Eddy-driven Jet in SH, especially

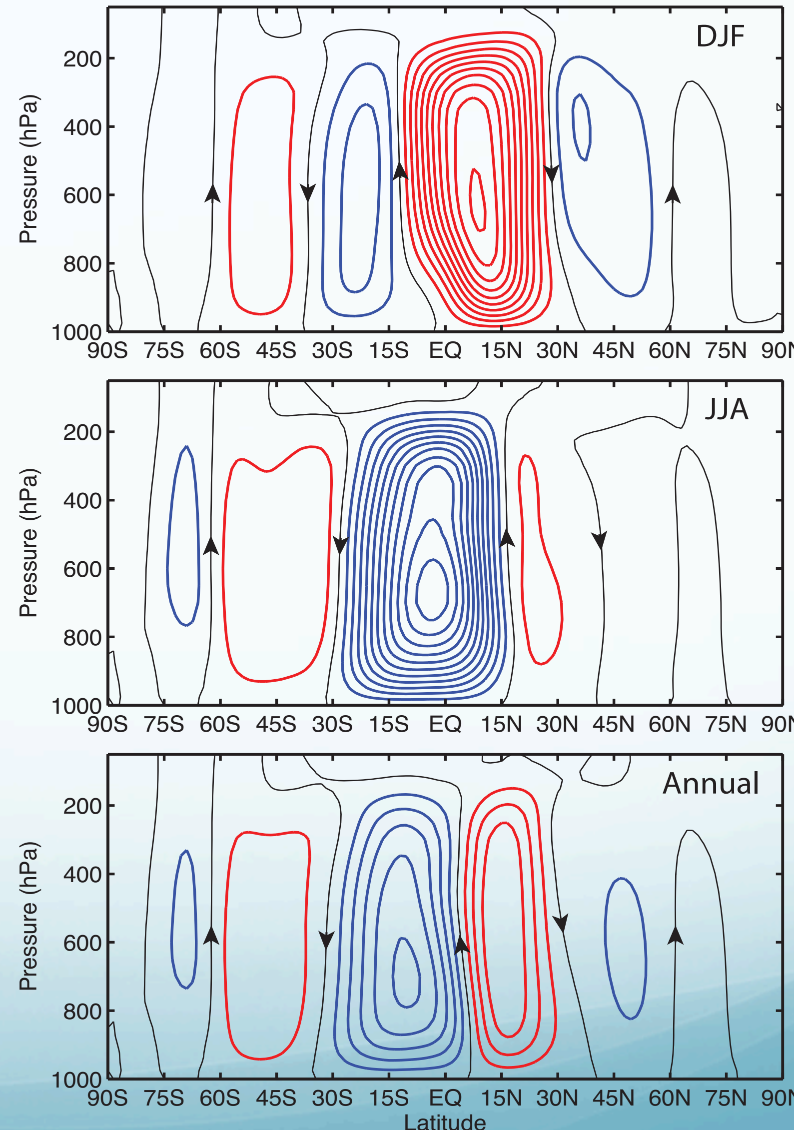
Mean Meridional Circulation

- Mass Streamfunction

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

$$\upsilon = \frac{g}{2\pi a \cos\phi} \frac{\partial \Psi_M}{\partial p}$$

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



Mean Meridional Circulation

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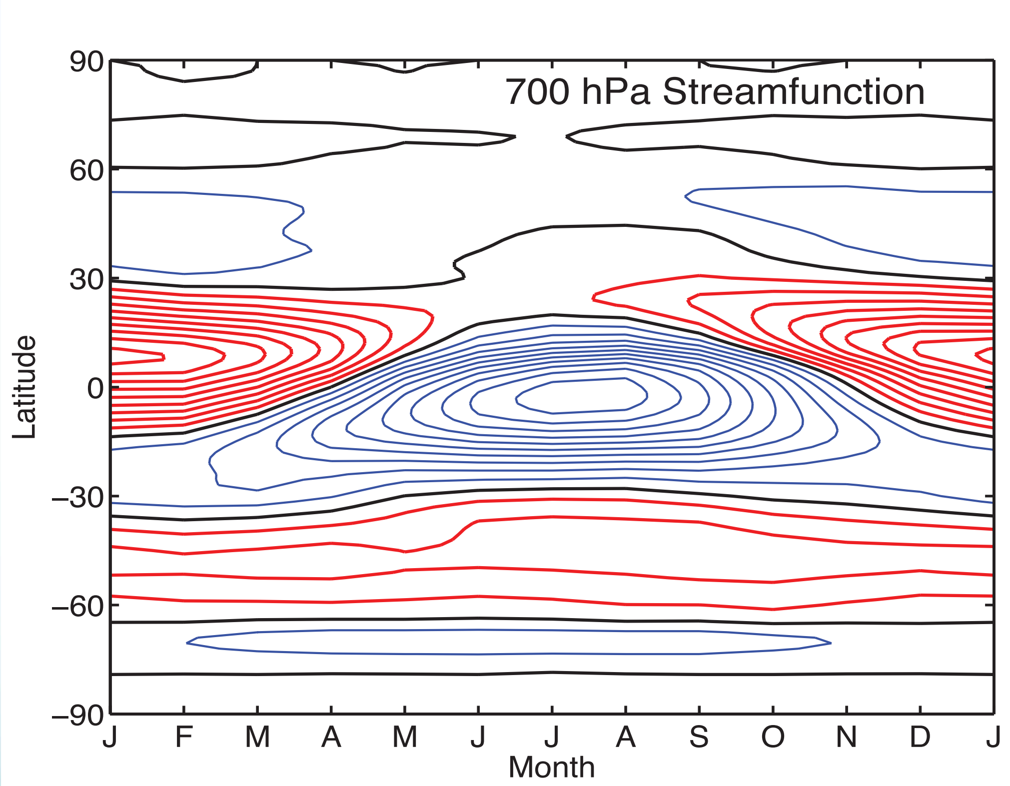


