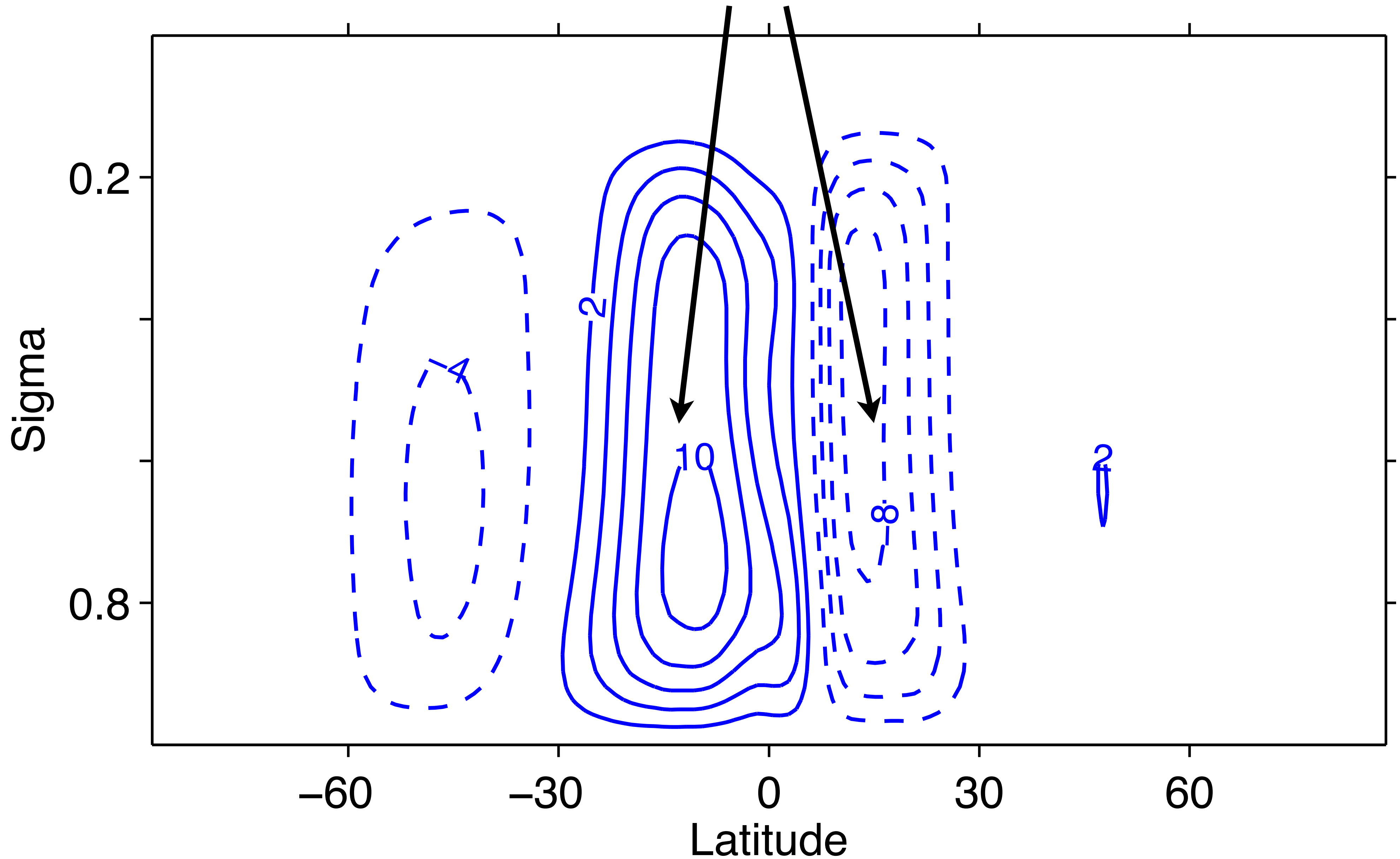
12.810 Dynamics of the Atmosphere

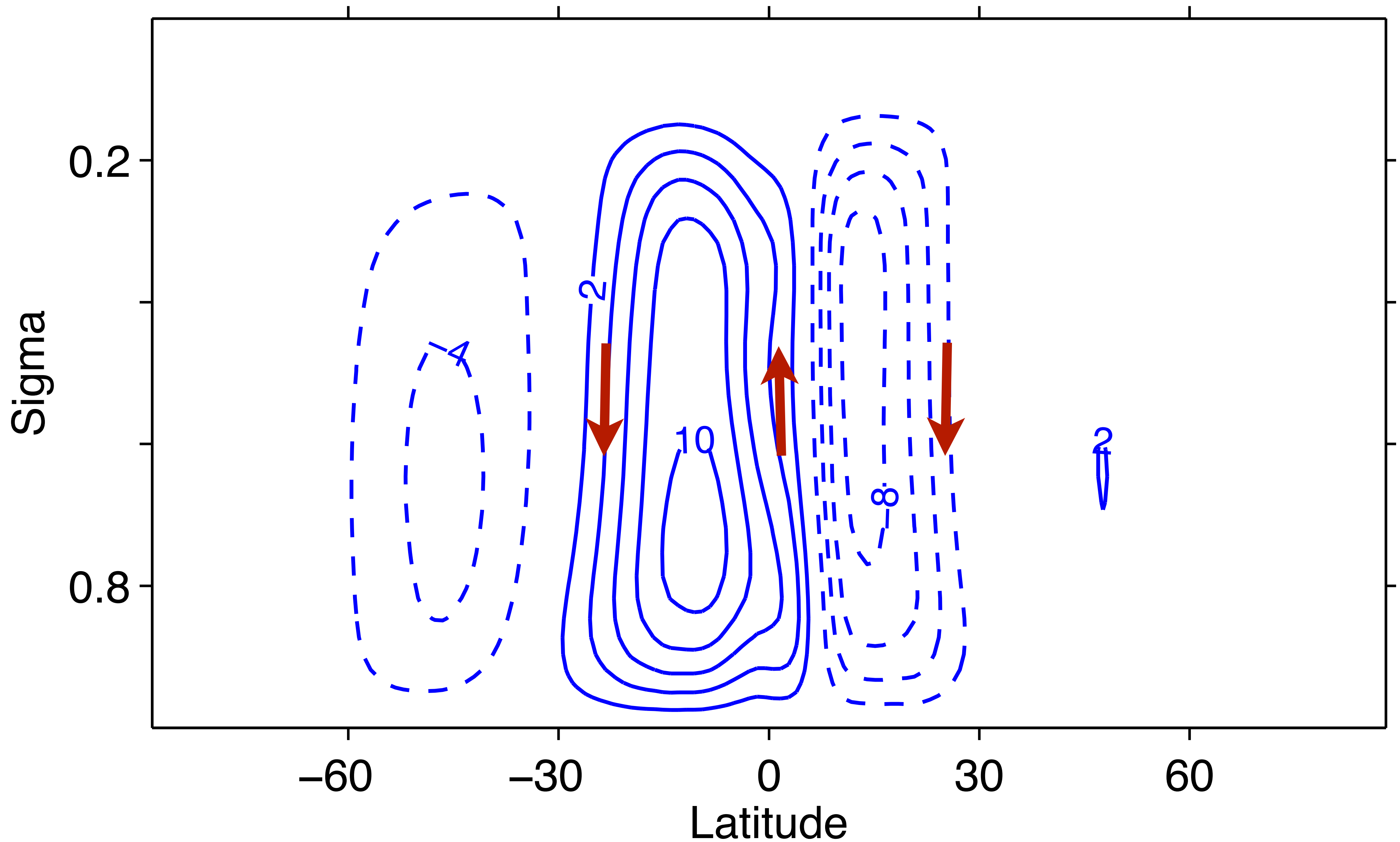
Hadley cells and zonally symmetric circulations

