Large-scale atmospheric turbulence – Part 1

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Outline of lectures

- Phenomenology of large-scale atmospheric turbulence, and its role in climate
- Balanced and unbalanced dynamics in the shallow-water equations
- 2D and shallow-water turbulence; Gage-Nastrom spectrum and predictability
- Rossby waves and pseudomomentum
- Barotropic wave, mean-flow interaction
- 2D turbulence and zonal jets

Phenomenology of large-scale atmospheric turbulence, and its role in climate

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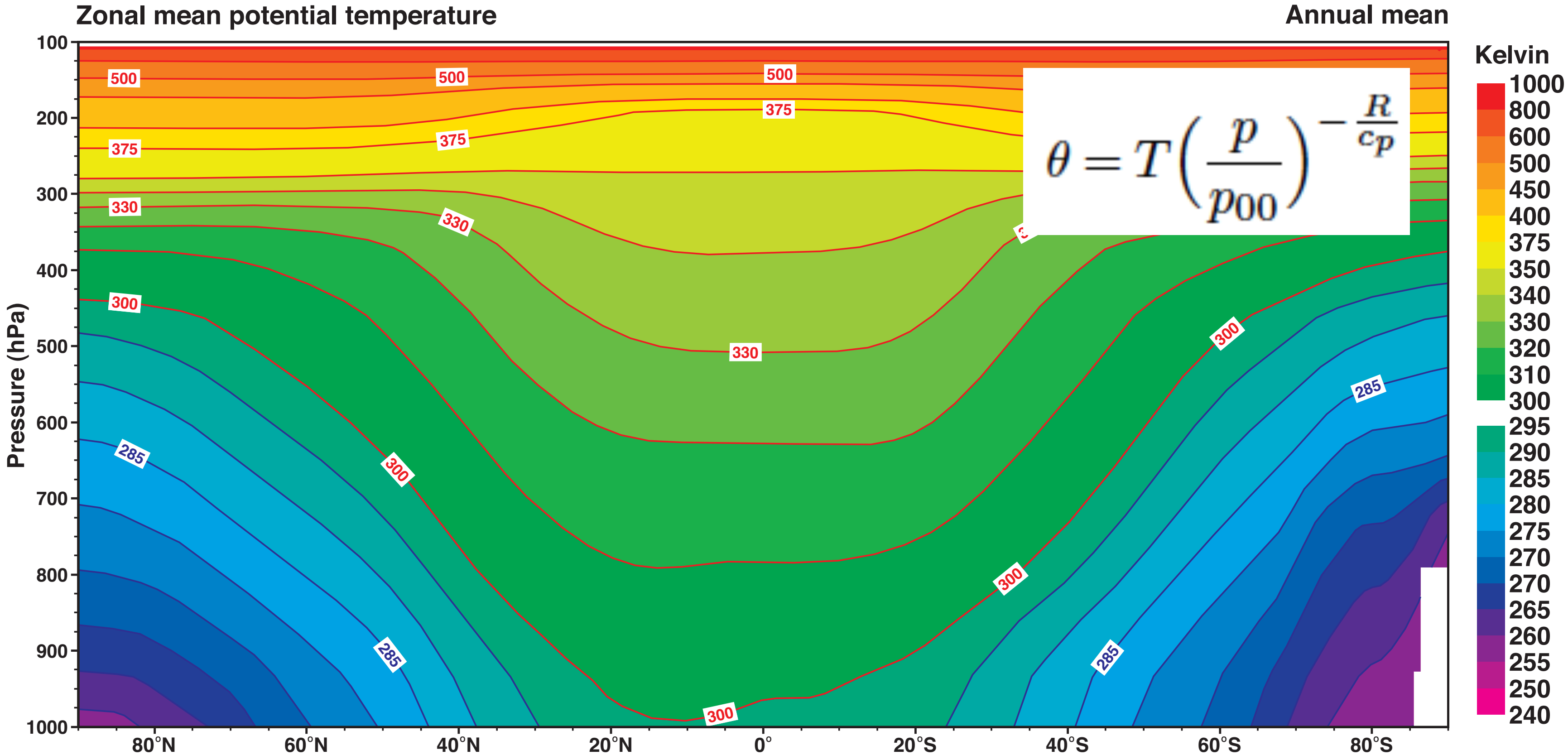
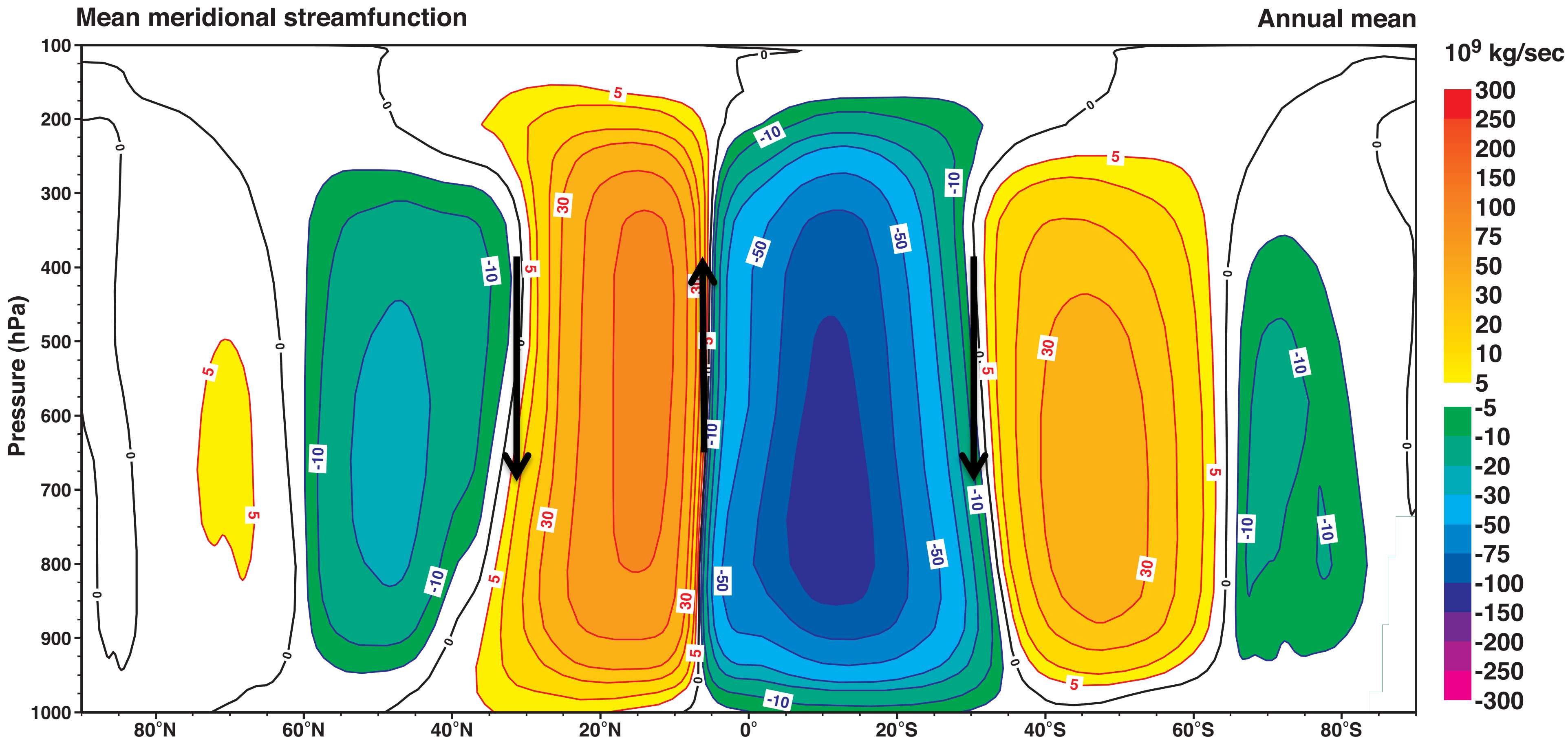
- Observed **potential temperature distribution** shows that temperature is horizontally uniform in the tropics, but has a strong meridional gradient in the extratropics
  - This "baroclinicity" indicates *available* potential energy, which can be released to drive storms



$$\theta = T\left(\frac{p}{p_{00}}\right)^{-\frac{R}{c_p}}$$

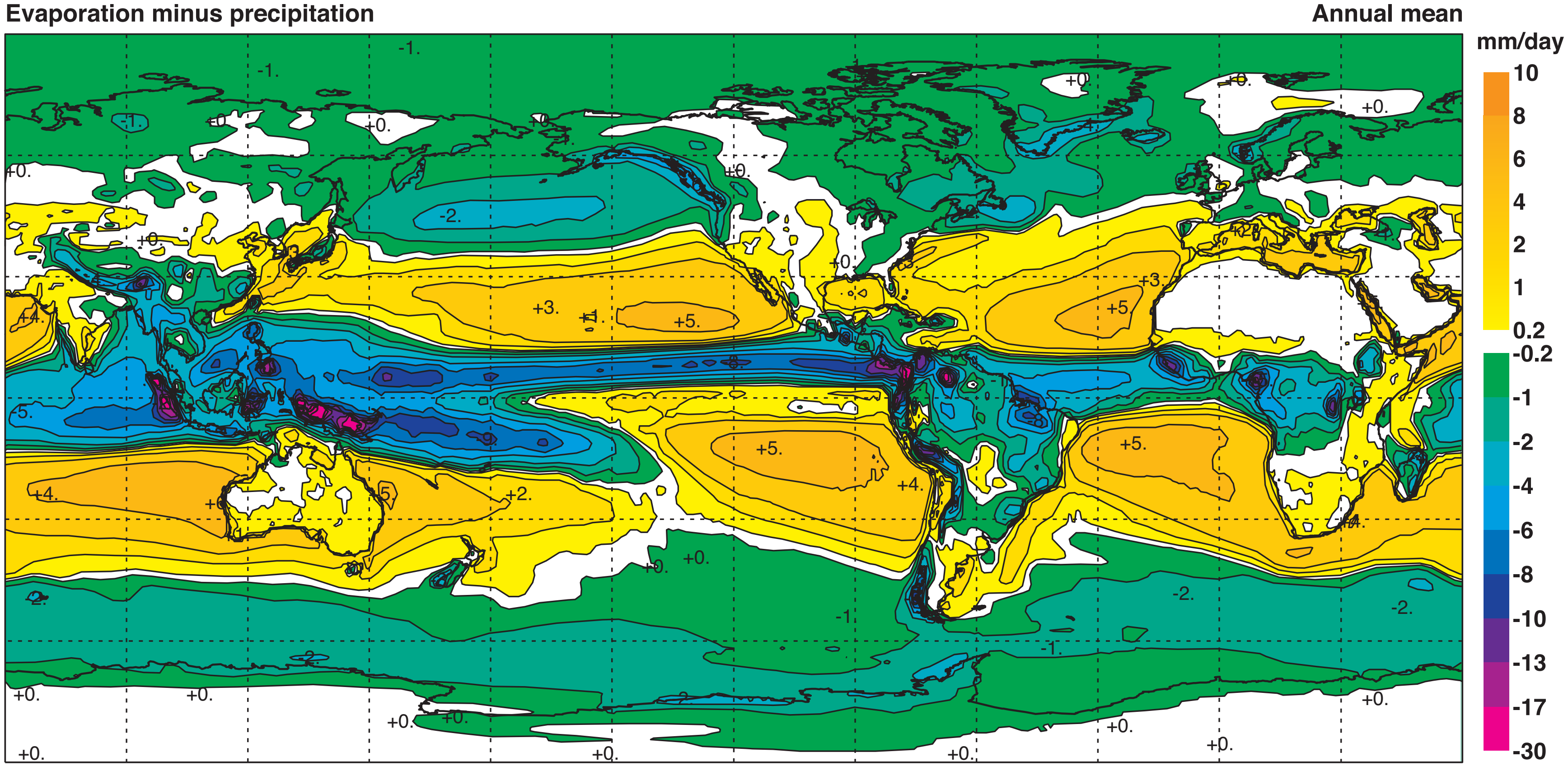
From ERA-40 Atlas (ECMWF)

- Large horizontal temperature gradients cannot be sustained in the tropics because of the small Coriolis force
- The **Hadley circulation** is driven by warm tropical sea-surface temperatures and latent heat release from convection