Eddy Fluxes – deviations from time and zonal averages

- Remember Reynolds decomposition into mean and eddy transports
- Deviation from time mean = *transient*

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

- Deviation from zonal mean of time average = *stationary eddy*

$$\overline{x}^{*} = \overline{x} - \left[\overline{x}\right]$$

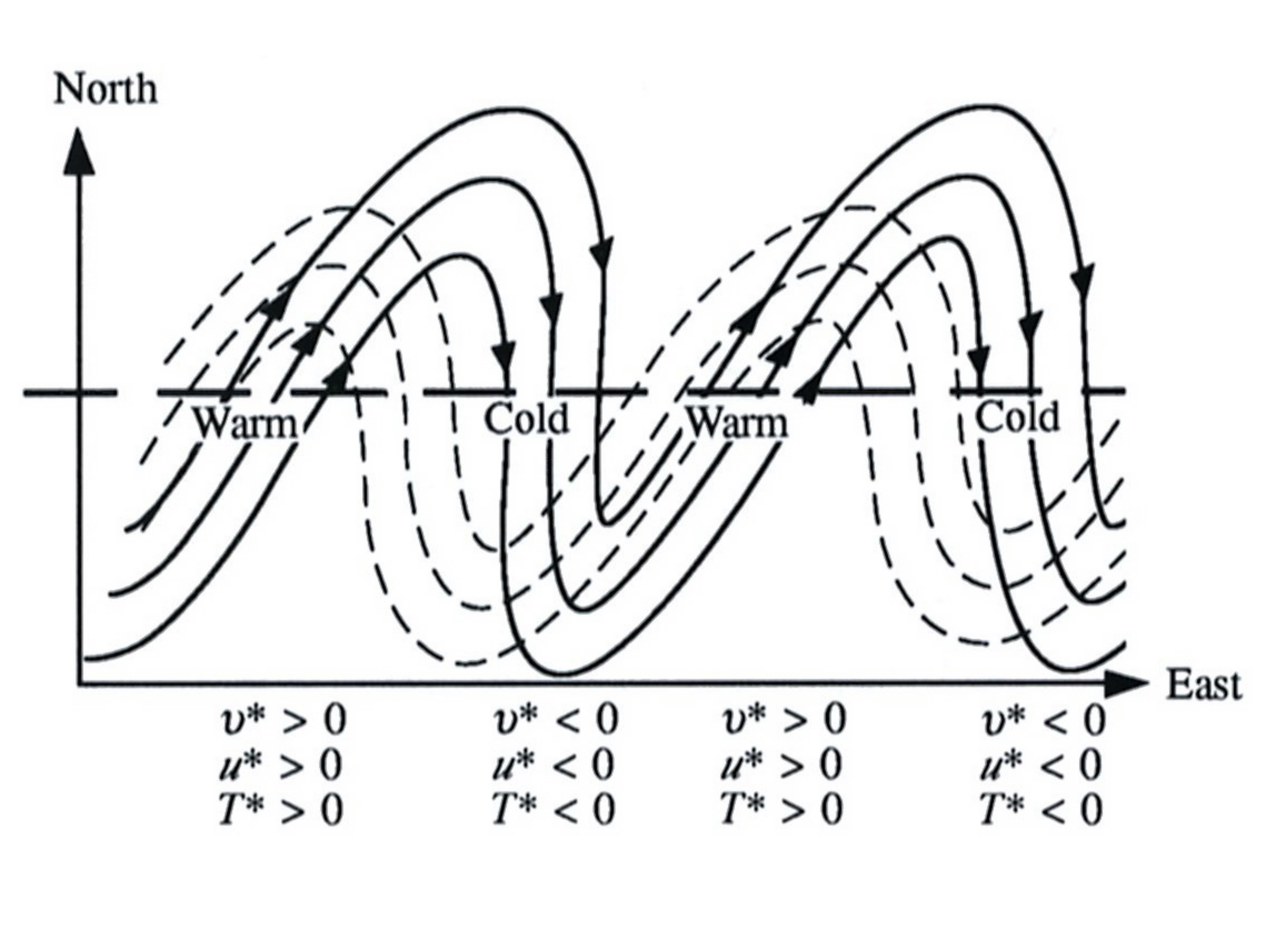