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

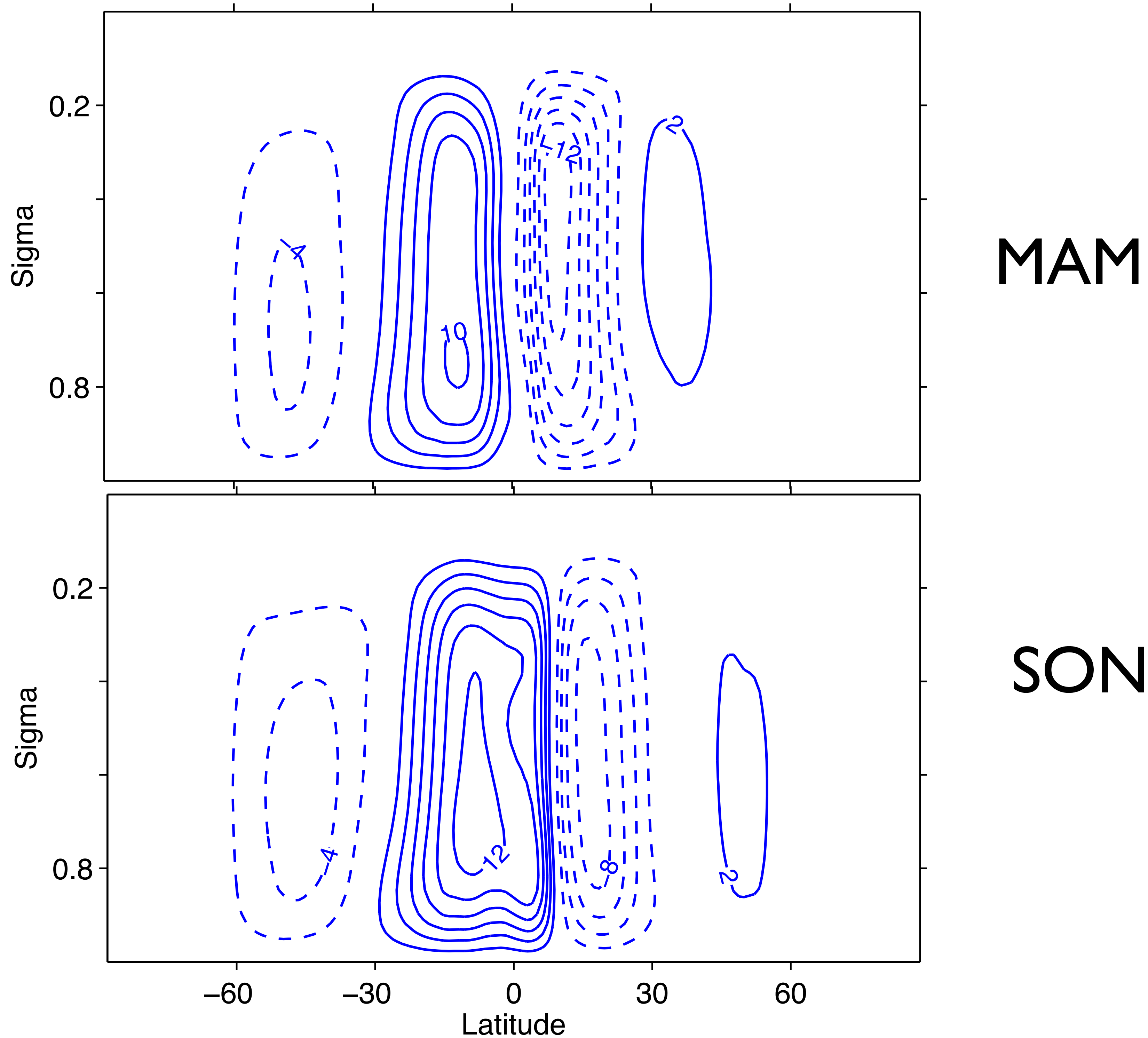
Hadley cells: key for determining precipitation in the tropics and subtropics



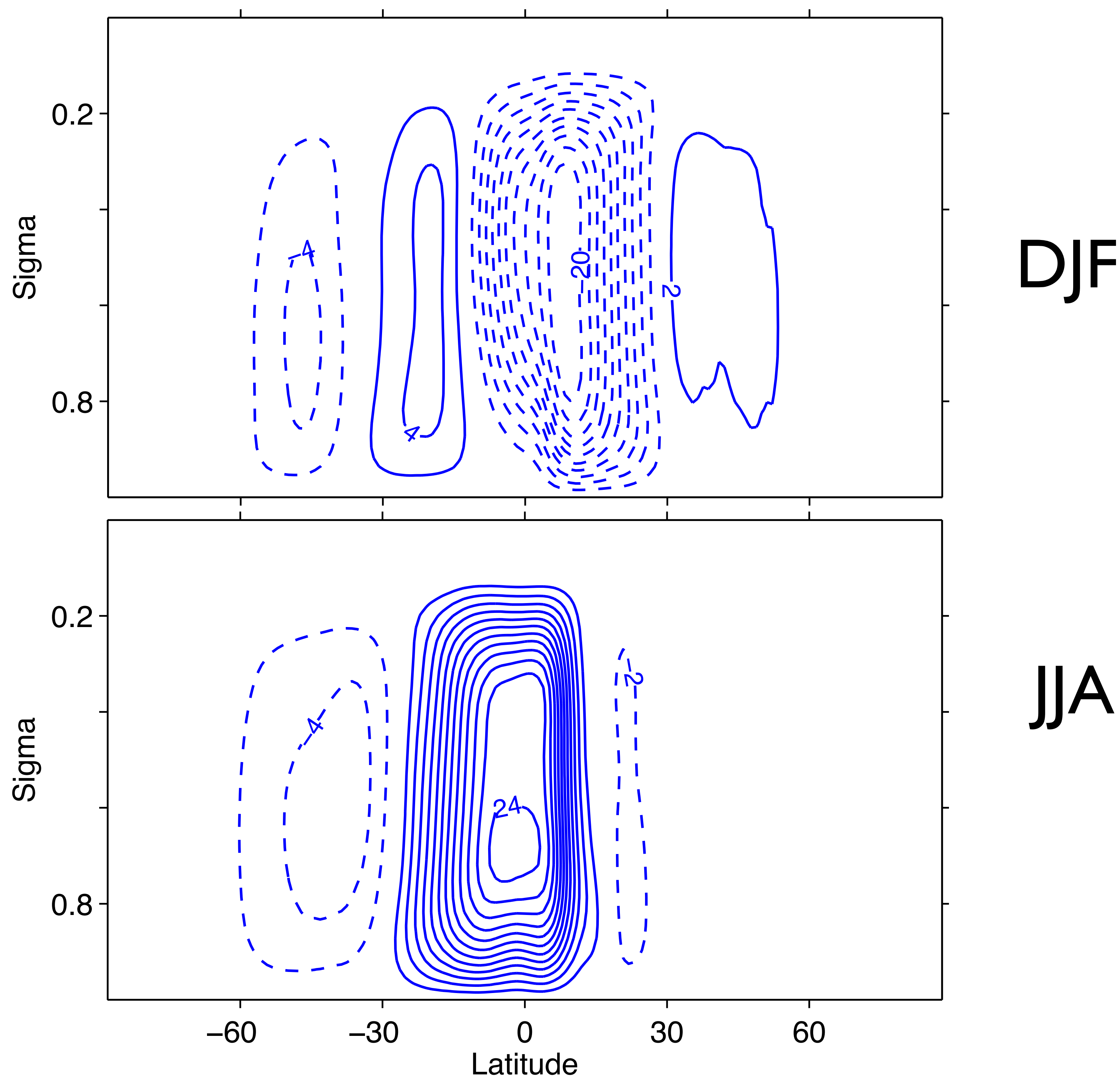
Mean meridional streamfunction (10^{10} kg s^{-1}) (annual mean)