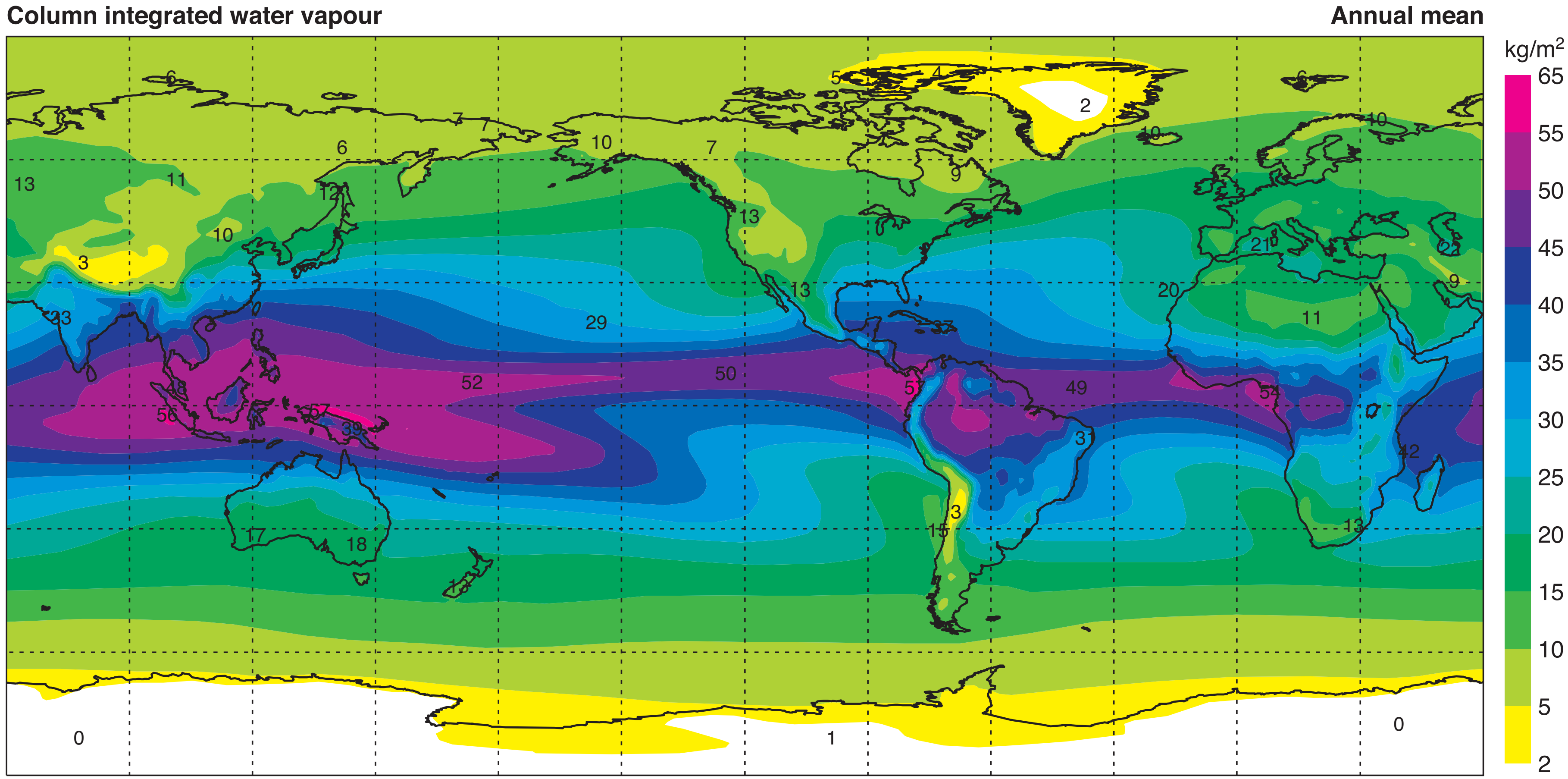
ERA-40 Atlas

- Evaporation minus precipitation field implies **atmospheric moisture transport** from subtropics to both deep tropics and to higher latitudes
- Tropical rainbelts and desert regions are very evident



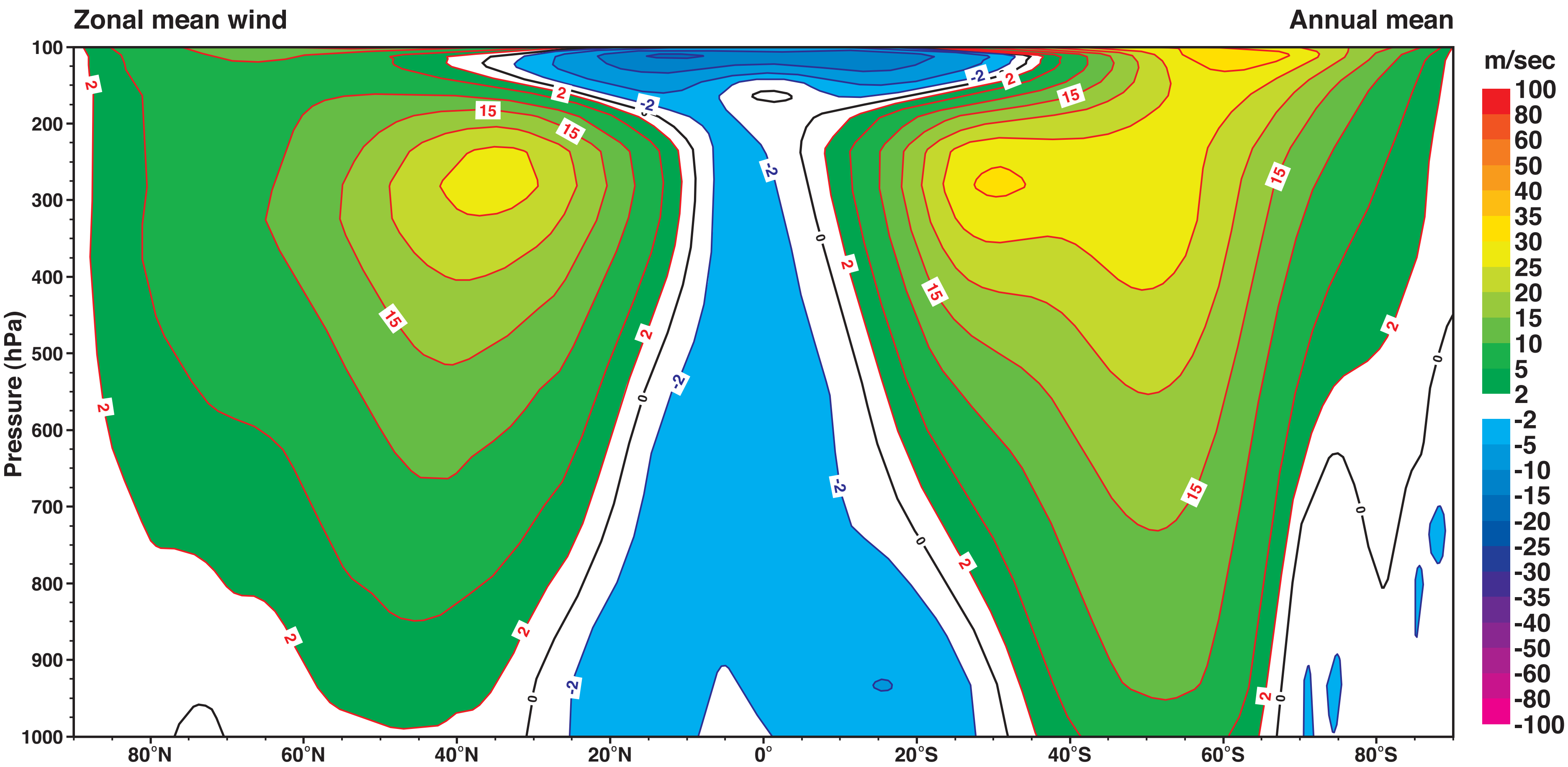
ERA-40 Atlas

- Total atmospheric water vapour content is highest in tropics
- Water vapour transport to tropics is *upgradient*; transport to high latitudes is downgradient



ERA-40 Atlas

- Warm tropics implies **westerly zonal jets in the extratropics**, maximizing around the tropopause: the "jet stream"
- SH has distinct midlatitude jet, with strong surface winds



ERA-40 Atlas

- First-order explanation of the upper-tropospheric subtropical jets comes from **conservation of angular momentum**

$$M = a\cos(\phi)\big(\Omega a\cos(\phi) + u\big)$$

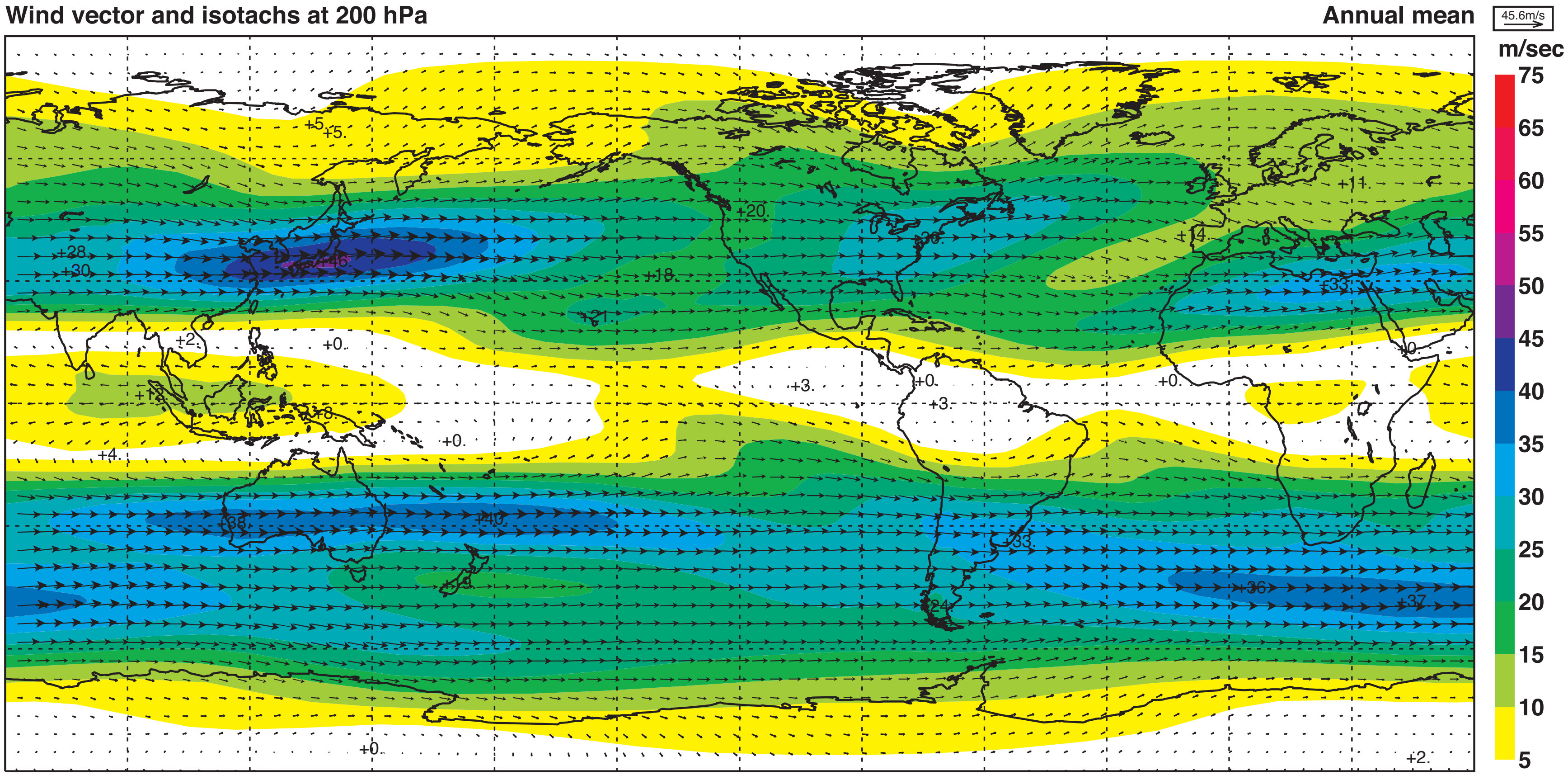
- Upper branch of the Hadley circulation moves air parcels poleward; if they begin with *u = 0* at the equator, then

$$a\cos(\phi)\big(\Omega a\cos(\phi) + u\big) = M(\phi) = M(0) = a^2\Omega$$
$$\Rightarrow u(\phi) = \frac{\Omega a\sin^2(\phi)}{\cos(\phi)}$$

which diverges as $\phi \to \pm\frac{\pi}{2}$

- Physical limit is provided by the equator-to-pole temperature difference; implies a Hadley cell extent of about 30° latitude (Held & Hou 1980)

- There is considerable longitudinal structure to the jet, especially in the NH
- The SH "double jet" consists of distinct structures at different longitudes