Eddy Fluxes of Stuff

- For example, heat

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

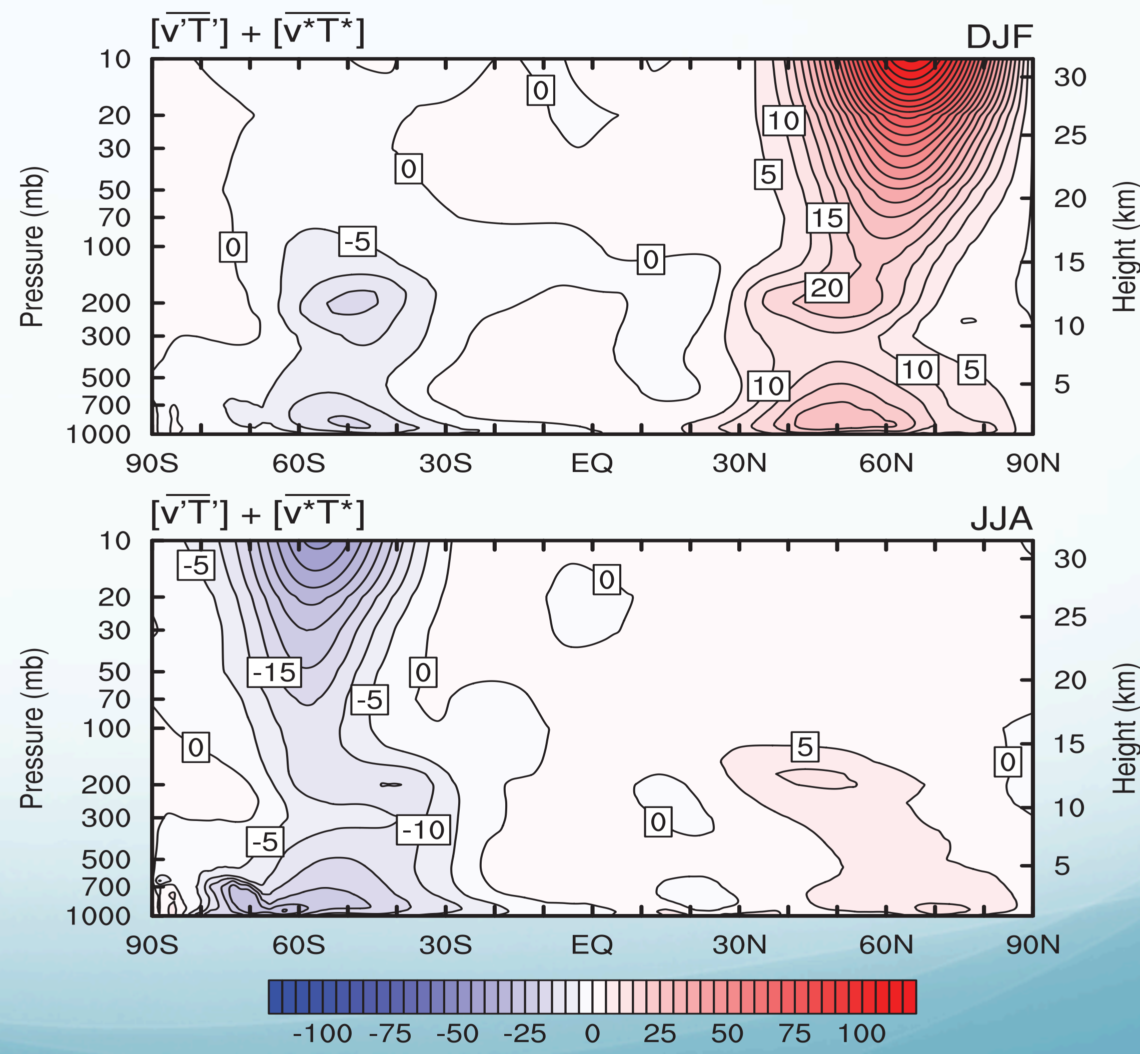
- total = mean meridional circulation + stationary eddies + transient eddies

Northward Eddy Fluxes in Extratropical waves



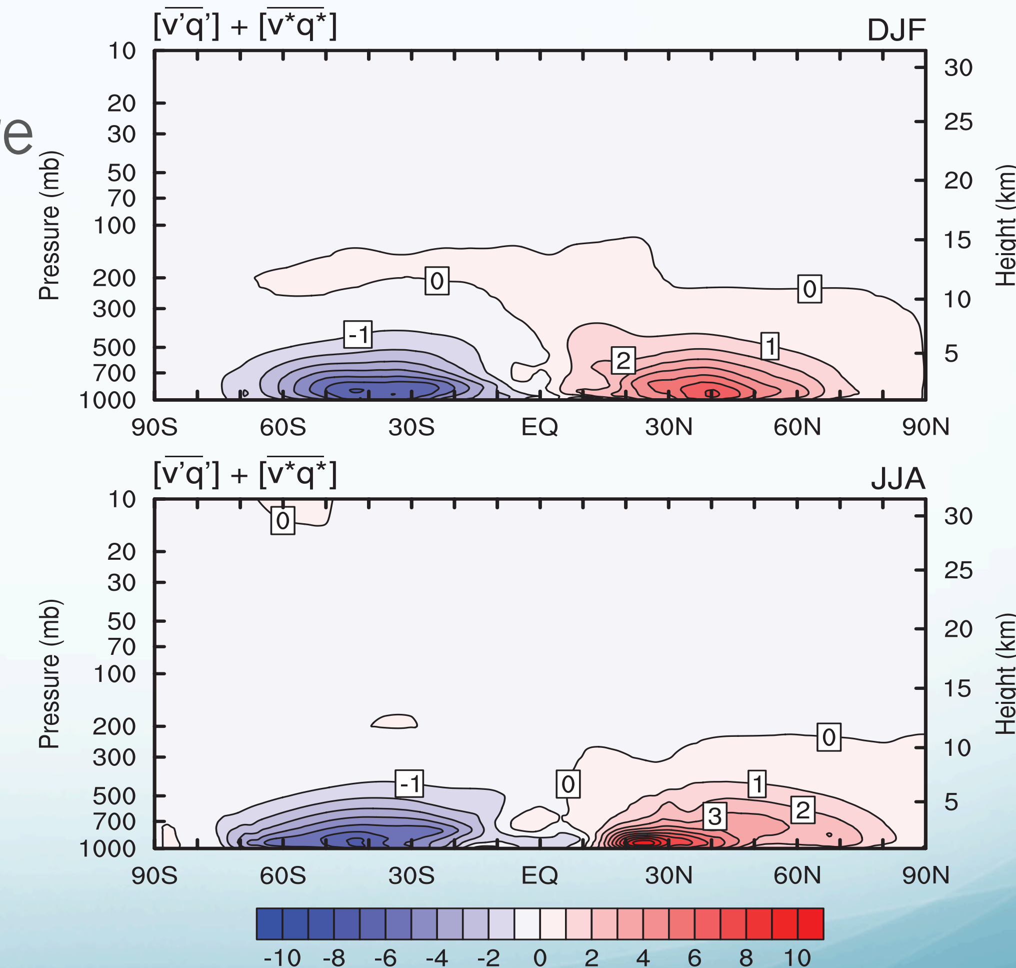
Eddy Heat Flux latitude-height cross-section