Mean meridional streamfunction (10^{10} kg s^{-1}): different seasons

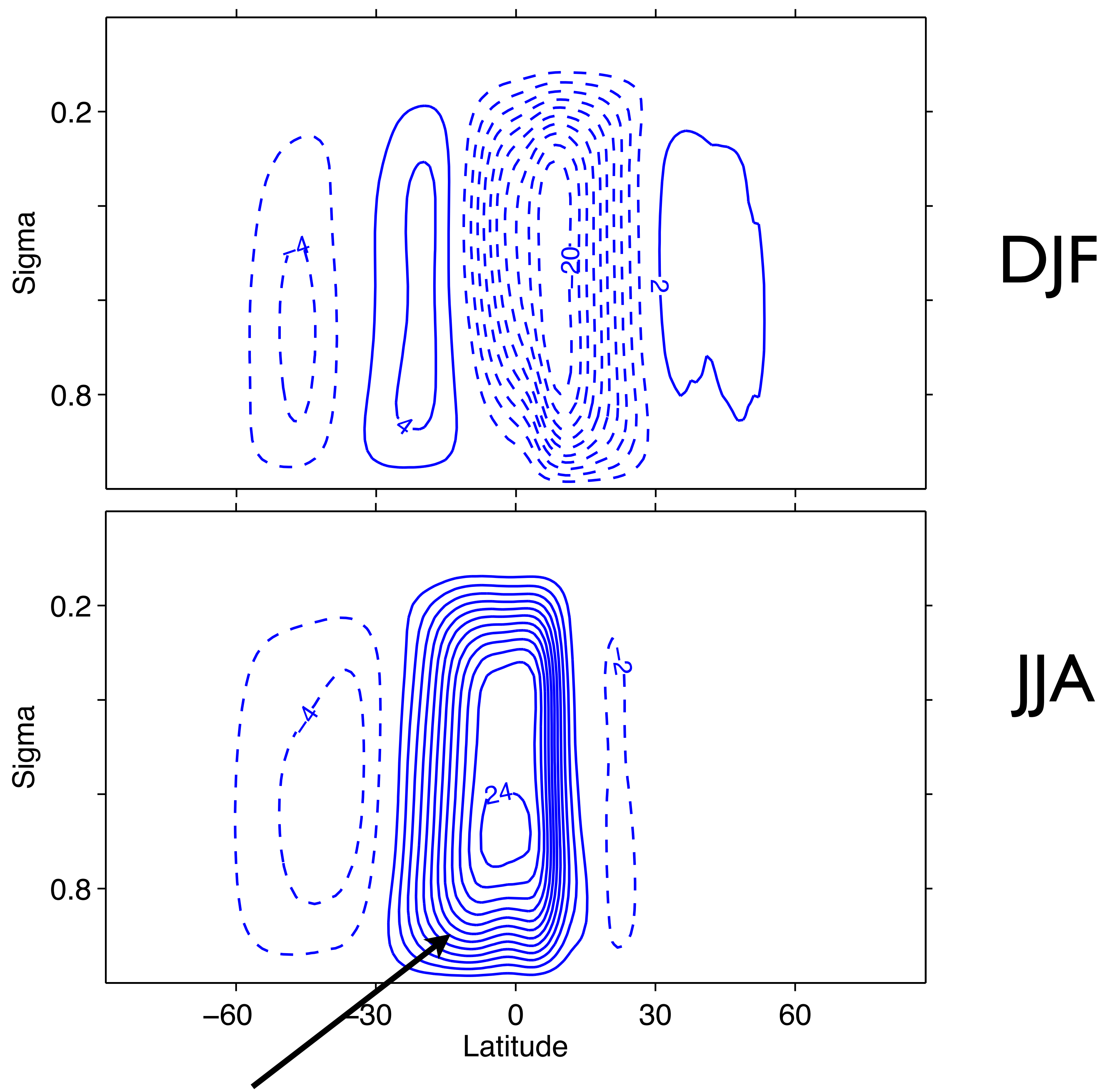


Mean meridional streamfunction (10^{10} kg s^{-1}): different seasons



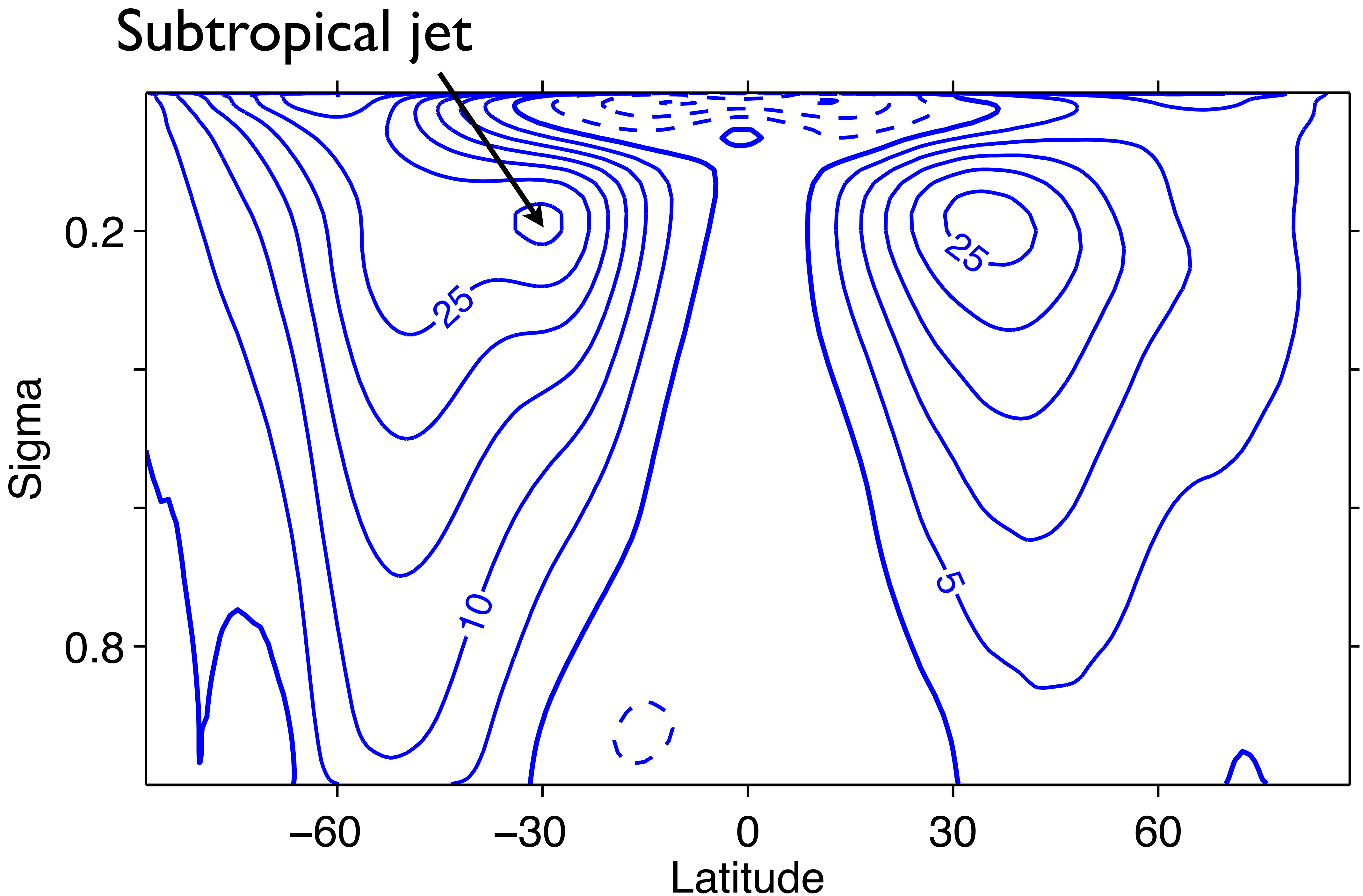
Basic aspects we would like to understand about the tropical atmosphere

Mean meridional streamfunction (10^{10} kg s^{-1}): different seasons

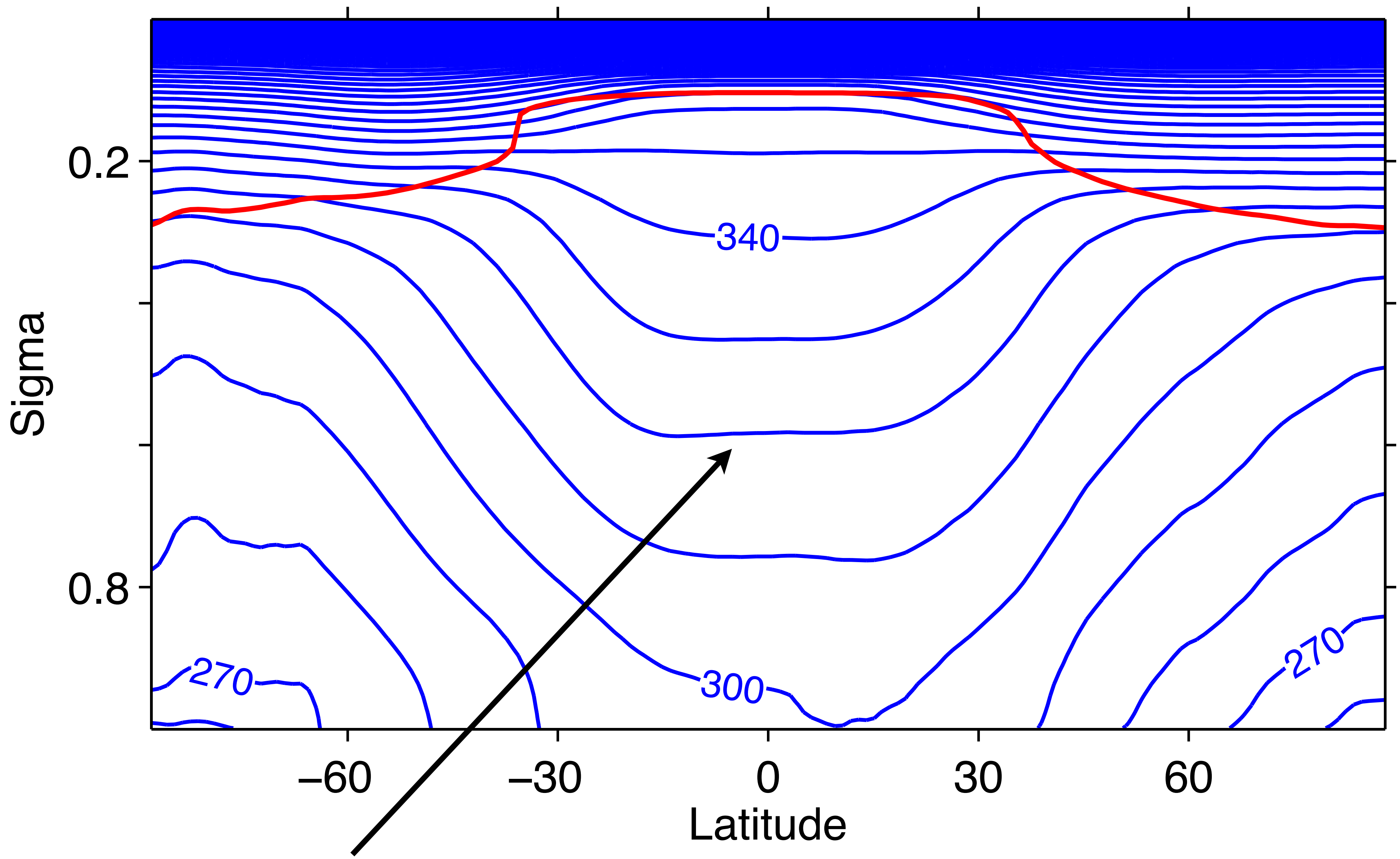


Strong cross-equatorial cell

Zonal and time-mean zonal wind (m/s)