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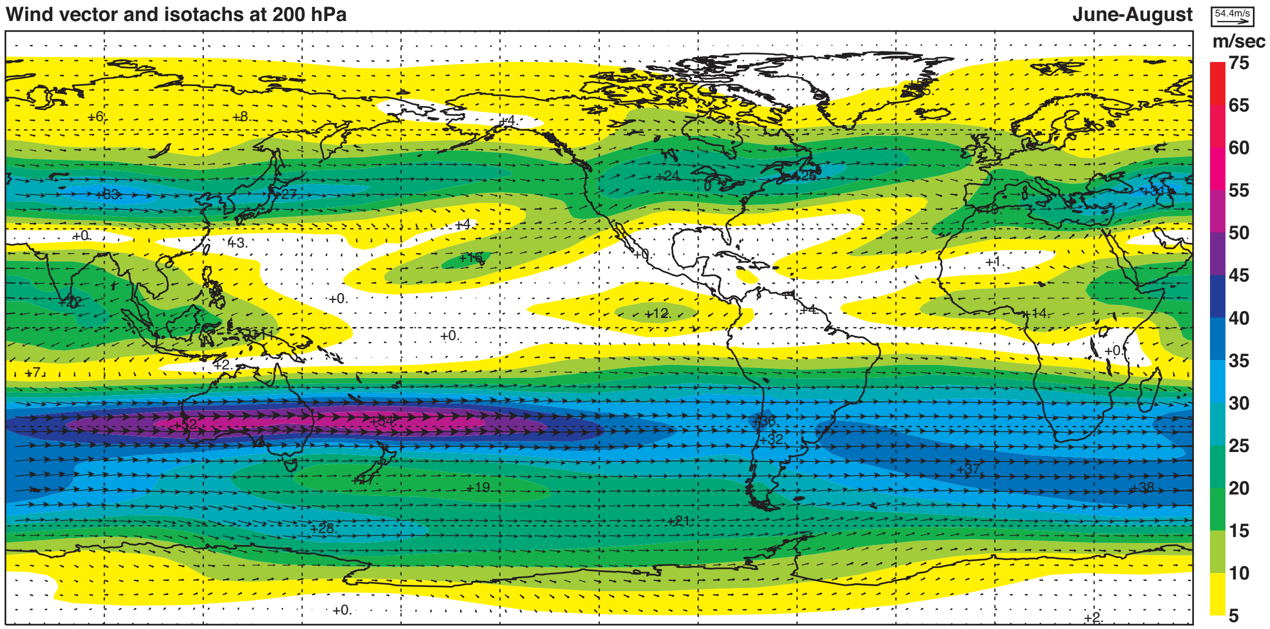
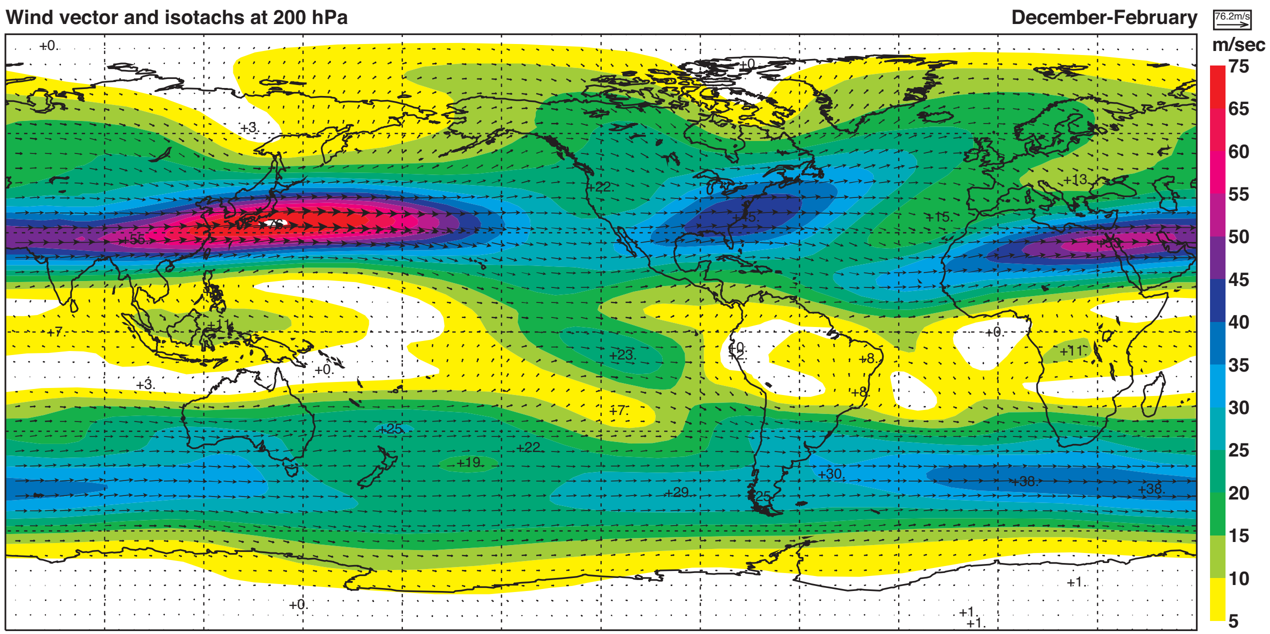
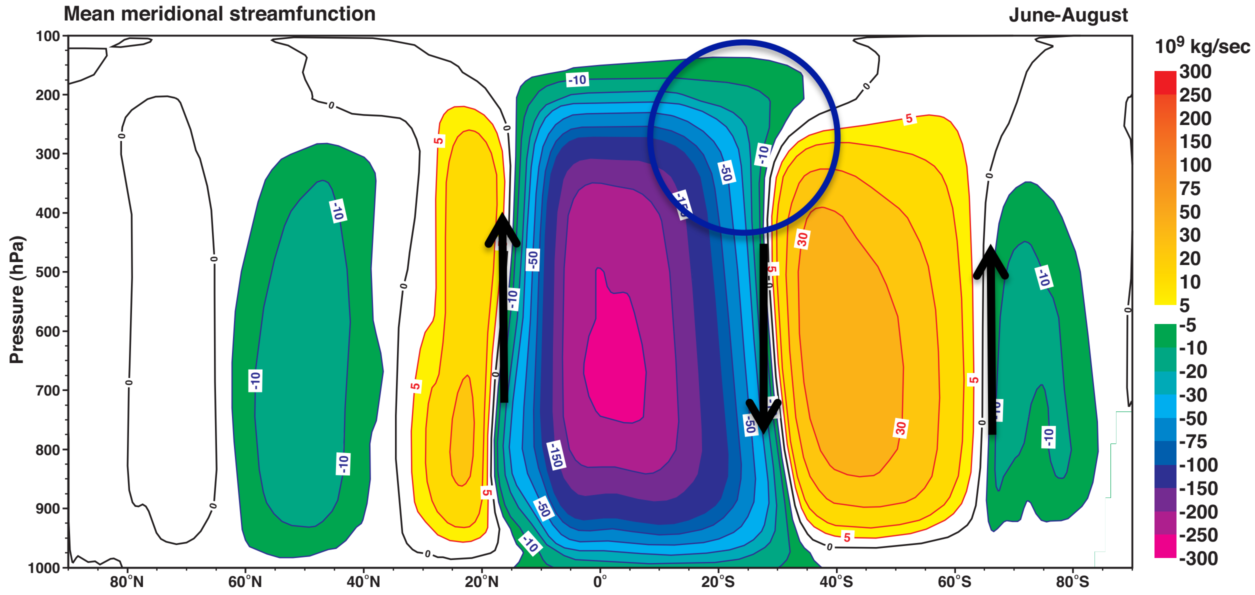
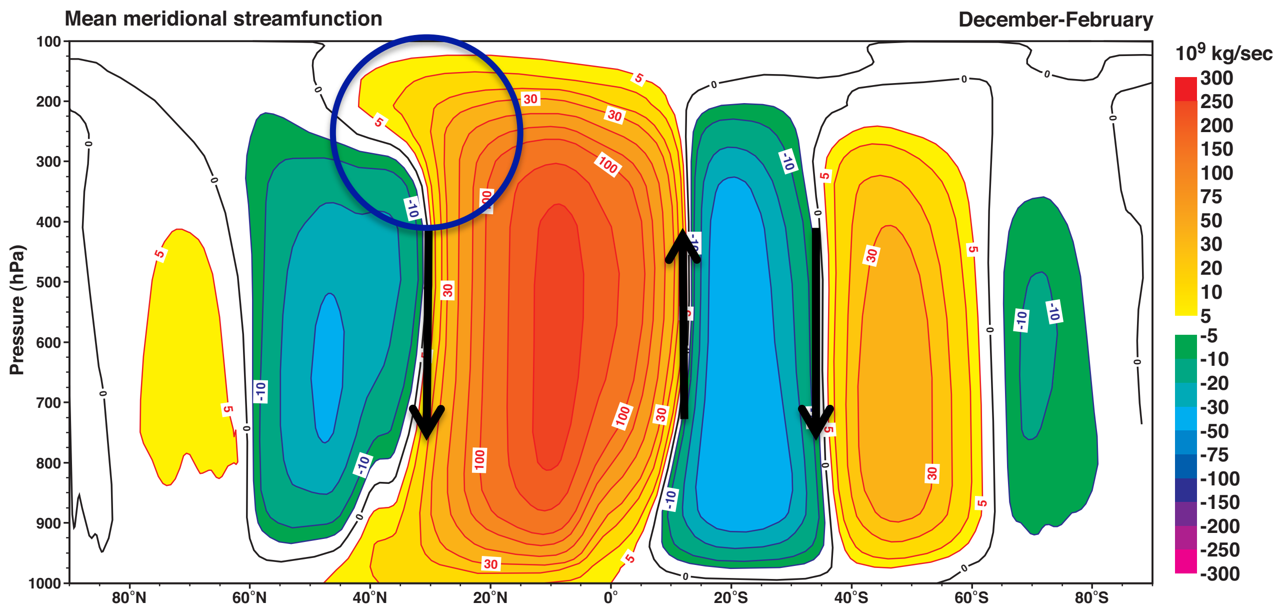




- The jet stream is **strongest by far in the wintertime**
- Wintertime jet is mainly located in subtropics (though with some tendency for poleward extension and split jet)
- Summertime jet **is located at higher latitudes**