- Of temperature flux
- Second Edition Data
- ERA-40
- Maximum 50N and 50S



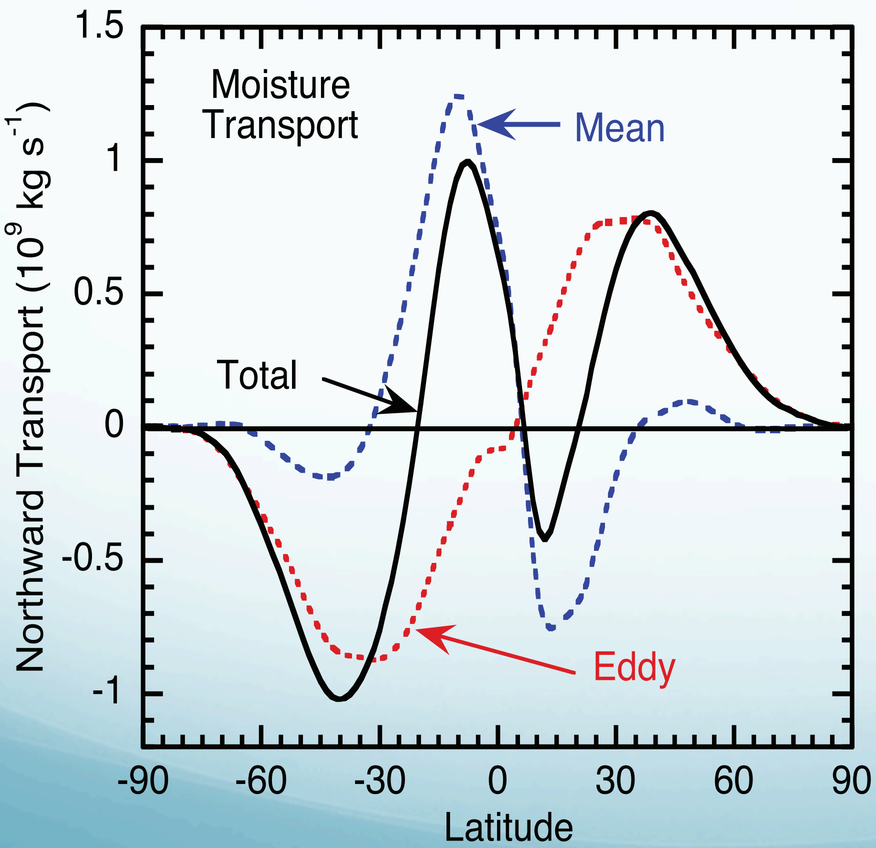
Eddy flux of moisture

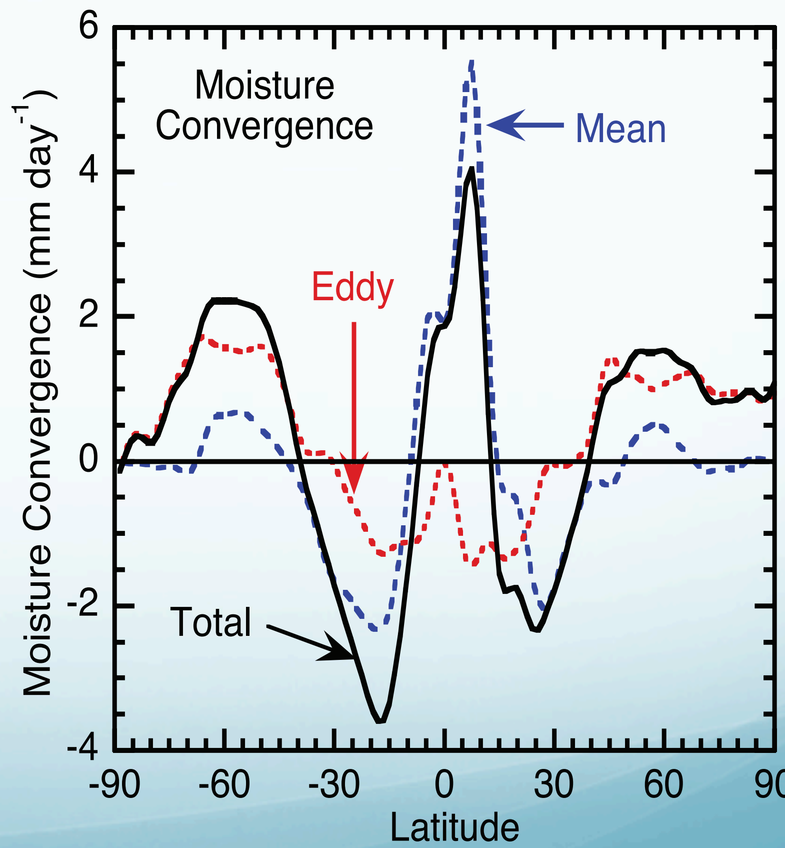
- Confined near the surface like moisture itself, of course
- But strongly poleward
- Maximum around 40N and 40S



Water Transport vs Latitude

- Water Transport (left) and Convergence(right)