Zonal and time mean temperature (K) (annual average)



Weak horizontal temperature gradients in tropics

Observed angular momentum mainly varies with latitude, decreases as move poleward

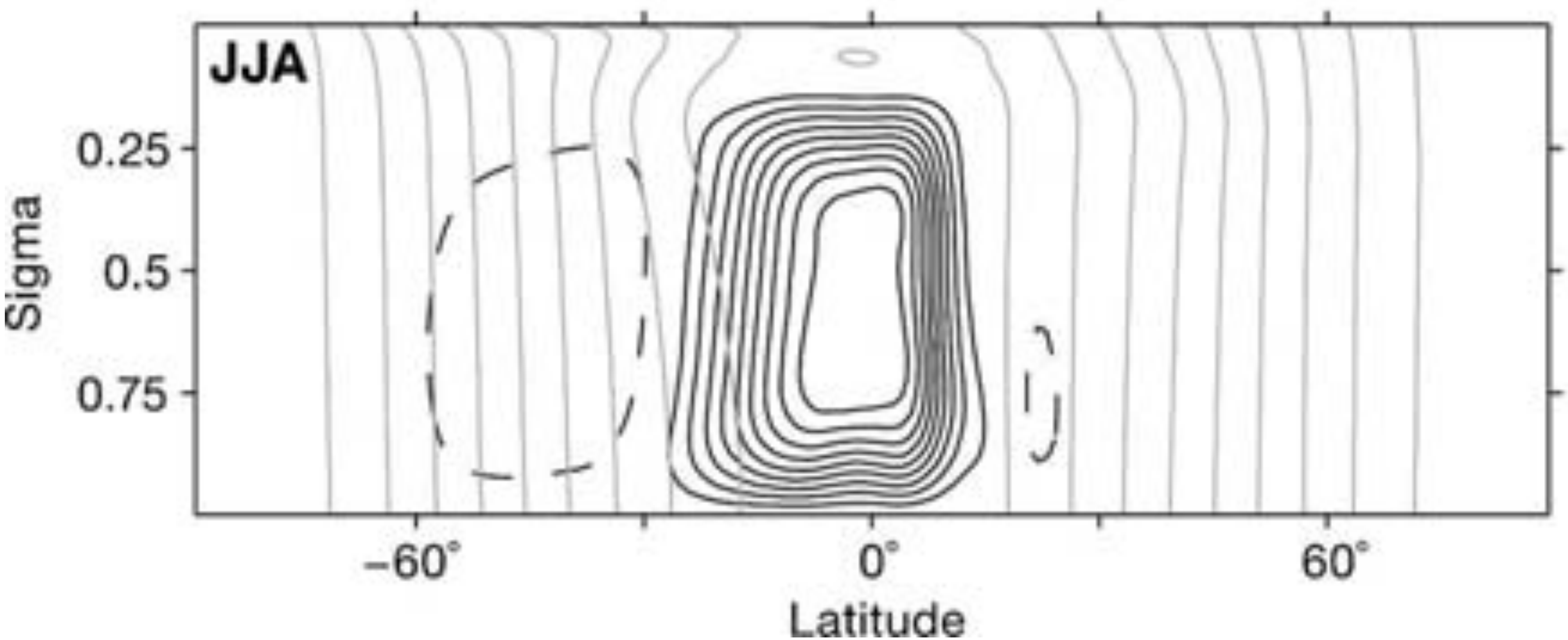


Fig. 0

Black contours: Mass flux streamfunction (contour interval 25×10^9 kg/s)

Gray contours: Angular momentum (contour interval $0.1\Omega a^2$, with values decreasing monotonically away from the equator)

Superrotation may occur on Earth in a very warm climate

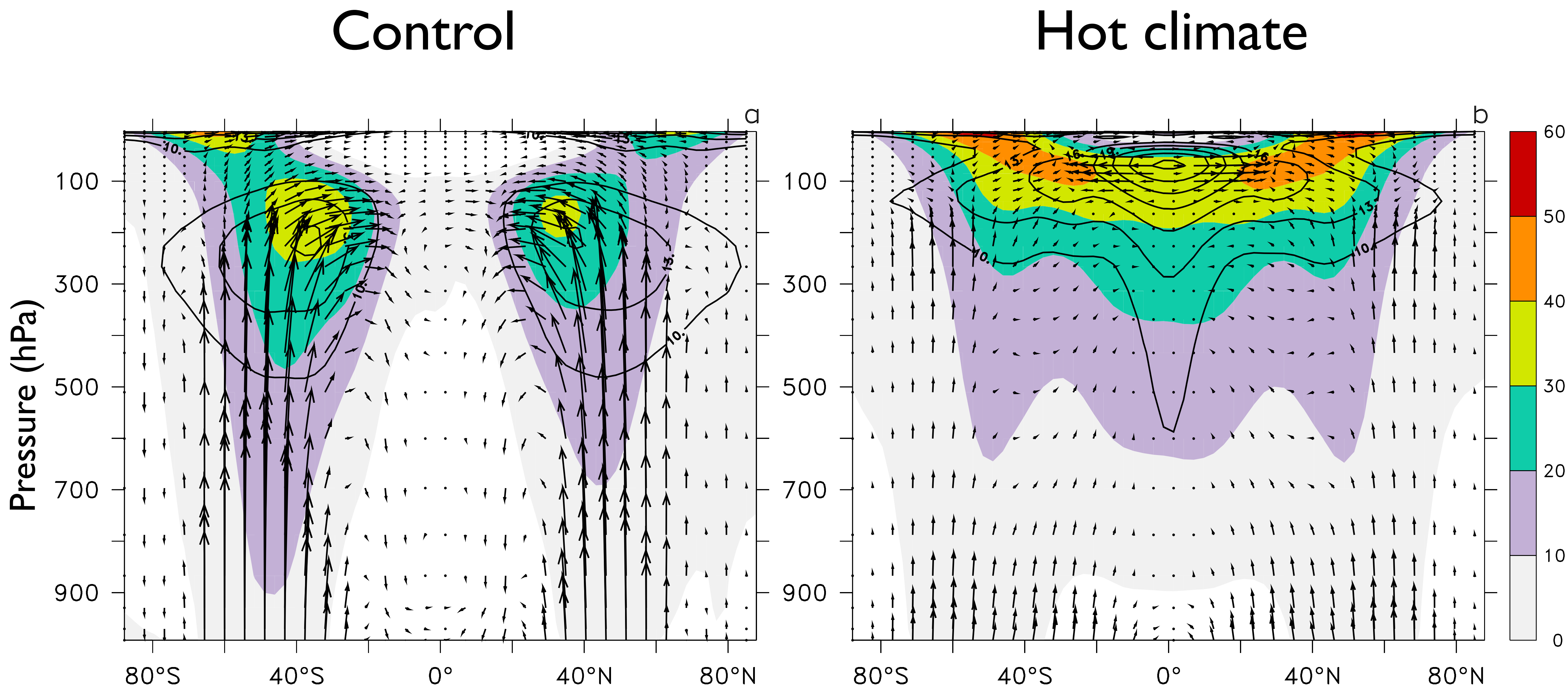


Fig 1.

Color shading: mean zonal wind (m/s)
Contours: standard deviation of zonal wind (m/s)
Arrows: Eliassen-Palm flux (see later in course)

Aquaplanet simulations, Caballero and Huber, GRL, 2010

List 1. Held-Hou model assumptions

- Zonally symmetric circulation on sphere
- No time dependence (steady)
- Boussinesq and hydrostatic approximations
- Rigid wall at upper (z=H) and lower (z=0) boundaries (upper is stress free, lower has drag)
- Radiation is represented by "Newtonian" relaxation of potential temperature to a specified radiative-equilibrium potential temperature $\theta_E(z,\Phi)$

Use handout to review the Boussinesq approximation.