ERA-40 Atlas

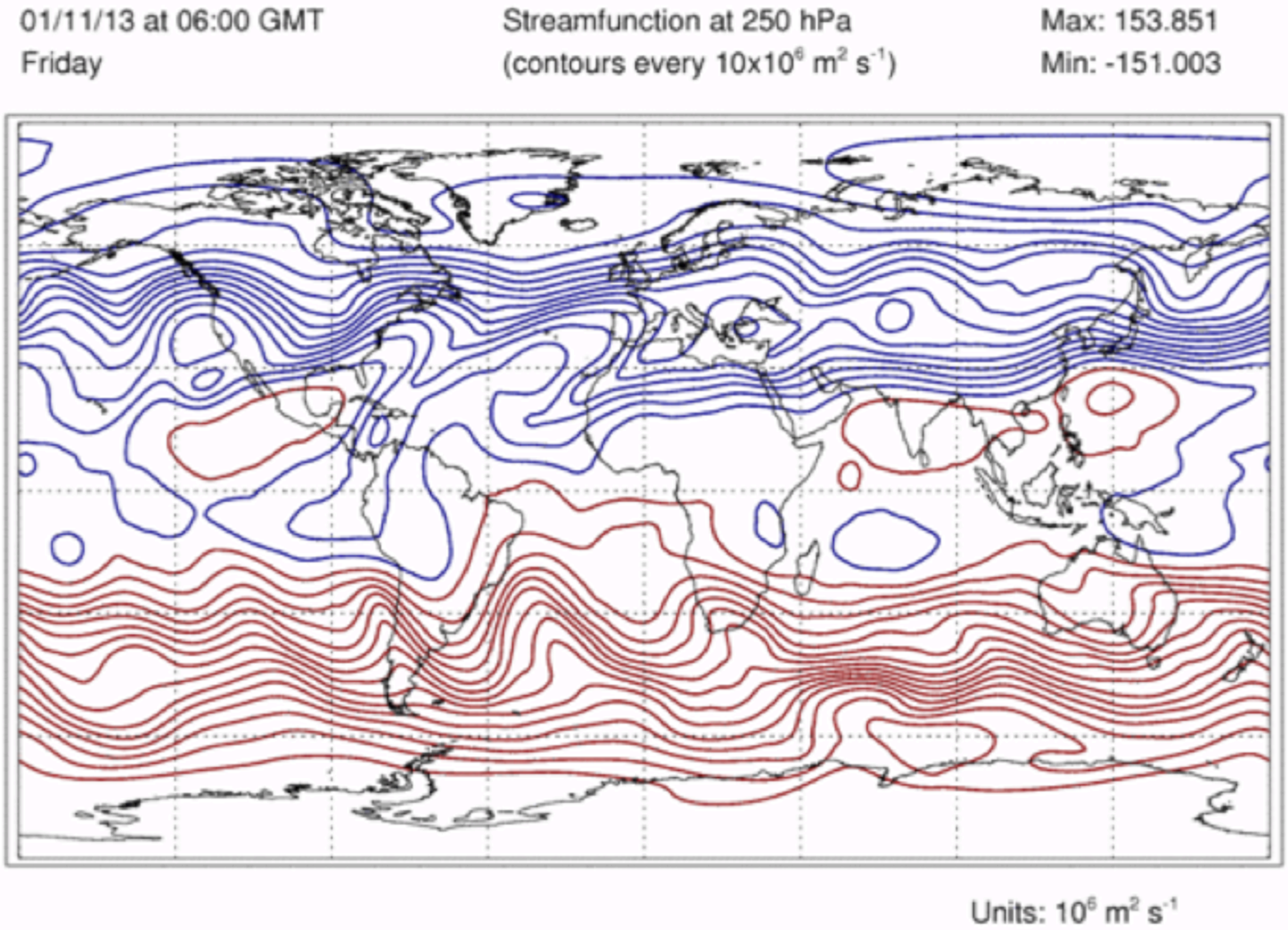


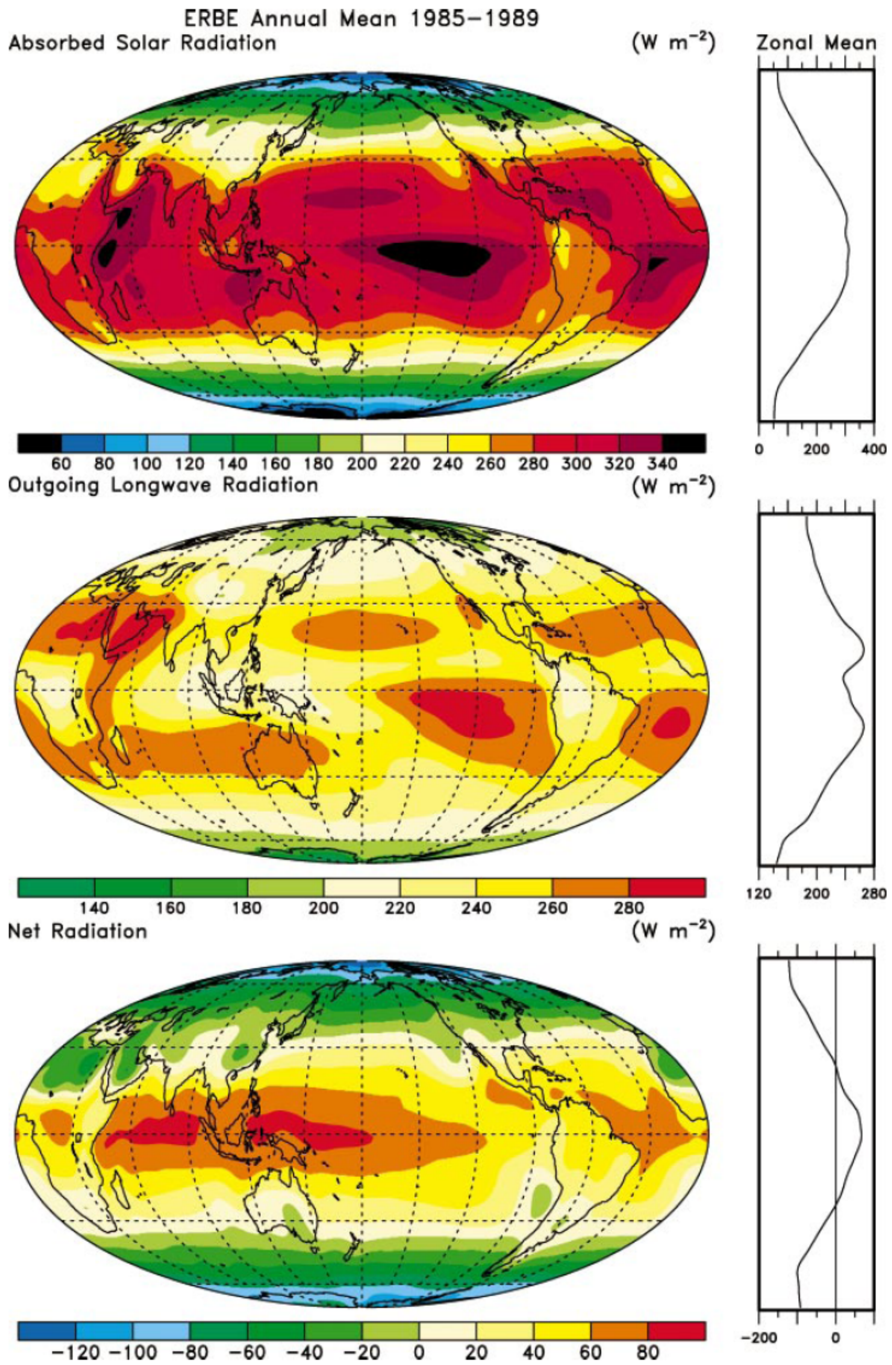


- The strong wintertime subtropical jet is explained by the seasonality of the Hadley circulation
- Tropical ascent occurs on the summer side of the equator, but with the strongest cell extending into the winter hemisphere

ERA-40 Atlas

- The jet exists instantaneously (i.e. doesn't require averaging), but does meander quite a bit
    - ECMWF analysis on a given day (streamfunction)

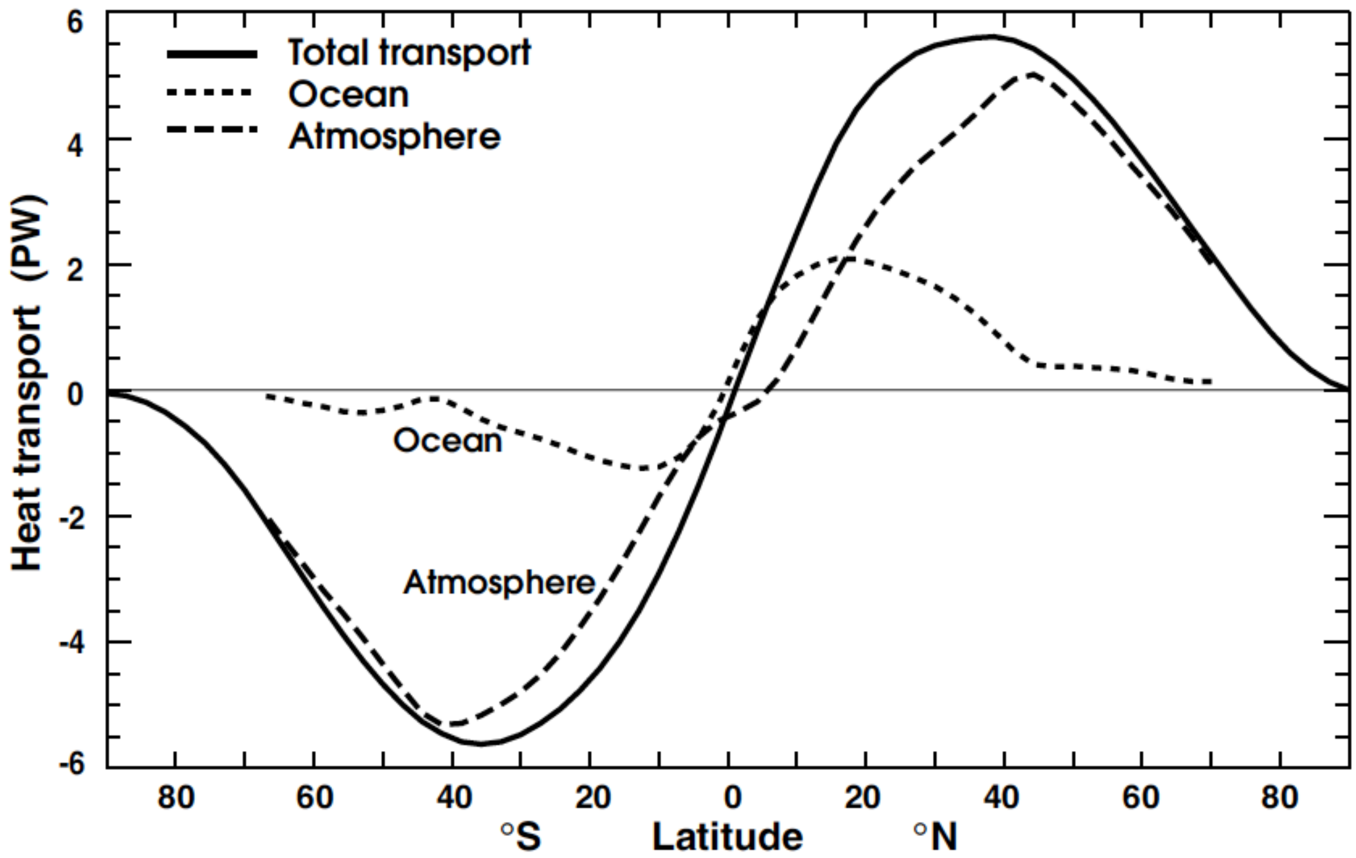




- Annual mean top-of-atmosphere energy budget as observed by satellite (ERBE)
- Net heating of climate system in tropics, net cooling in extratropics
- 2nd law of thermodynamics implies it must be this way!
- Implies **poleward heat transport** by climate system

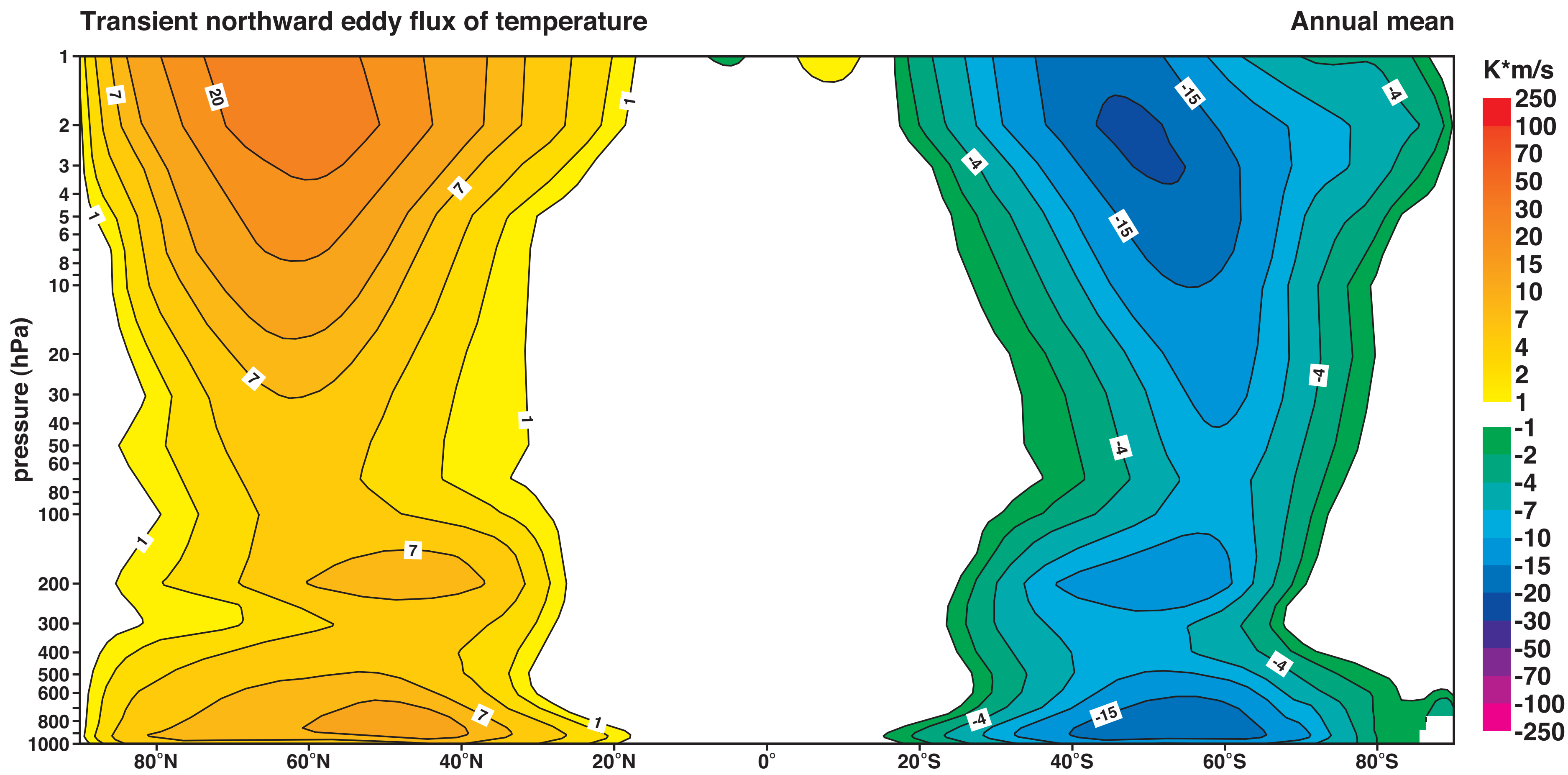
Trenberth & Stepaniak (2003 J. Clim.)