Types of Energy
that the atmosphere can transport

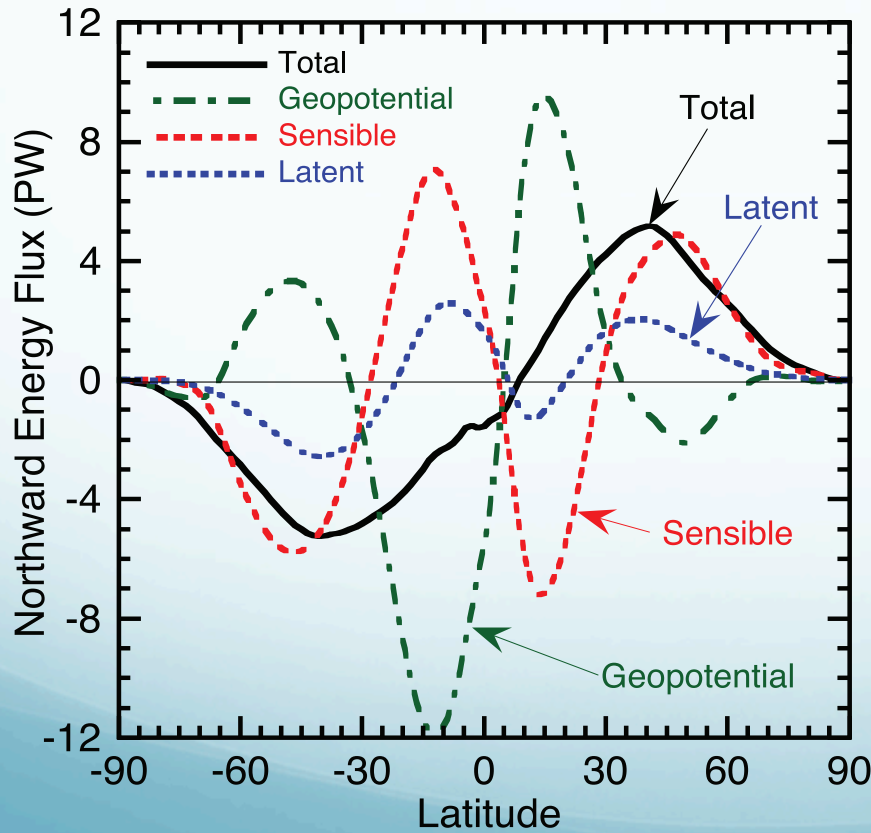
- Energy Types, mostly internal and potential

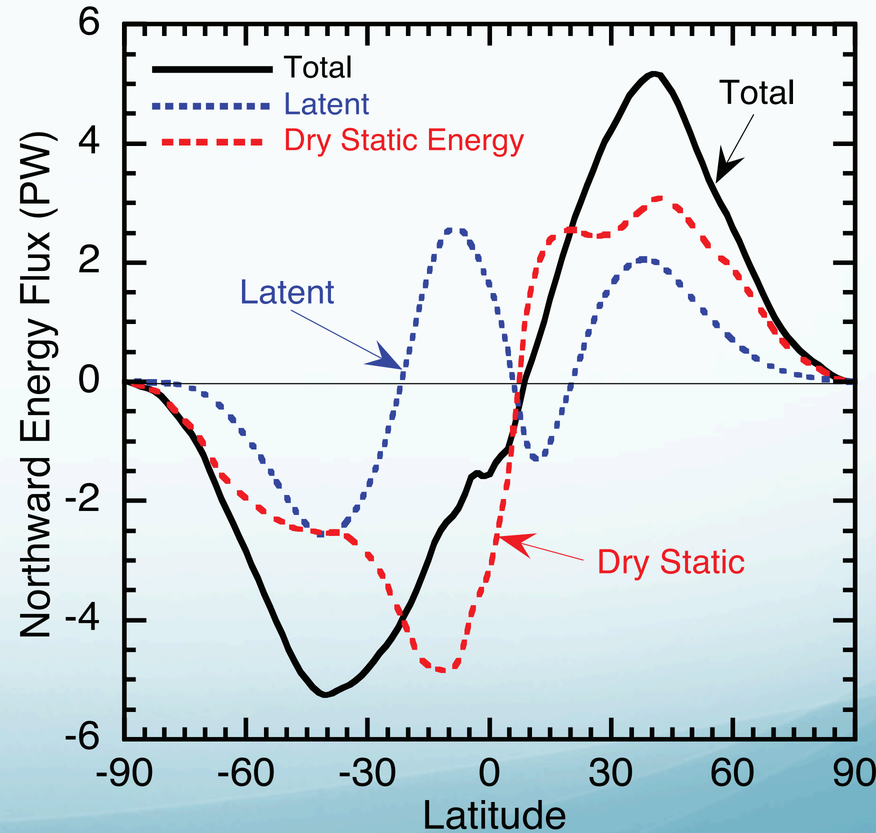
Table 6.1 Kinds and amounts of energy in the global atmosphere.