Can also read about it in the textbooks:

- Holton section 2.8
- Vallis section 2.5 for the anelastic approximation and Boussinesq limit for the atmosphere

Schematic of Held-Hou model circulation

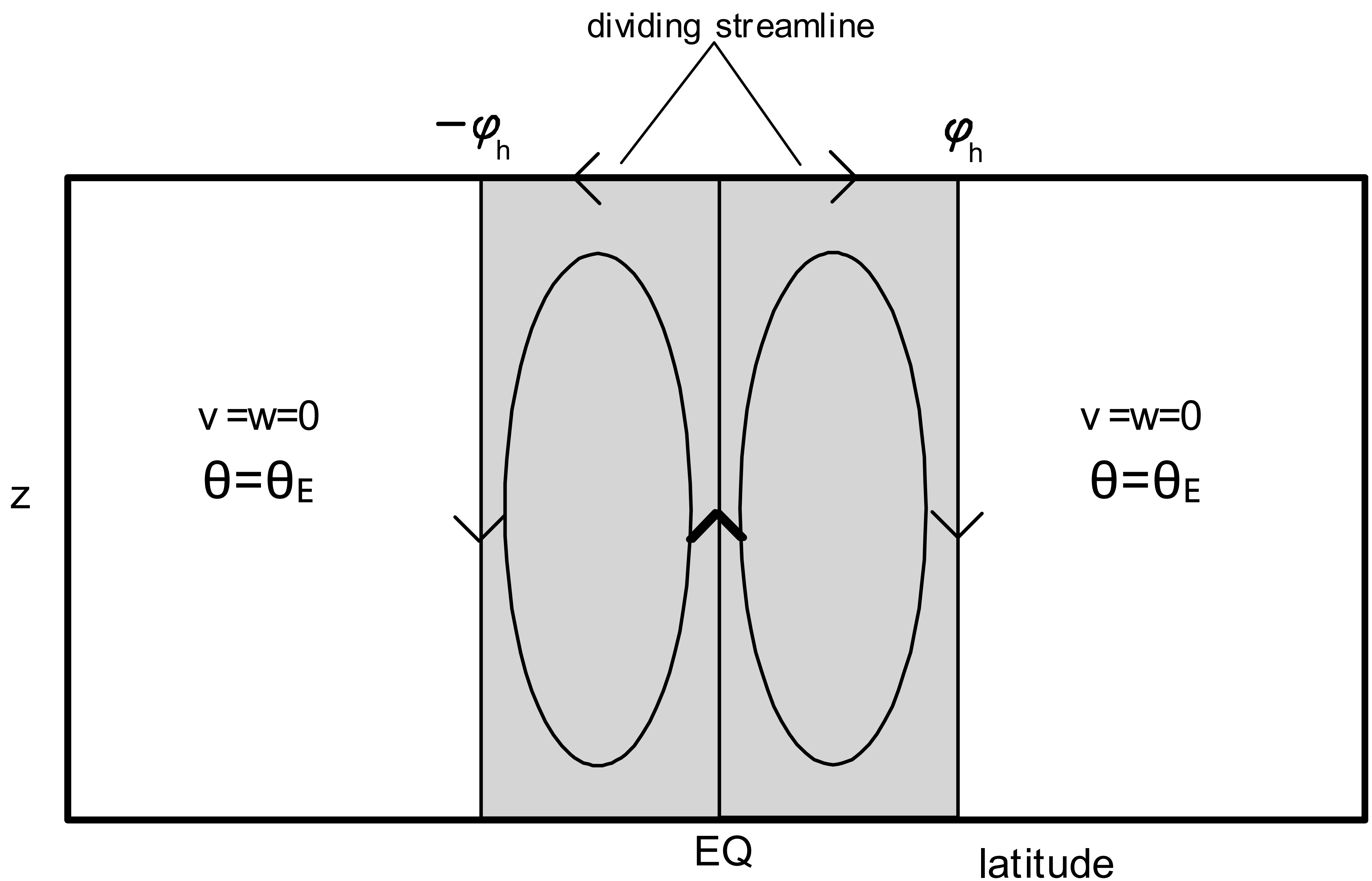


Fig 2. Angular momentum conserving (AMC) region is shaded
Radiative equilibrium (RE) region is unshaded

Application of matching conditions to find solution to Held-Hou model

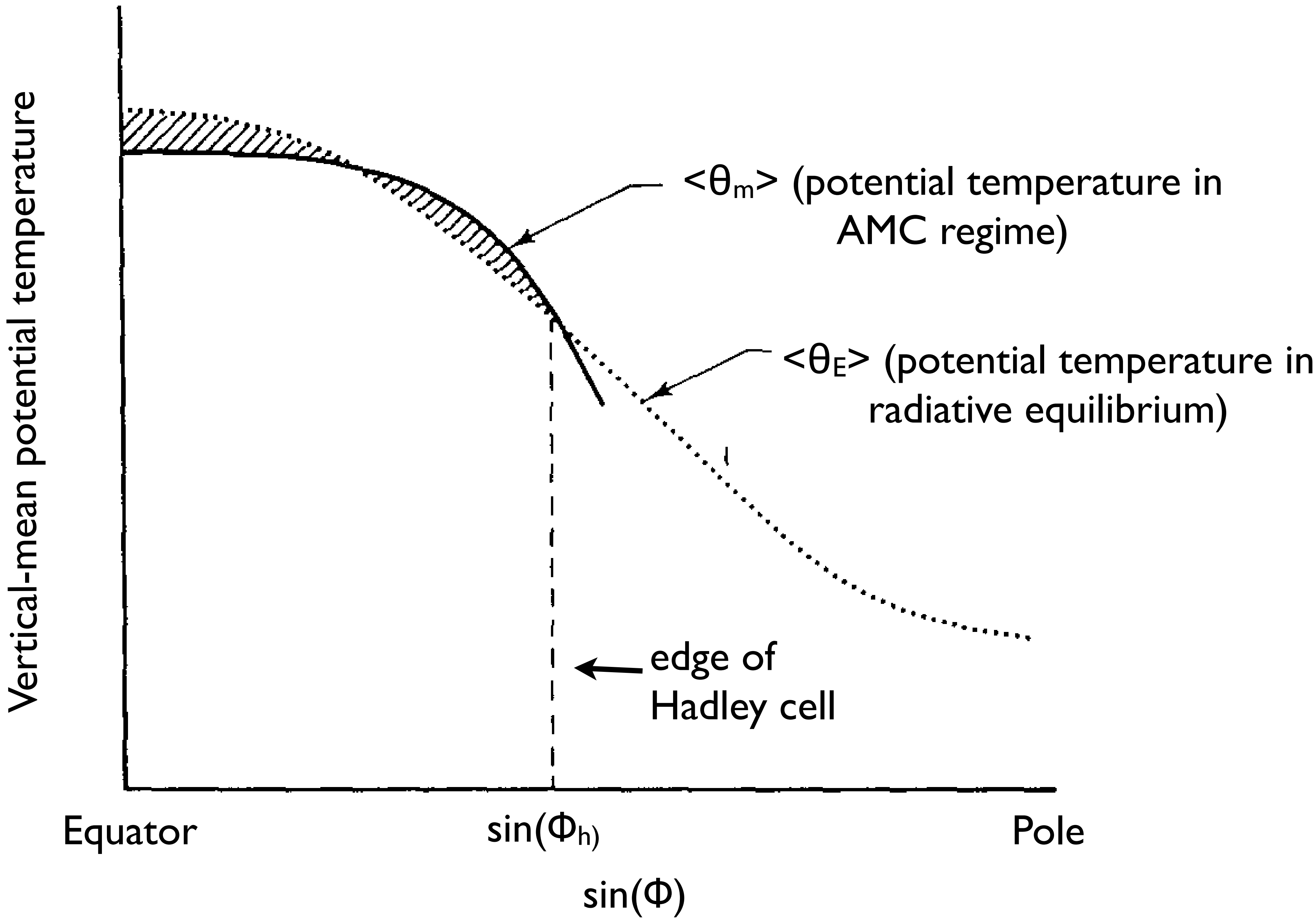


Fig 3. The $\langle\theta_m\rangle$ curve is moved up or down until the two shaded areas have equal area