- Poleward energy transport mainly carried by the atmosphere, peaks in midlatitudes
- Despite significant differences in phenomenology between the hemispheres, the **total energy transports are remarkably similar!**



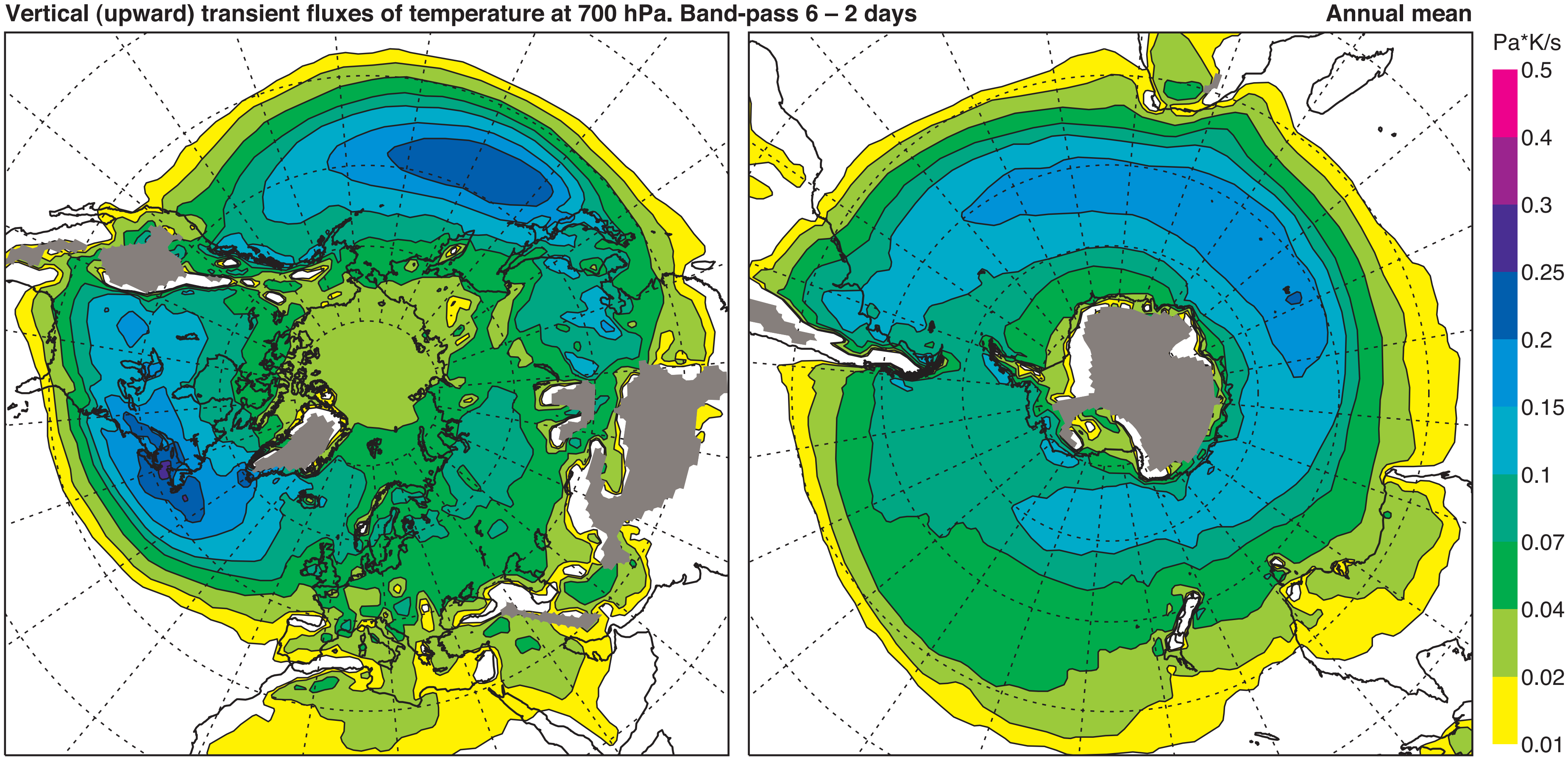
Trenberth & Stepaniak (2004 QJRMS)

- Outside the tropics, the poleward heat flux in the atmosphere is mainly accomplished by “eddies” (**macroturbulence**) arising from baroclinic instability



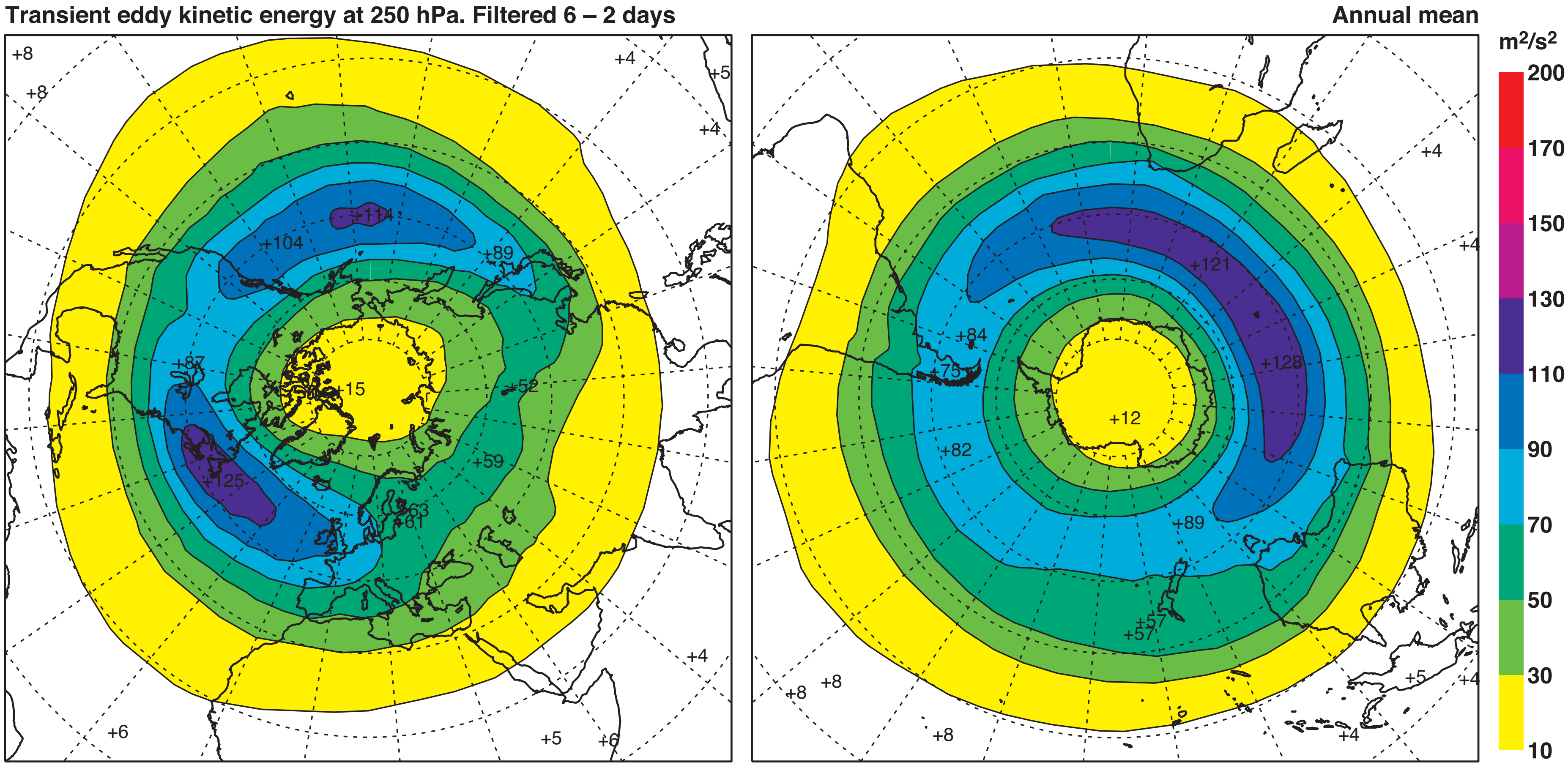
ERA-40 Atlas

- The upper-level jet maxima are associated with maxima in low-level baroclinic storms (the "storm tracks")
    - Makes sense since vertical shear implies baroclinicity
- Exception is the SH jet over Australia, which is subtropical



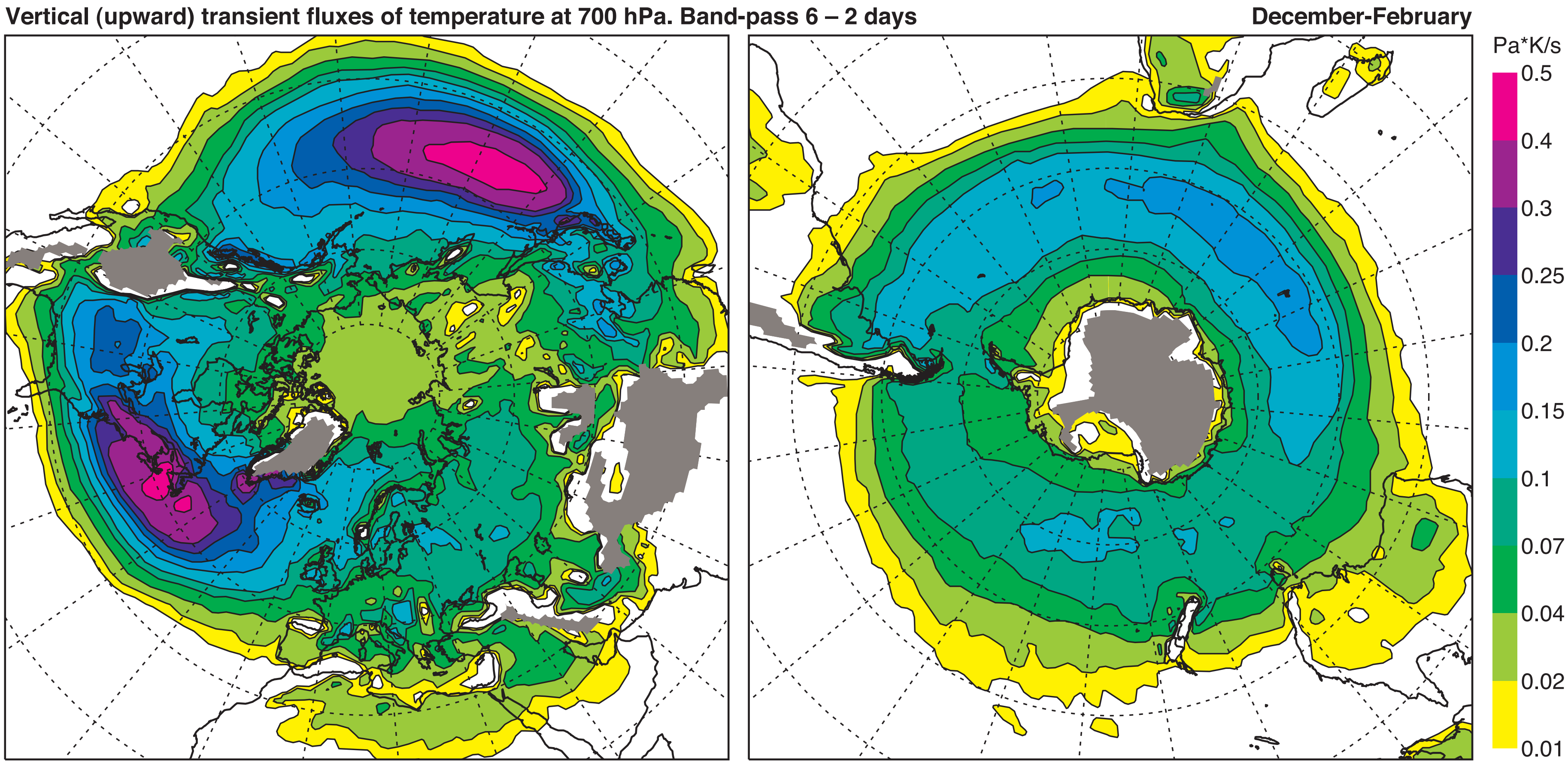
ERA-40 Atlas

- Storm tracks strongest over ocean
- Especially in the North Atlantic, there is a distinct poleward downstream tilt