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

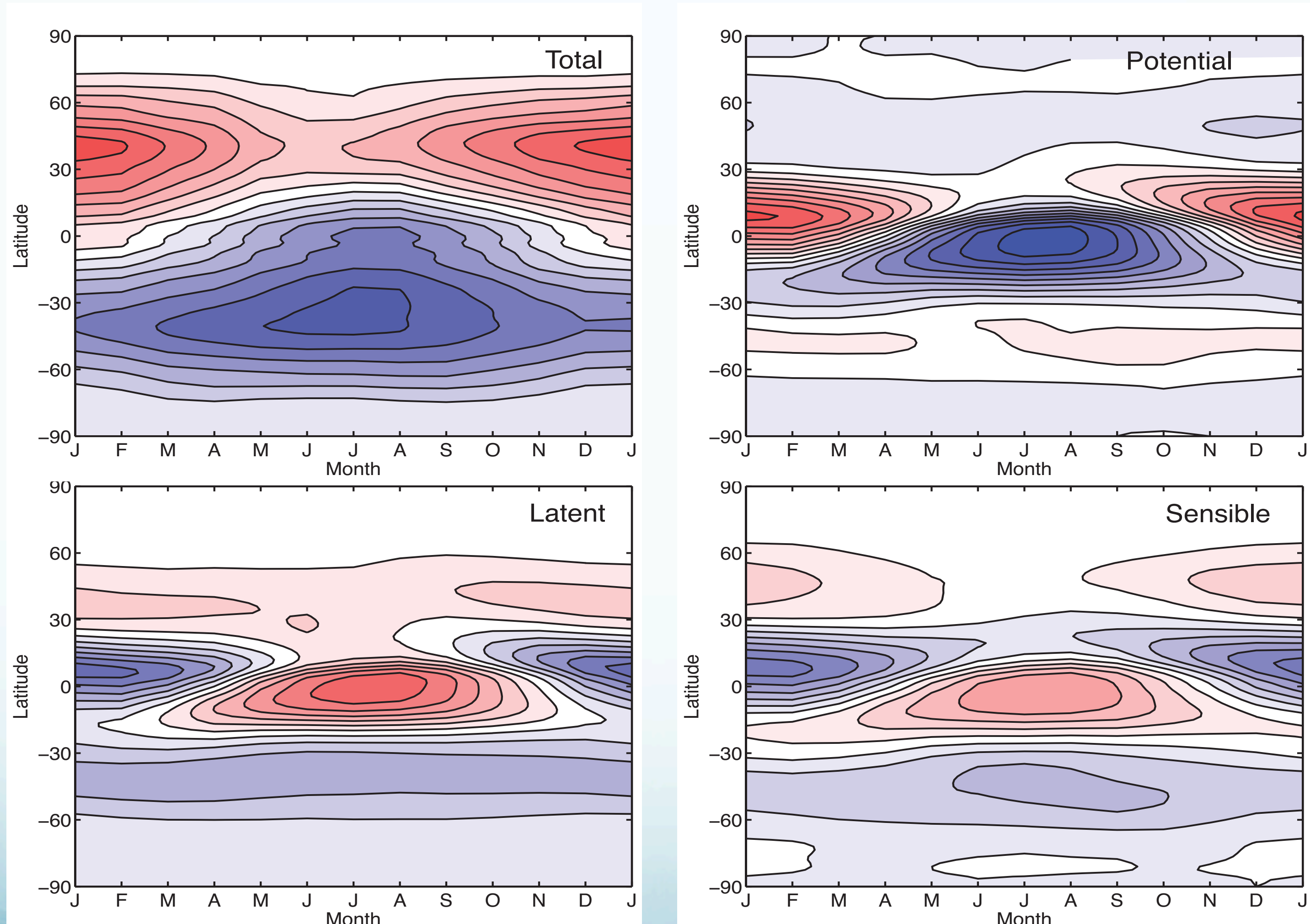
Energy Transport

- Meridional transport of Energy, on right combine sensible and geopotential into dry static energy