Adapted from Held and Hou 1980

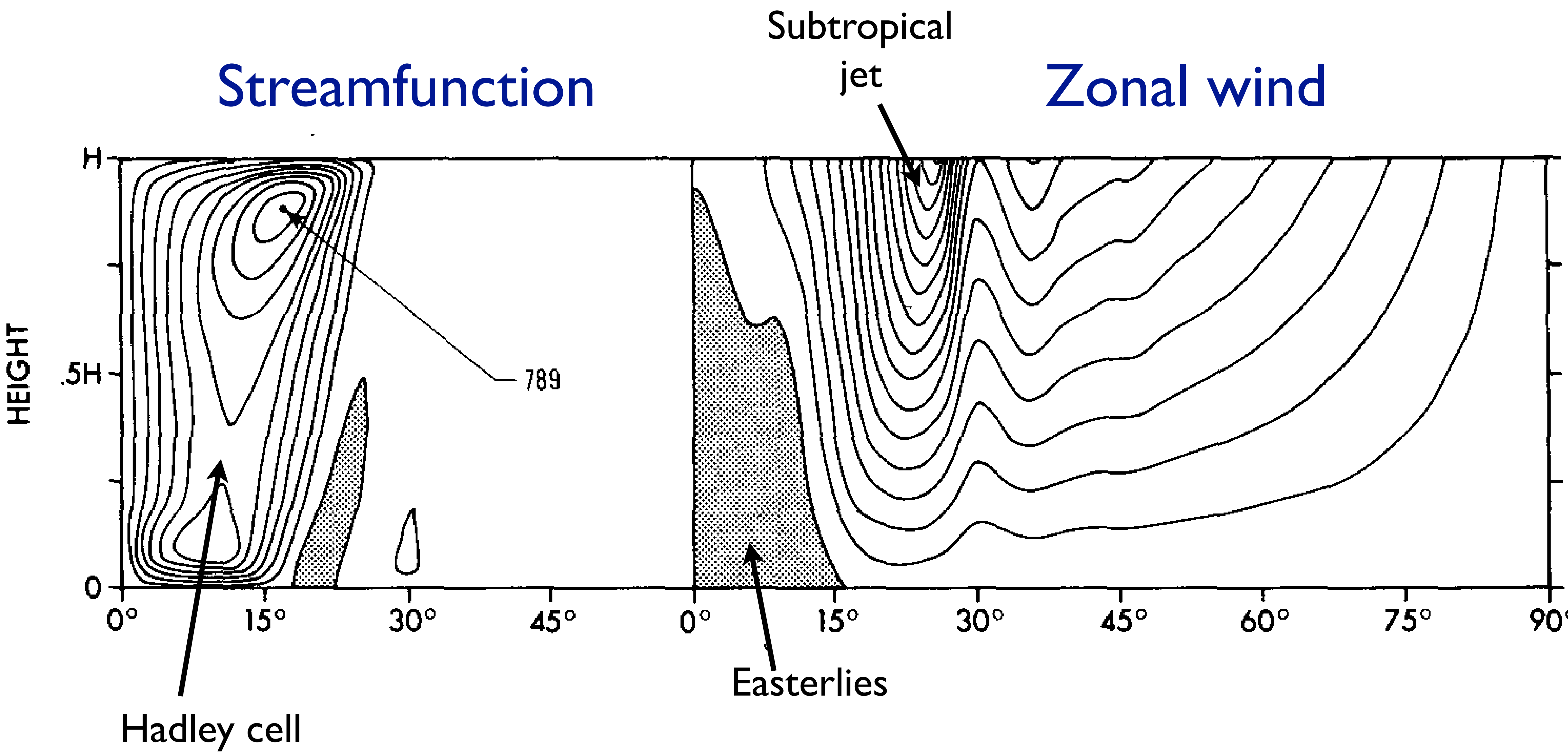
Breakout

How would the latitudinal extent of the Hadley cell on Titan (a moon of Saturn) compare to that of the Earth?

Titan day is ~16 Earth days
Titan radius is 0.4 Earth radii

$$\phi_h = \left(\frac{5}{3}R\right)^{1/2} \qquad R = \frac{gH\Delta_h}{\Omega^2 a^2}$$

Fig 4. Numerical solution of Held-Hou model for ν=1m²/s



Contour interval for zonal wind is 5 m/s
Streamfunction is in m²/s rather than kg/s

Adapted from Held and Hou 1980

List 2. Properties of Held-Hou model solution that are *similar* to observations

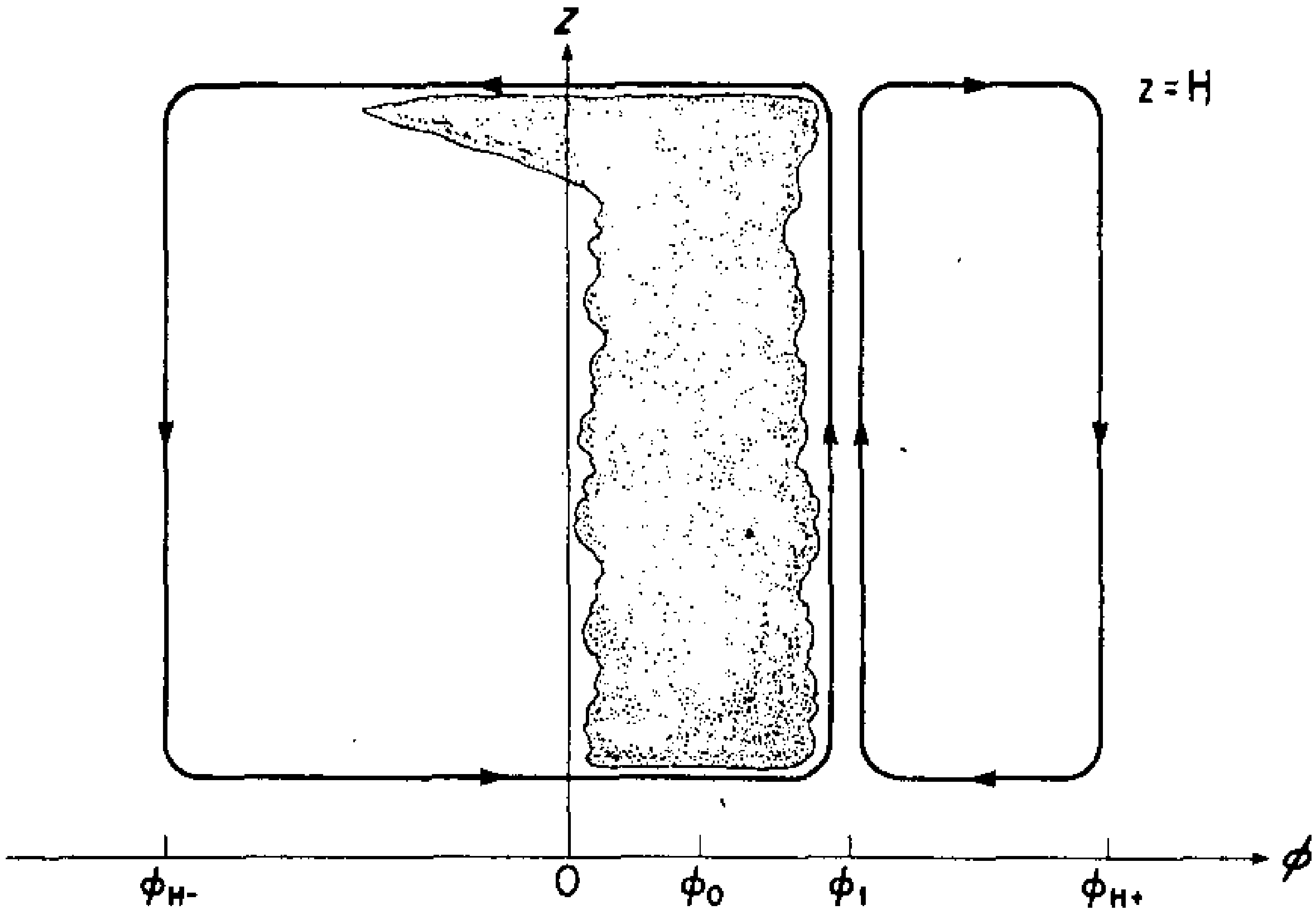
- Subtropical jet
- Surface easterlies in deep tropics and westerlies at higher latitudes (Hadley cell transports zonal momentum poleward)
- u=0 line slopes equatorward with height
- Meridional temperature gradients are smaller than in radiative equilibrium ($\theta_E \propto \Phi^2$, $\theta_m \propto \Phi^4$)
- Hadley cell width 20-30 degrees (coincidence?)

List 3. Properties of Held-Hou model solution that are *different* to observations

- Missing Ferrel cell and surface westerlies at midlatitudes because these are related to eddies

- Subtropical jet too strong (~90 m/s rather than 25 m/s in annual mean) because eddies cause deviation from angular momentum conservation

Fig 5. Seasonal Hadley cells: location of maximum radiative-equilibrium temperature off the equator