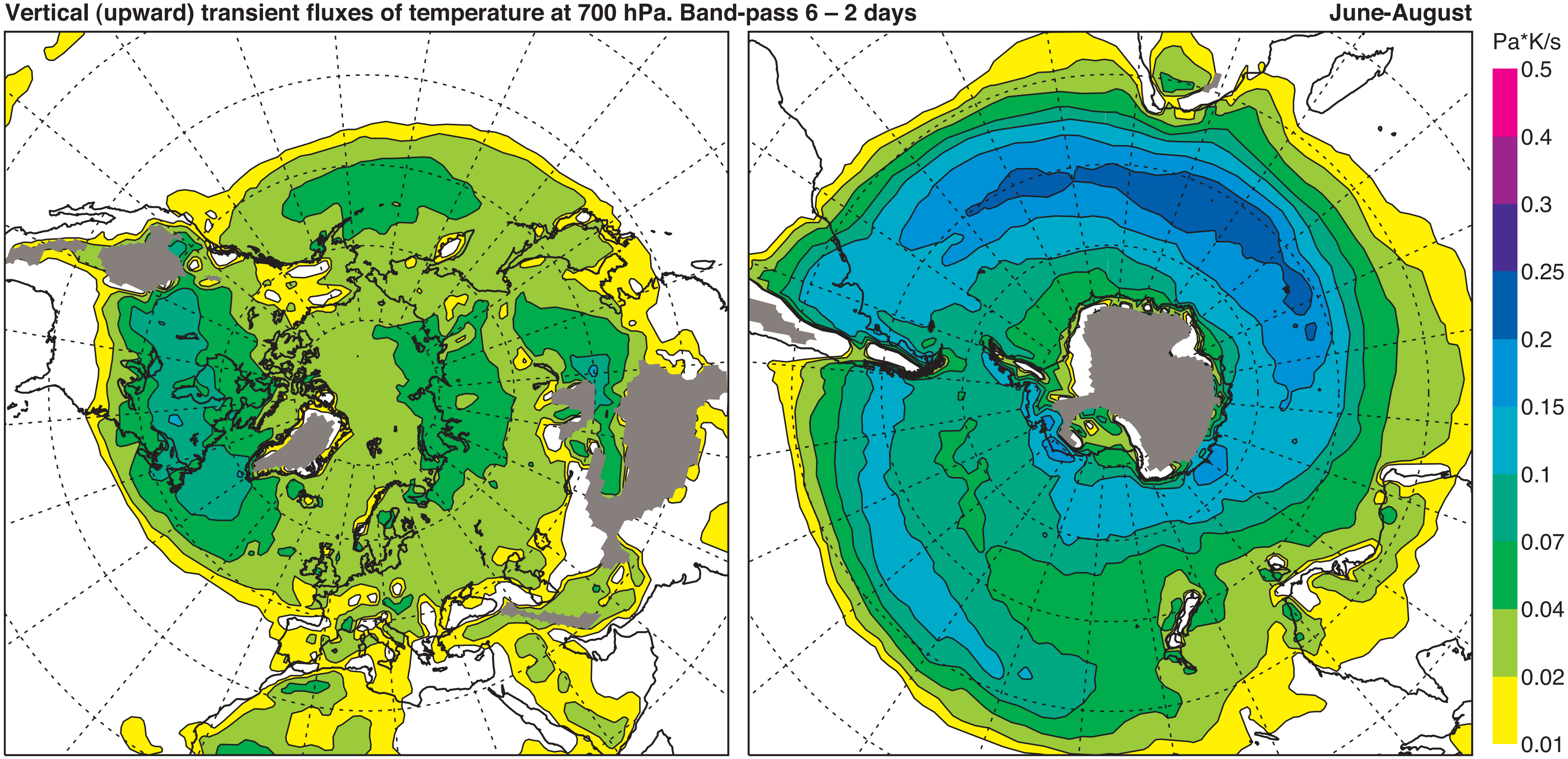
ERA-40 Atlas

- There is a strong seasonal cycle to the storm track intensity, maximizing in the winter season (here for NH, on left)



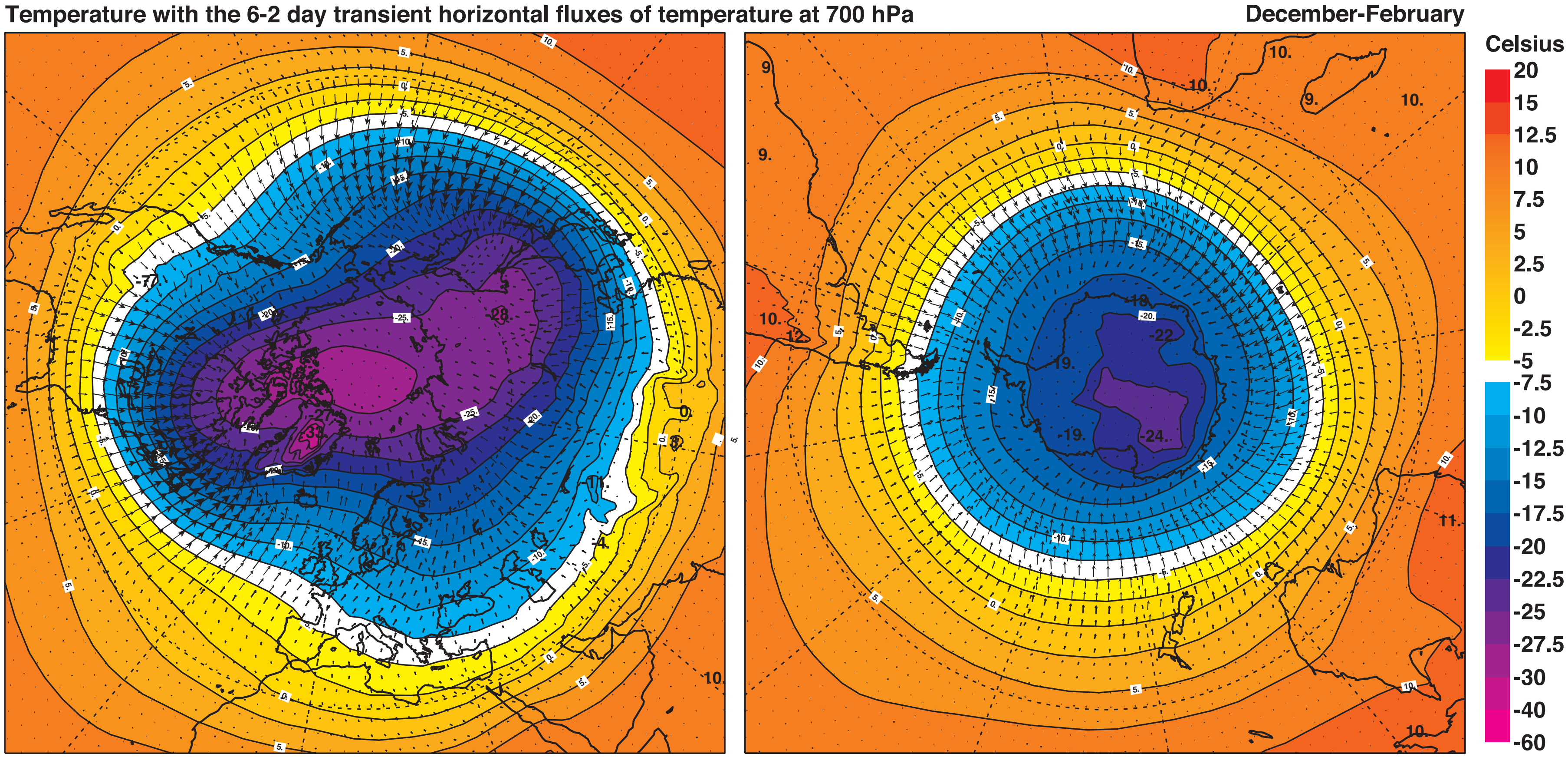
ERA-40 Atlas

- Contrast the previous picture with this one for northern summer/southern winter



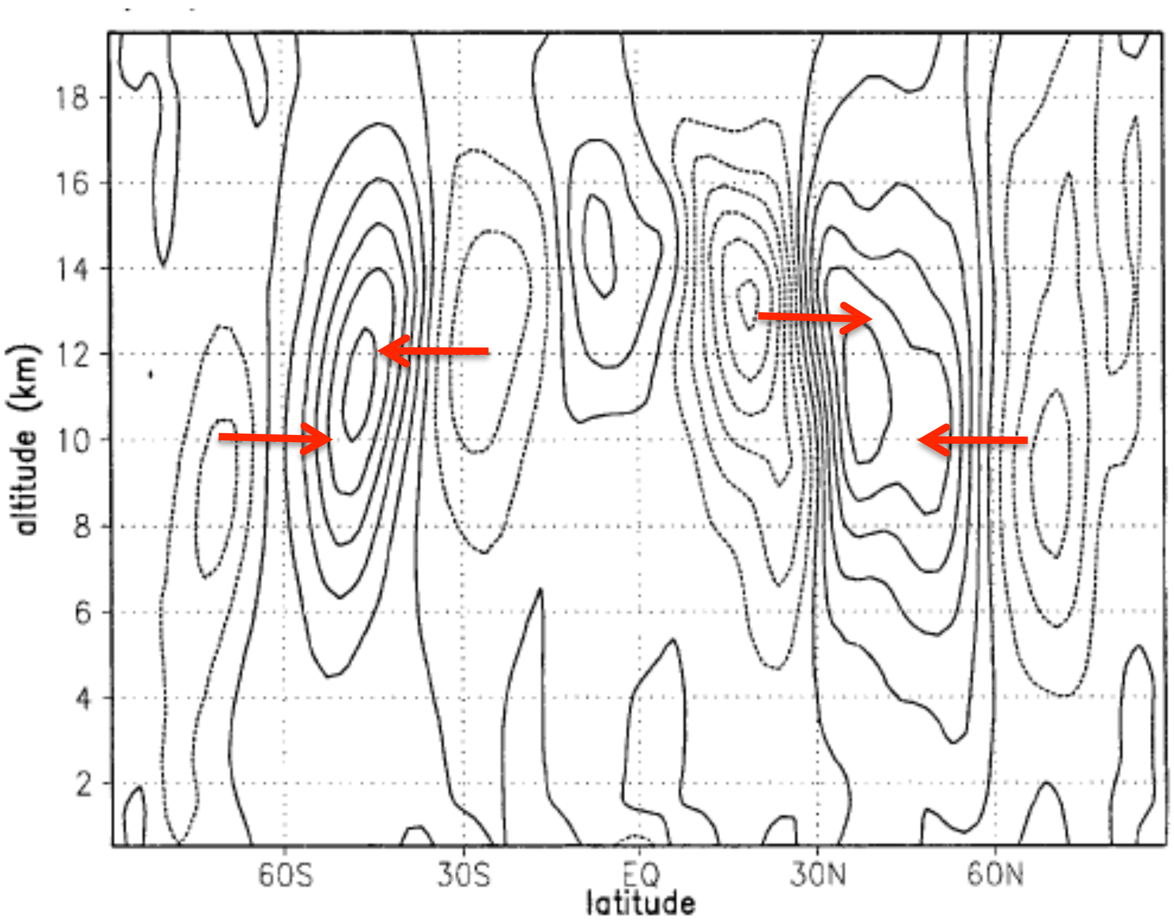
ERA-40 Atlas

- The NH wintertime storm tracks over the western Pacific and western Atlantic are also evident in 2-6 day lower tropospheric (700 hPa) meridional heat fluxes (arrows), and are co-located with the strongest meridional temperature gradients (contours)



ERA-40 Atlas

- A key aspect of the atmospheric circulation is the structure of the **eddy zonal momentum fluxes**
  - Responsible for "maintenance of the westerlies"
  - Linked to surface winds through momentum balance



Observed horizontal eddy momentum flux convergence for January

Boehm & Lee (2003 JAS)

- **Angular momentum budget** (overbar is zonal average):

$$\frac{\partial}{\partial t}\overline{\int_0^{p_s} a\cos\phi u \frac{dp}{g}} - fa\cos\phi\overline{\int_0^{p_s} v\frac{dp}{g}} =$$

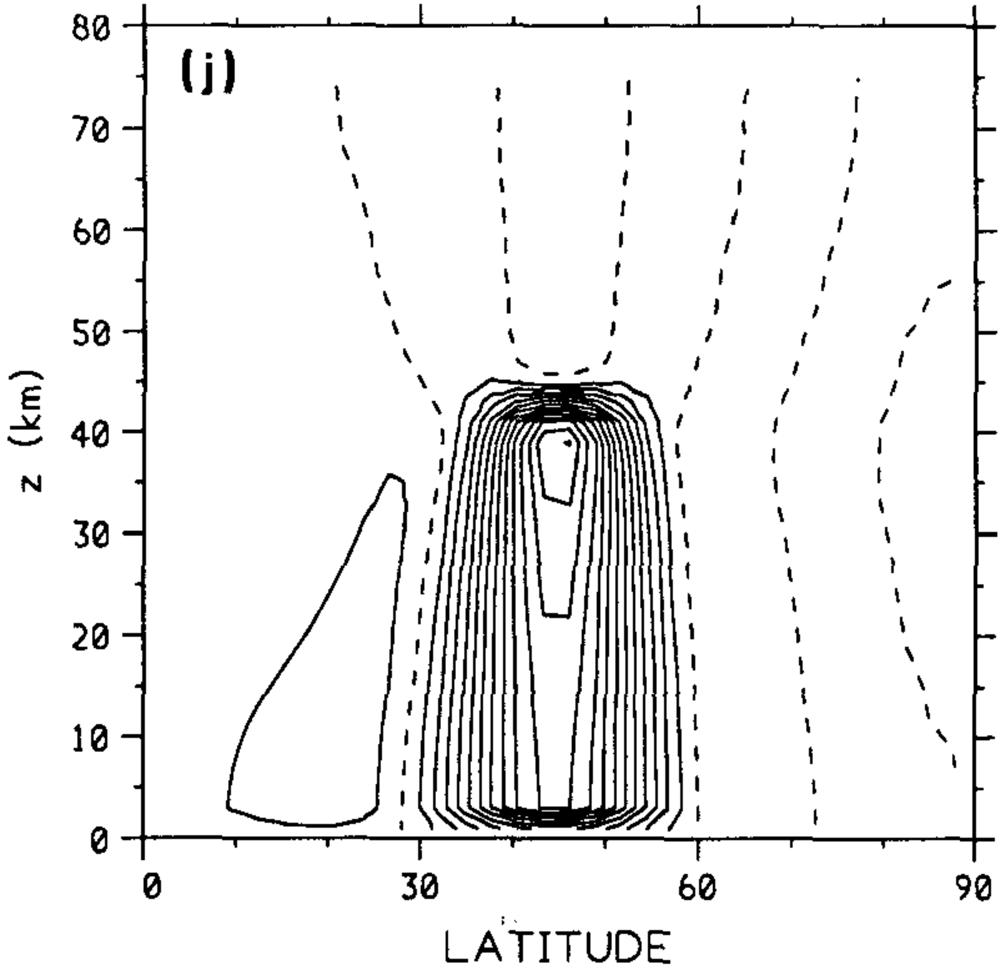
$$-\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\overline{\int_0^{p_s} a\cos\phi uv\frac{dp}{g}}\right) - \overline{p_s\frac{\partial h}{\partial\lambda}} - a\cos\phi\overline{\tau_s^{SGO}} - a\cos\phi\overline{\tau_s^{PBL}}$$

so in steady state,

$$-\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\cos\phi\overline{\int_0^{p_s} a\cos\phi uv\frac{dp}{g}}\right) = \overline{p_s\frac{\partial h}{\partial\lambda}} + a\cos\phi\overline{\tau_s^{SGO}} + a\cos\phi\overline{\tau_s^{PBL}}$$