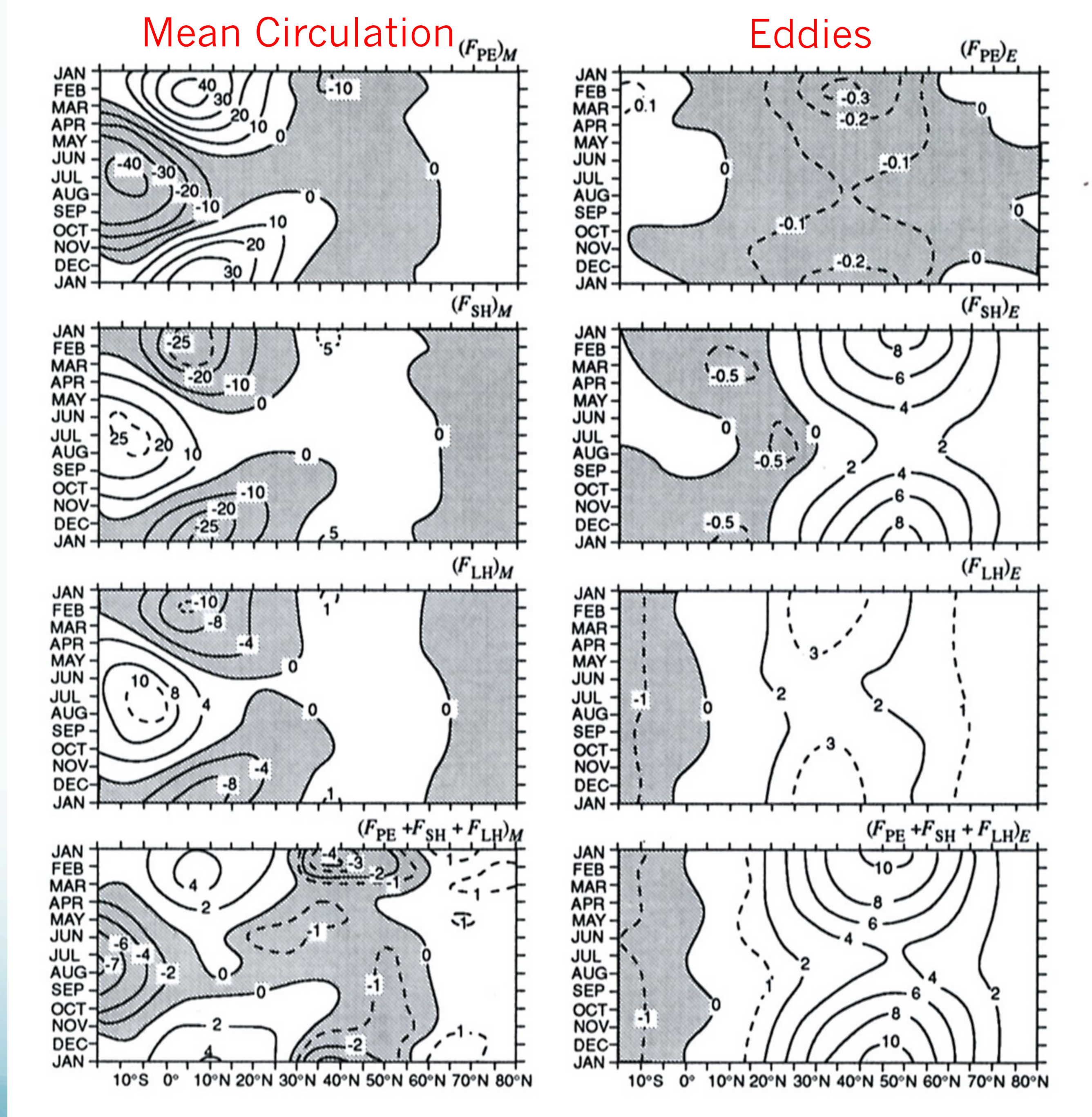


Energy Transport as Function of Season and Latitude



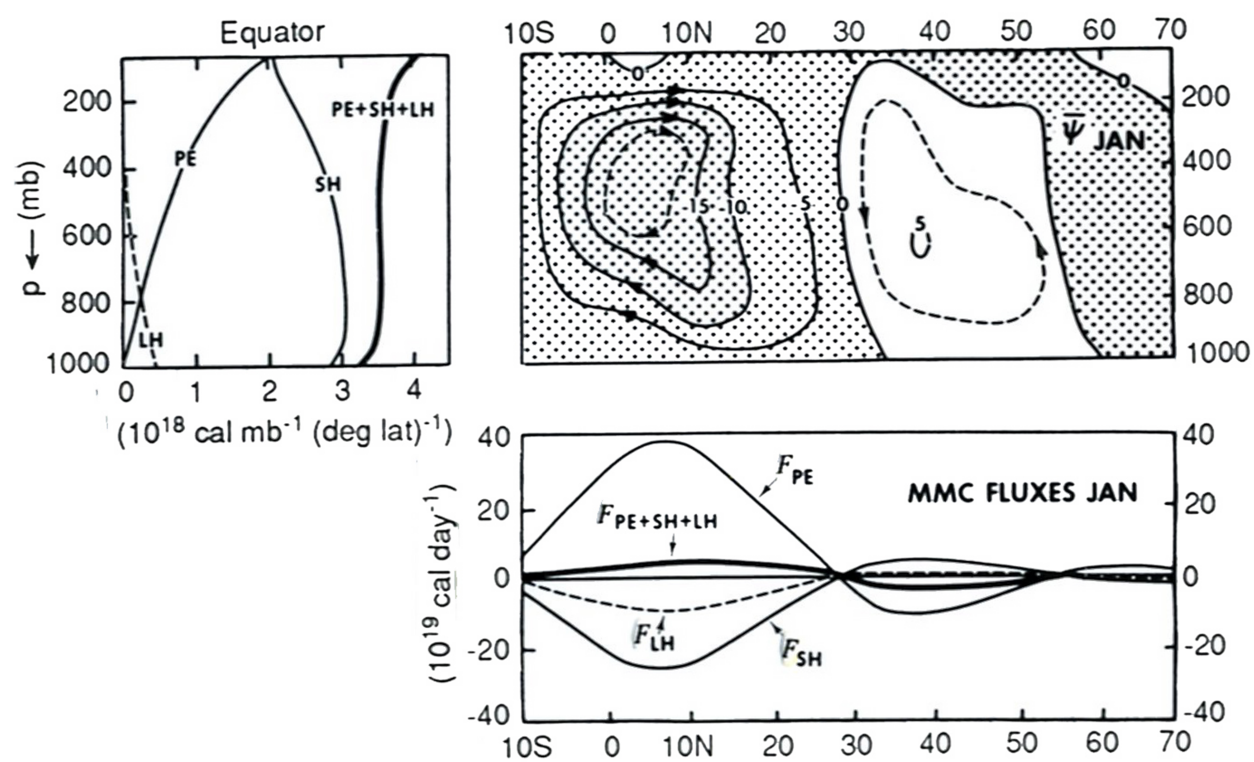
Contour interval is 1 PW for total and latent and 3 PW for potential and sensible energy. Red is Northward, blue is southward.