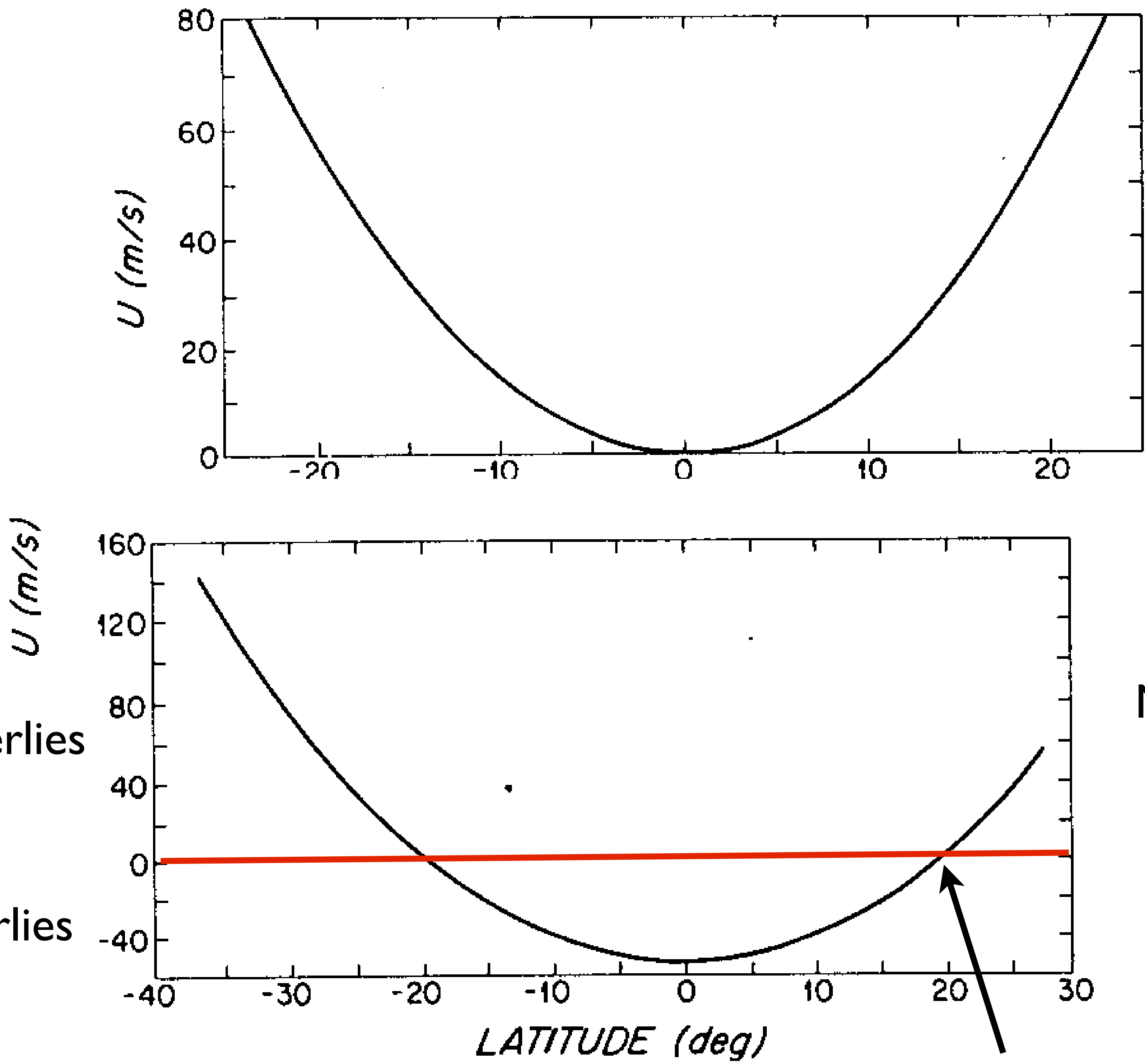


Φ_0: latitude where θ_E reaches a maximum
Φ_1: latitude of dividing streamline

The winter (cross-equatorial cell) is stronger, and the peak upward motion occurs near Φ_0 rather than Φ_1

Lindzen and Hou, JAS, 1988

Fig 6. Upper-level zonal wind is still symmetric about the equator (because assuming angular momentum conserved)



Max θ_E at equator (Φ_0=0)

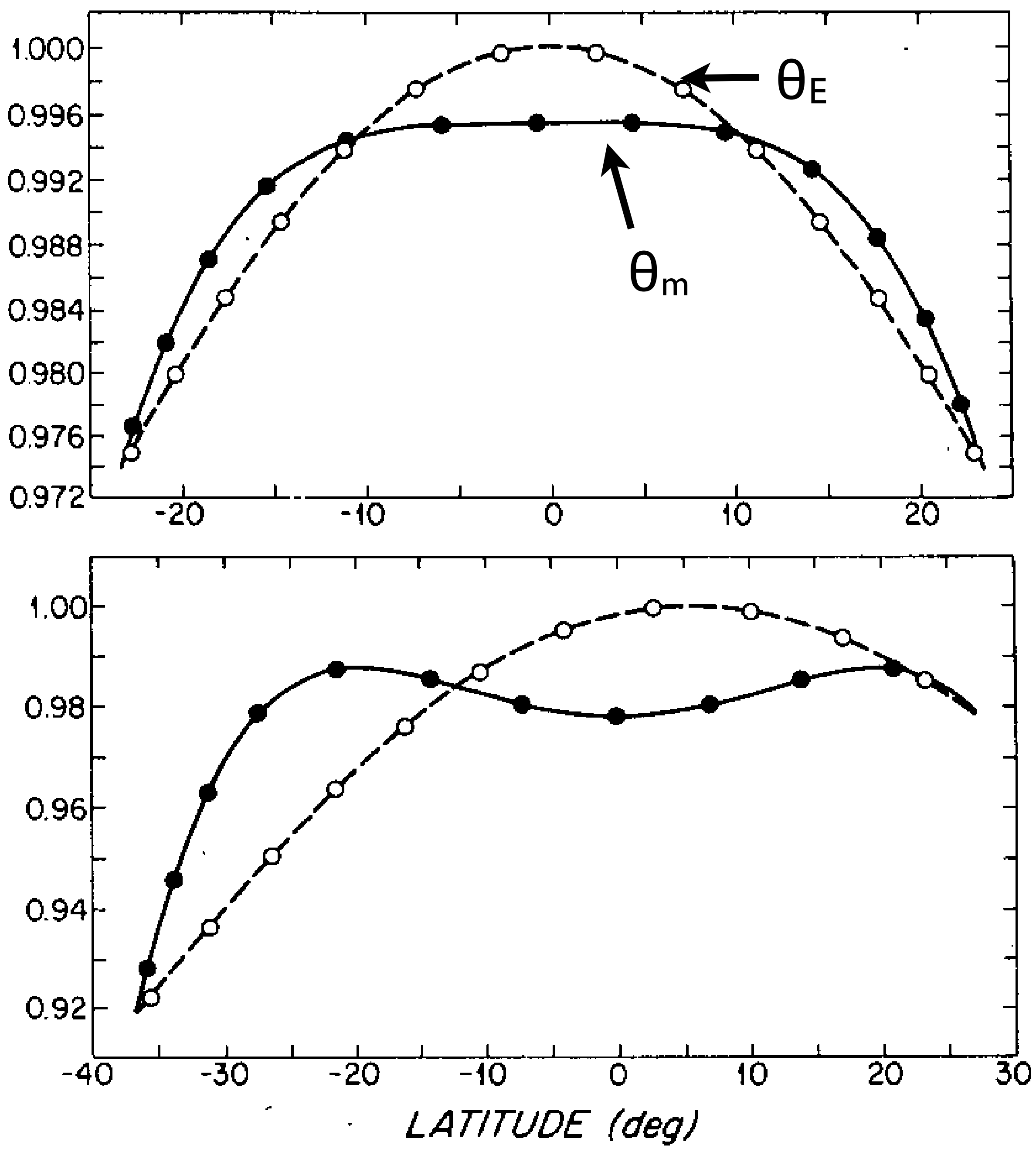
Max θ_E off equator (Φ_0=6 degrees)

Westerlies

Easterlies

Ascent with u=0 occurs here

Fig 7a. Can solve for temperature using nonlinear thermal wind balance and weak winds at surface (as before)



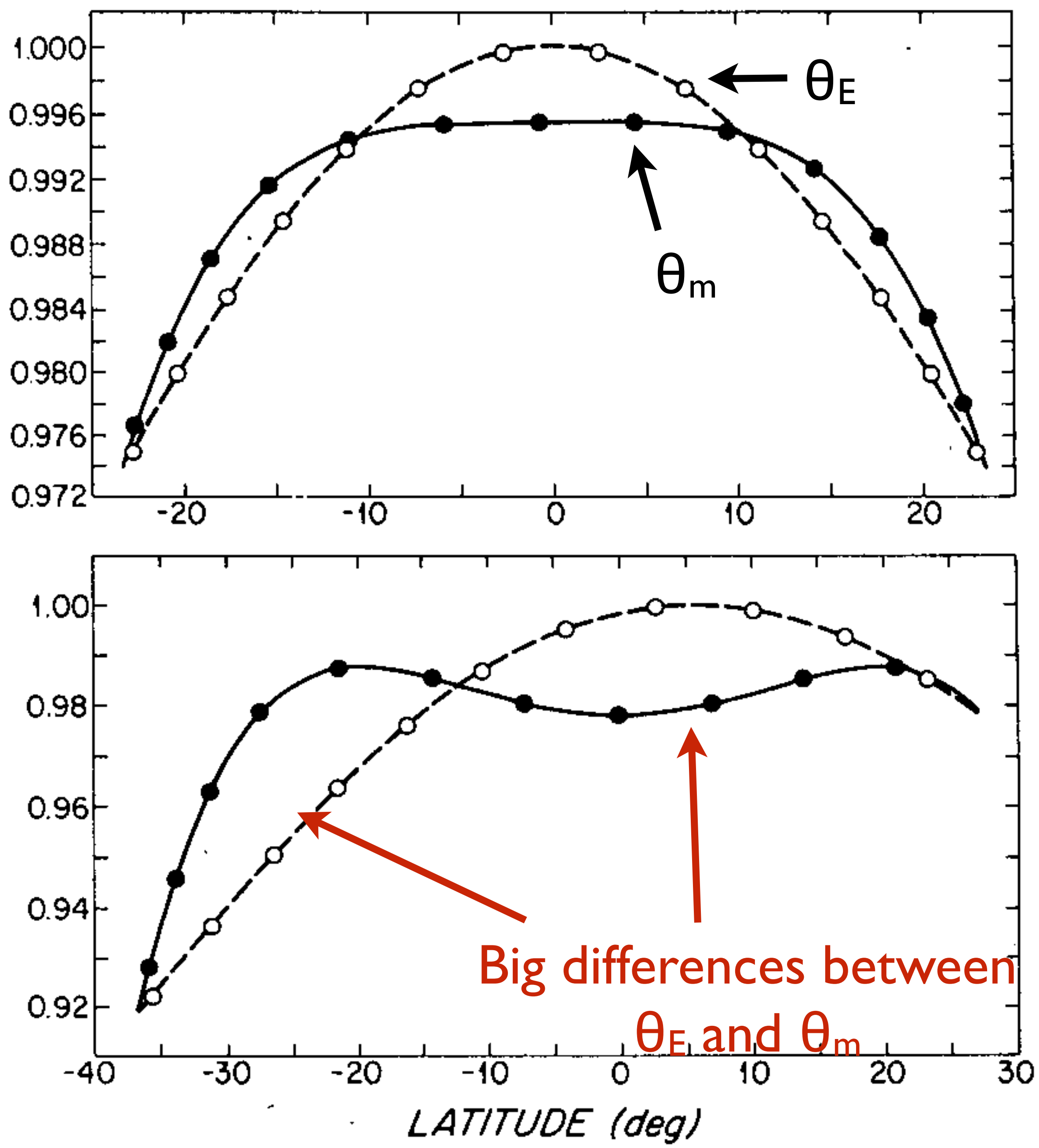
Max θ_E at equator (Φ_0=0)

Max θ_E off equator (Φ_0=6 degrees)

Temperatures have been normalized by reference temperature θ_0

Lindzen and Hou, JAS, 1988

Fig 7b. Big difference between θ_E and θ_m when $\Phi_0 \neq 0$
⇒ need strong cross-equatorial Hadley cell to transport energy!