- Terms on the RHS (resolved mountain torque and parameterized surface stresses) tend to act as a drag against the surface flow
- Leads to picture of surface drag balancing angular momentum fluxes in free atmosphere

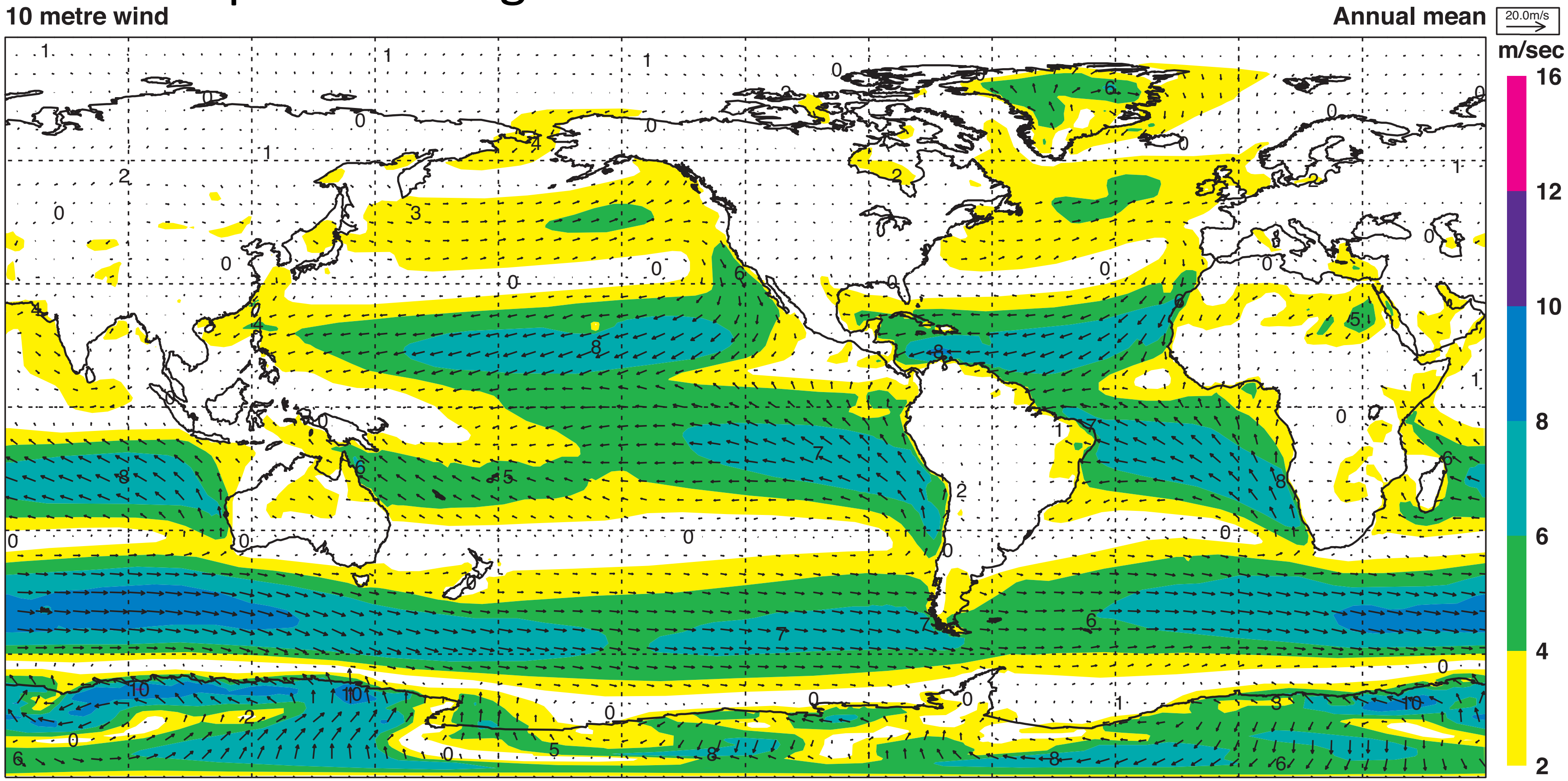
- **The large-scale dynamics view:** the surface flow is passive, and provides the drag required to balance the angular momentum fluxes (as assumed in "downward control")



Mean meridional circulation (stream function) response to an imposed torque in the free atmosphere, with a relaxational surface drag (and Newtonian cooling)

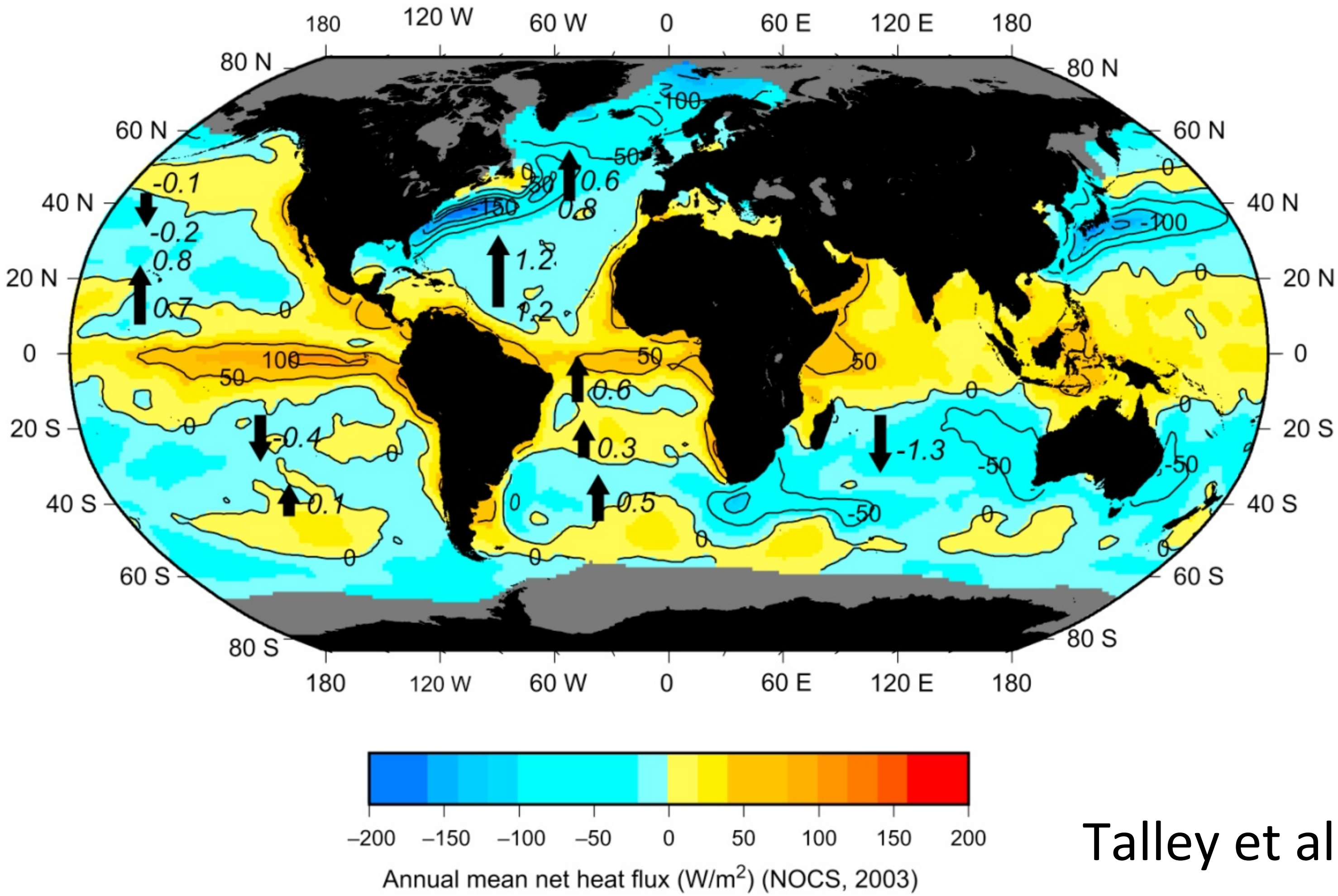
Haynes et al. (1991 JAS)

- Surface winds are easterly in the tropics (the “trade winds”), and westerly in midlatitudes: consistent with poleward momentum flux
- Very strong surface westerlies over the Southern Ocean
  - Important for global climate

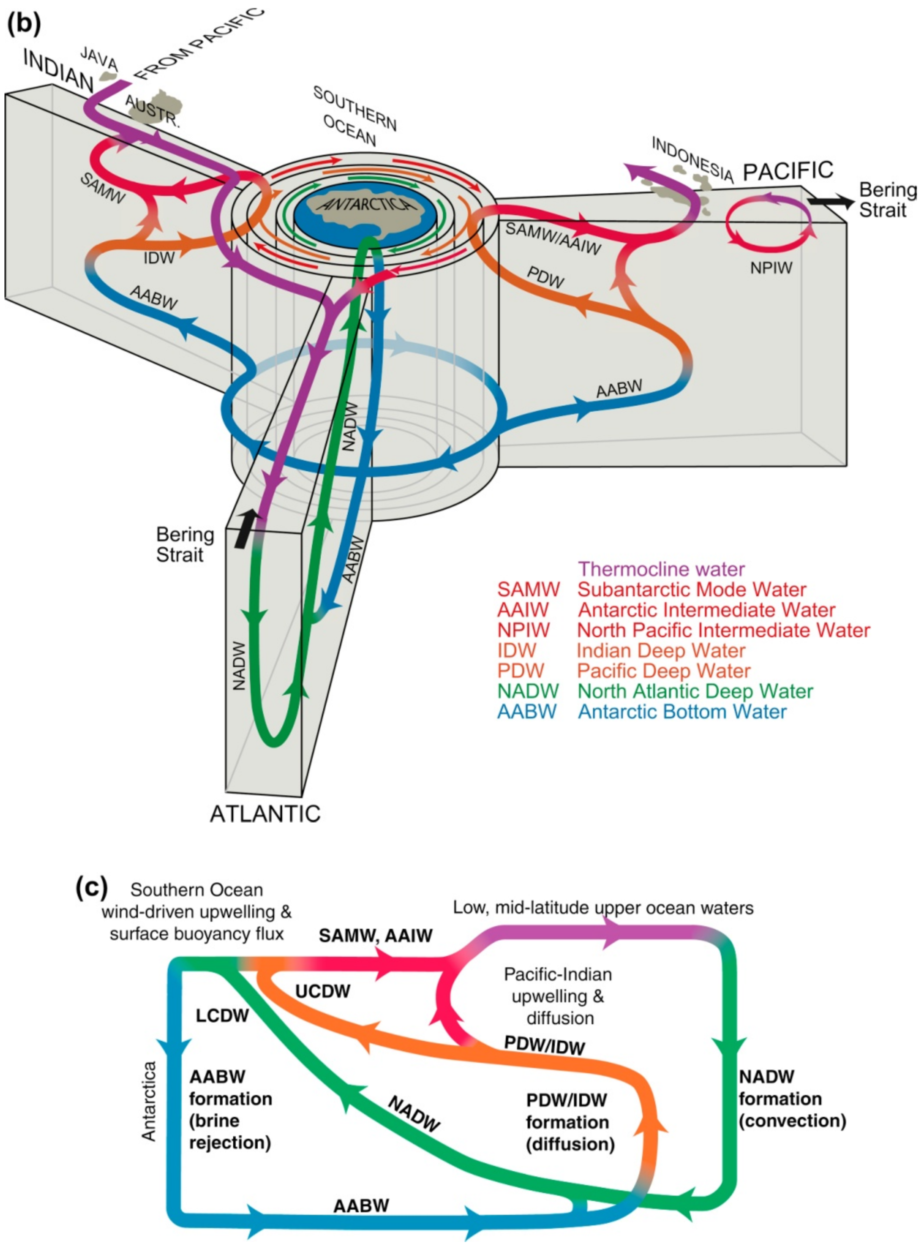


ERA-40 Atlas

- Strong heat flux from ocean to atmosphere over warm Gulf Stream and Kuroshio (wind-driven western boundary currents)
- Strong heat flux from atmosphere to ocean over equatorial cold tongues (wind-driven equatorial ocean upwelling)