Vertically integrated Energy Transport



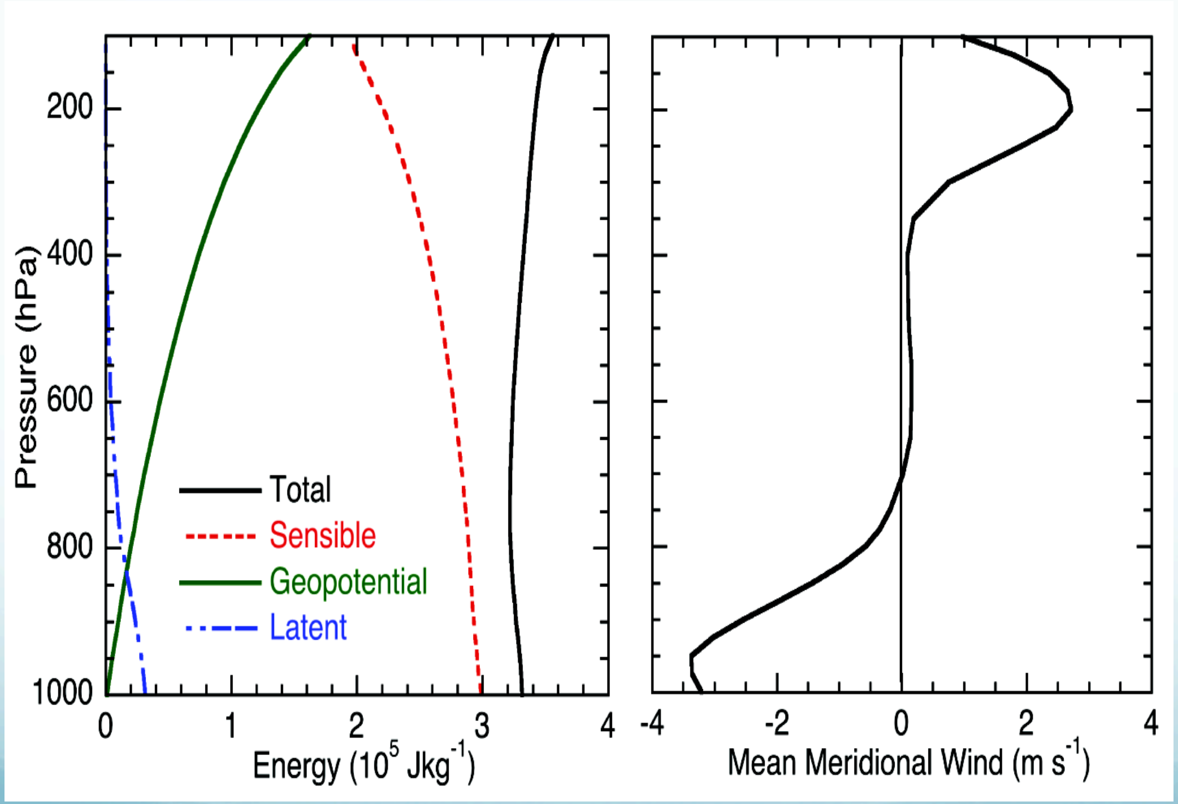
MMC Transport

- It moves heat and latent heat toward the equator, potential energy poleward.



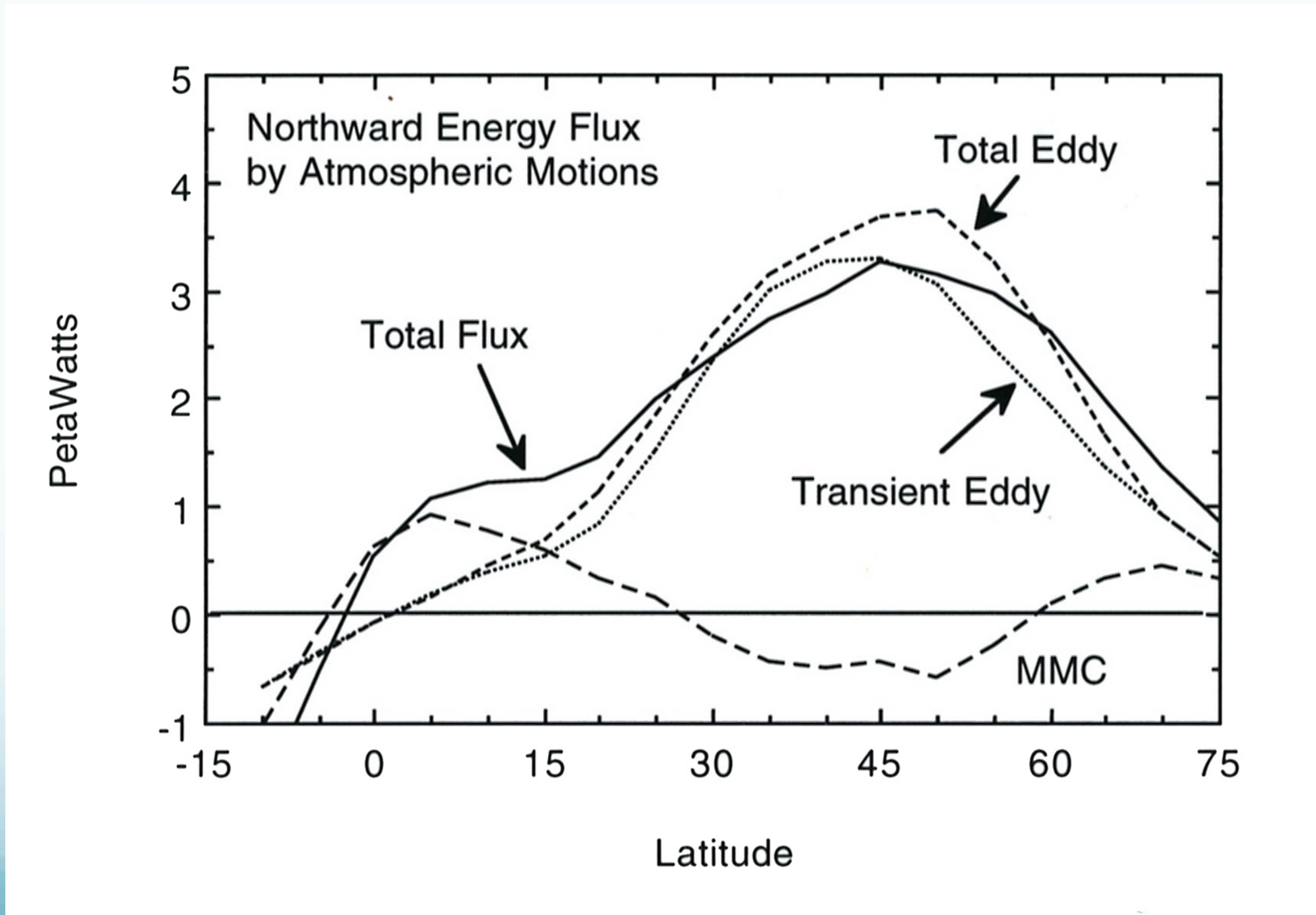
Energy Transport by Mean Meridional Circulation

- Total energy increases upward, but sensible and latent increase downward.



Mean and Eddy Energy Transports

- Transient eddies dominate outside the tropics



Thanks!