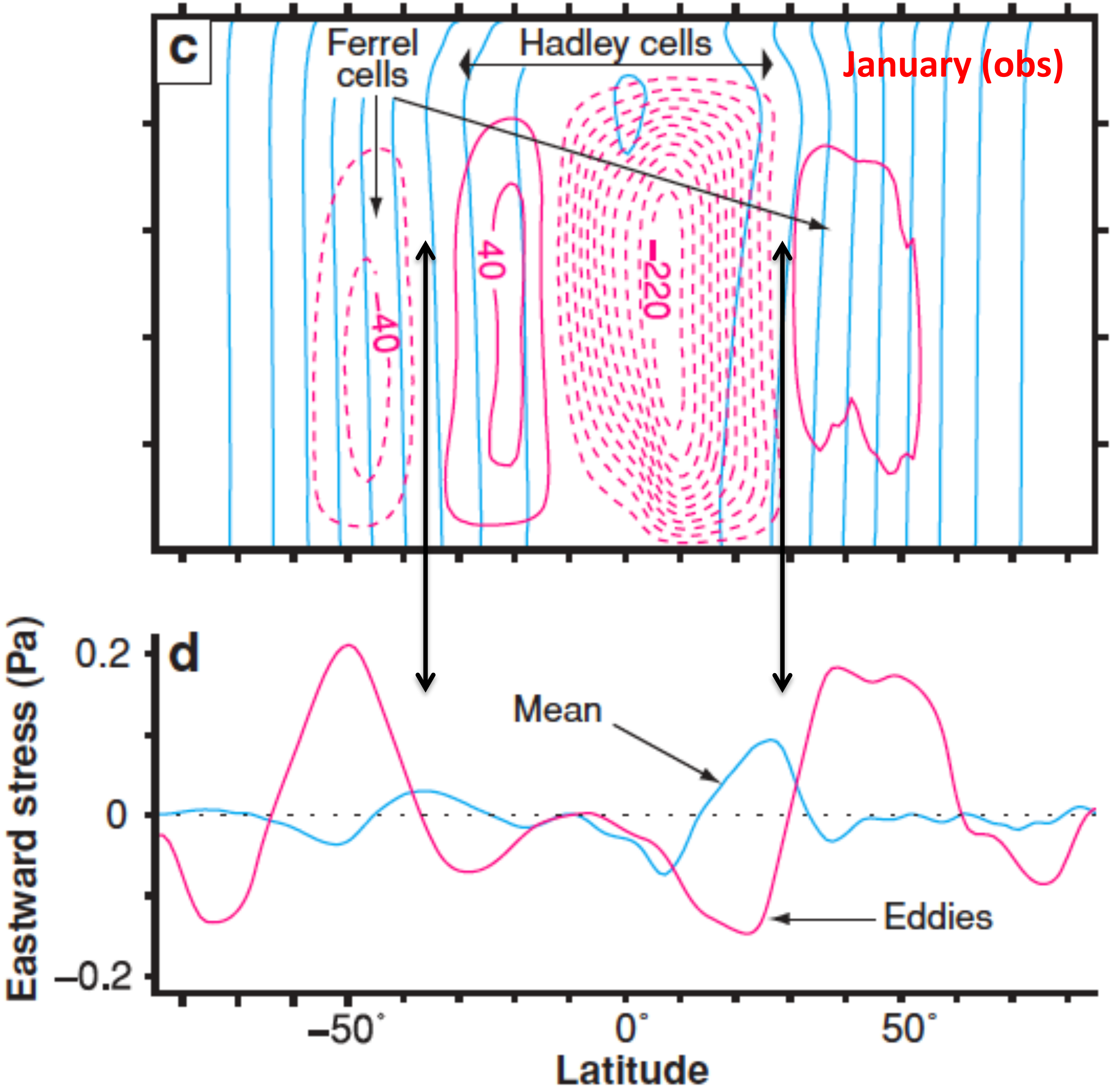


Talley et al. (2011)



- The Antarctic Circumpolar Current (ACC) is like a giant coastal upwelling current
- Westerly surface wind implies northward oceanic Ekman transport, requires upwelling
- Drives the upwelling branches of the oceanic thermohaline circulation (THC), drawing up NADW, PDW and IDW
- Very important for global ocean heat and carbon uptake

Talley et al. (2011)



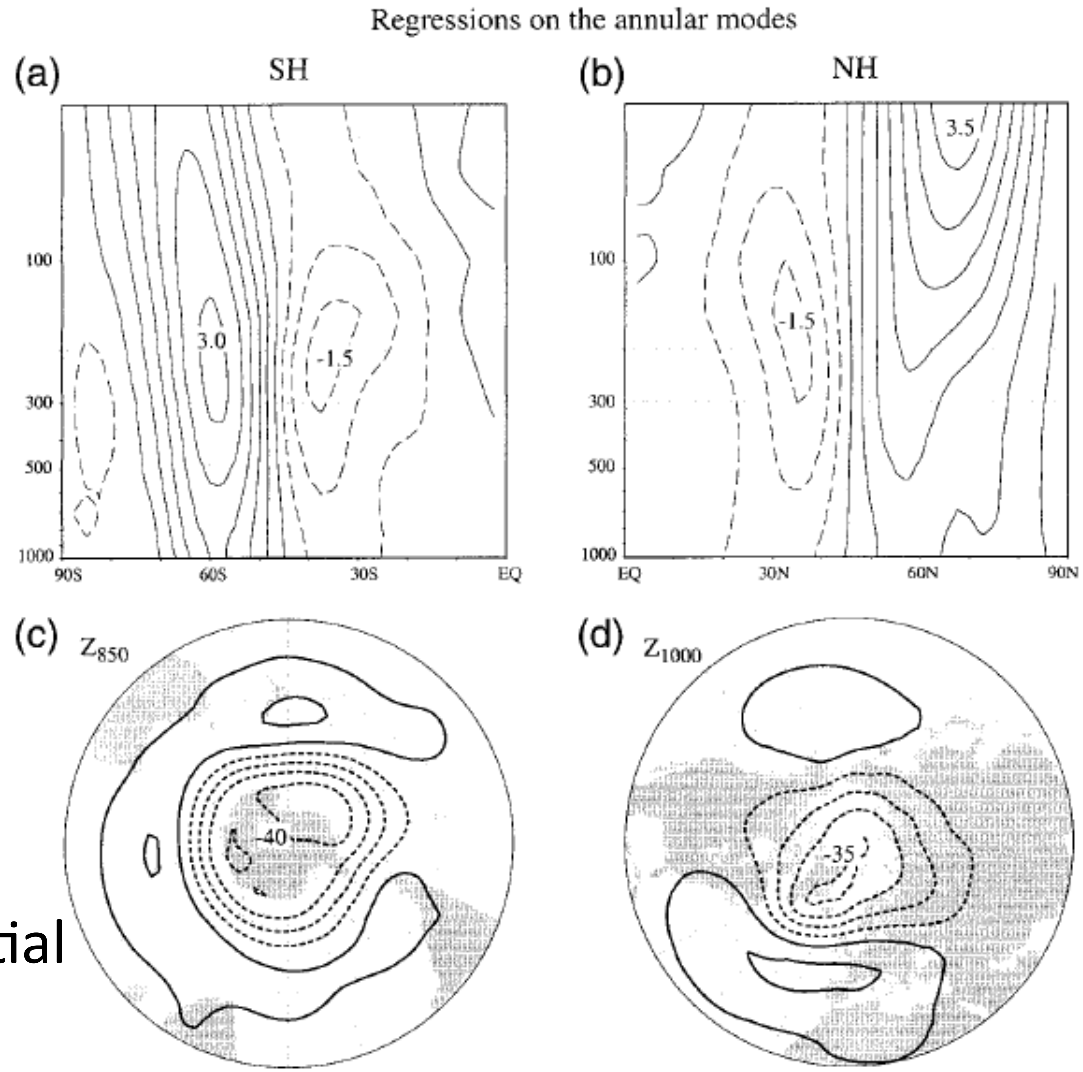
- Observations show Hadley cell (red) crosses angular momentum contours (blue)
- Hence **Hadley cell terminus is determined by momentum flux convergence**

Schneider (2006 AREPS)

- In both hemispheres, the **midlatitude jet exhibits variability corresponding to meridional shifts**: in the NH, the effect is strongest over the North Atlantic

Zonal wind

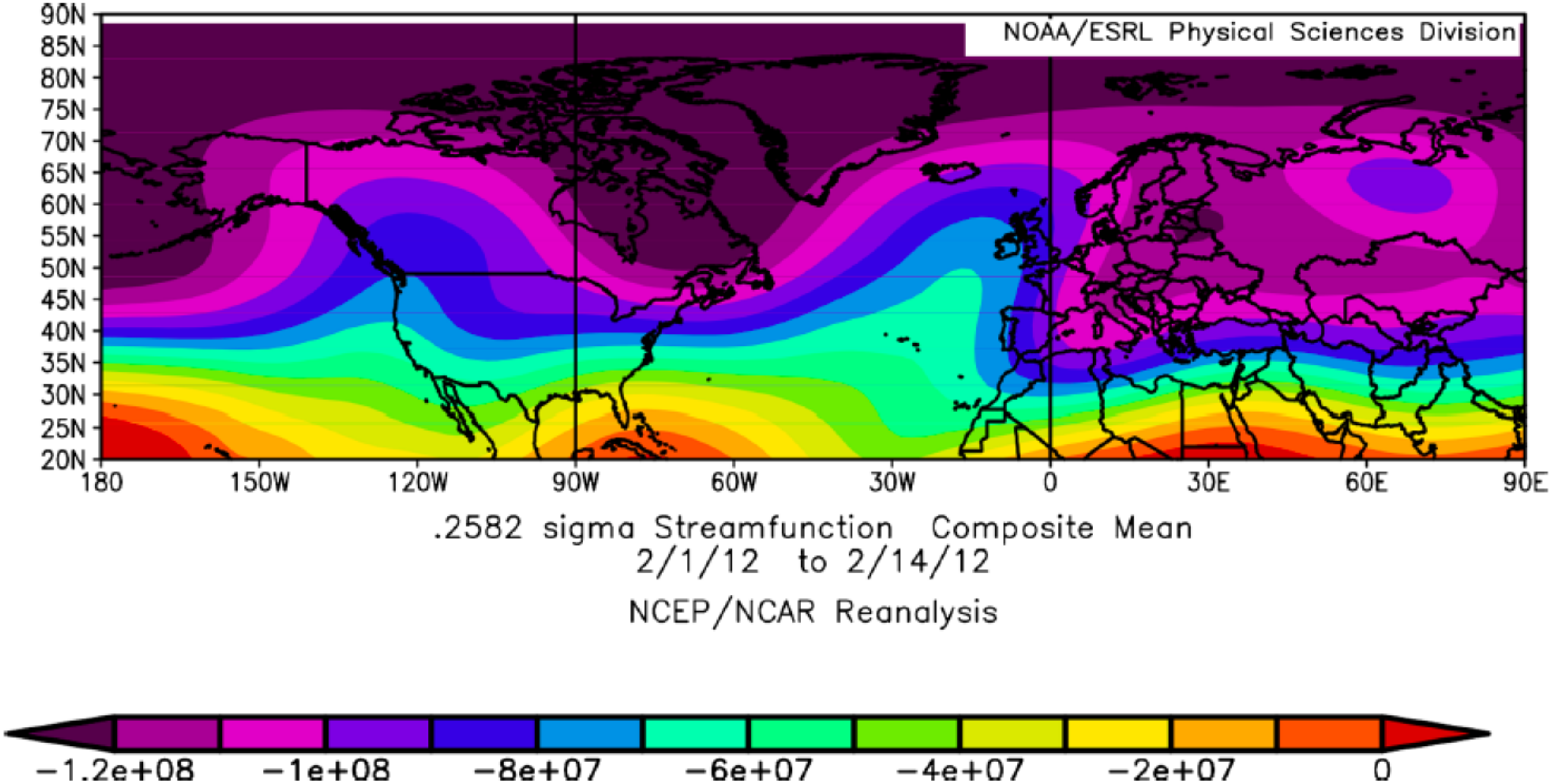
Surface geopotential



Southern and Northern Hemisphere “annular modes” (SAM and NAM), based on hemispheric EOFs

Thompson & Wallace (2000 J. Clim.)

- In the NH, the jet can become "blocked" in quasi-stationary coherent structures, which are generally associated with extreme temperature conditions
- There is no accepted theory for this!



Hoskins & Woollings (2015 Curr. Clim. Change Rep.)