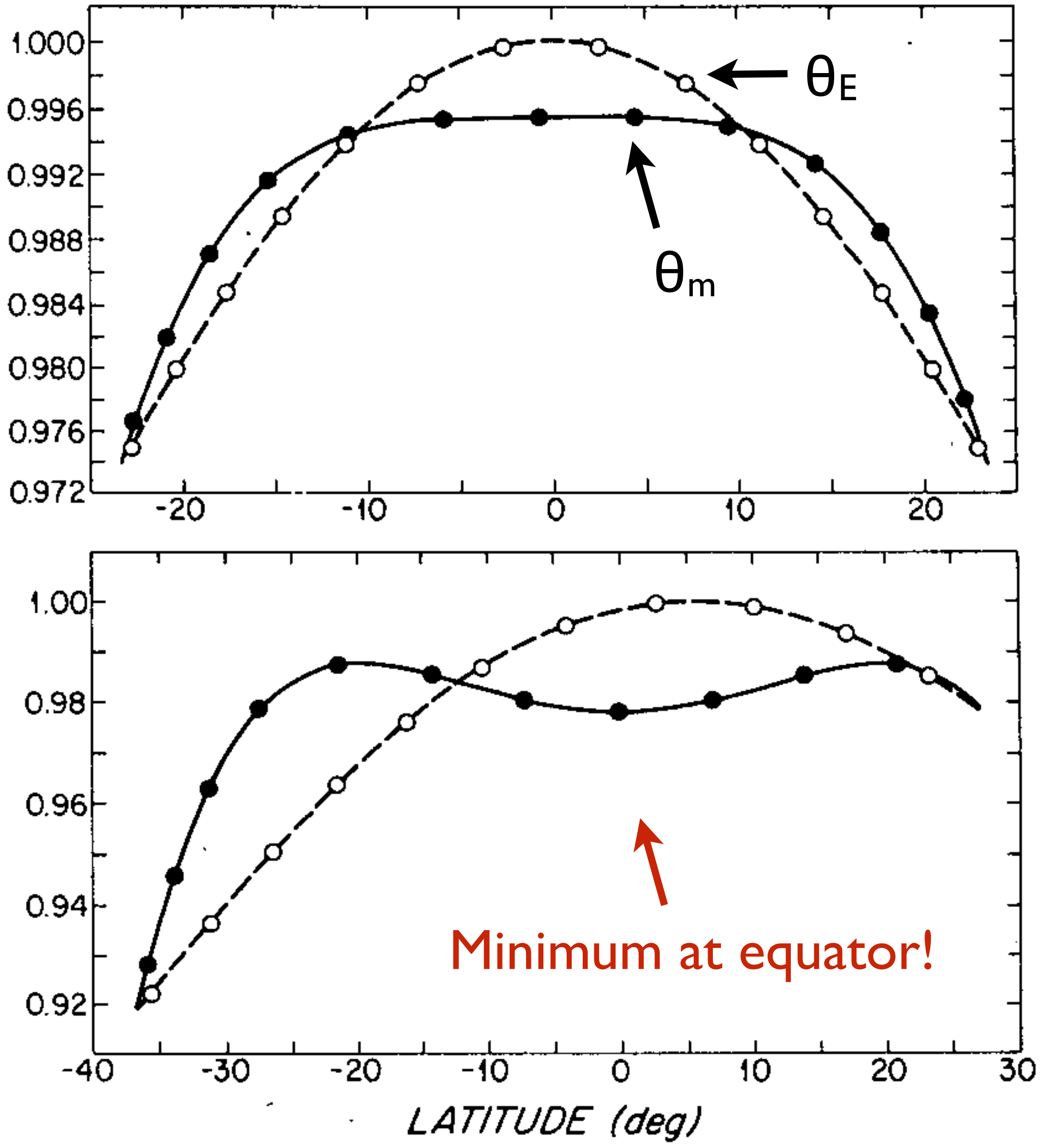
Max θ_E at equator (Φ_0=0)

Max θ_E off equator (Φ_0=6 degrees)

Temperatures have been normalized by reference temperature θ_0

Lindzen and Hou, JAS, 1988

Fig 7c. Upper level easterlies and thermal-wind relation ⇒ temperature reaches a minimum at the equator



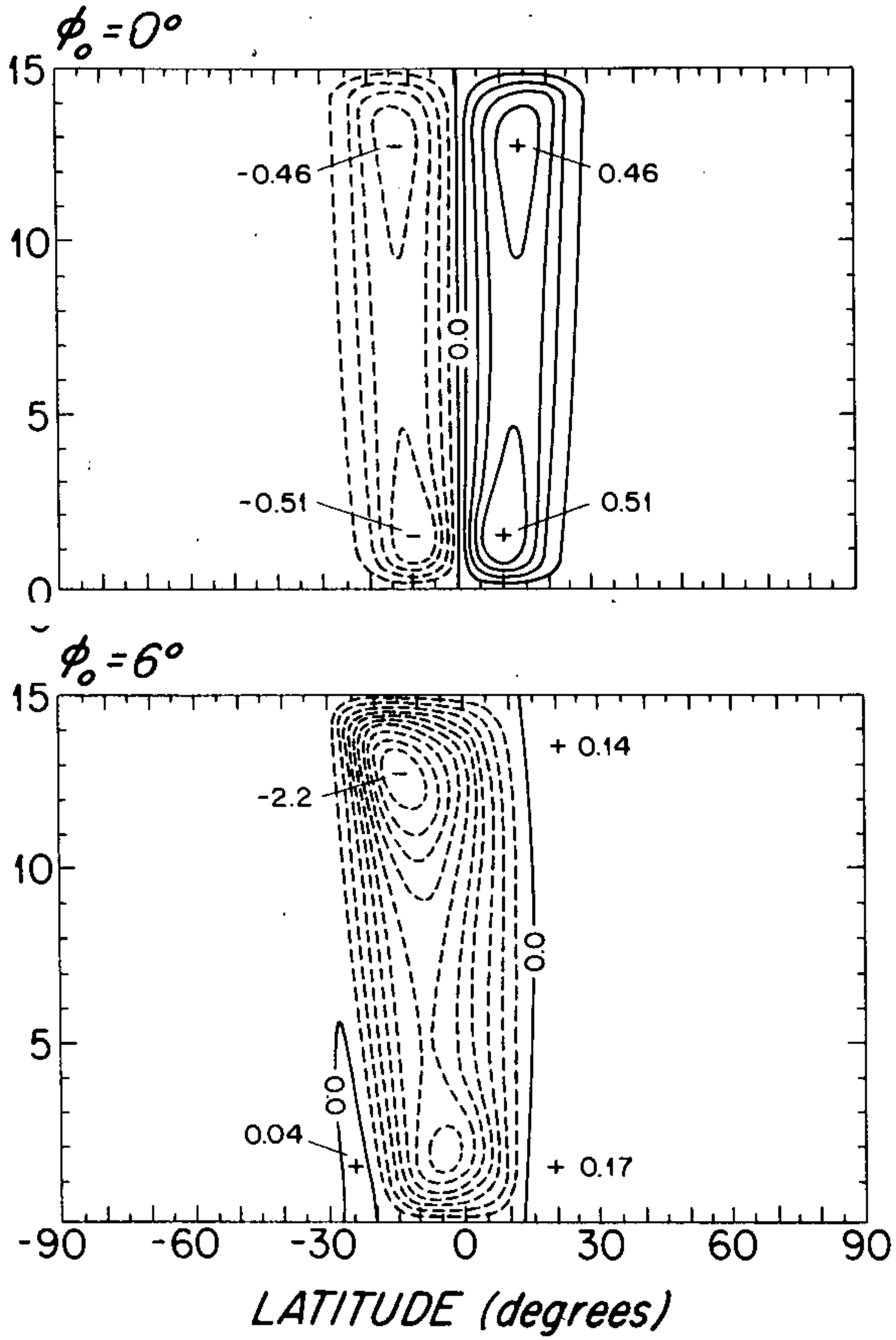
Max θ_E at equator (Φ_0=0)

Max θ_E off equator (Φ_0=6 degrees)

Temperatures have been normalized by reference temperature θ_0

Lindzen and Hou, JAS, 1988

Fig 8a. Small asymmetry in radiative forcing leads to large asymmetry in the circulation



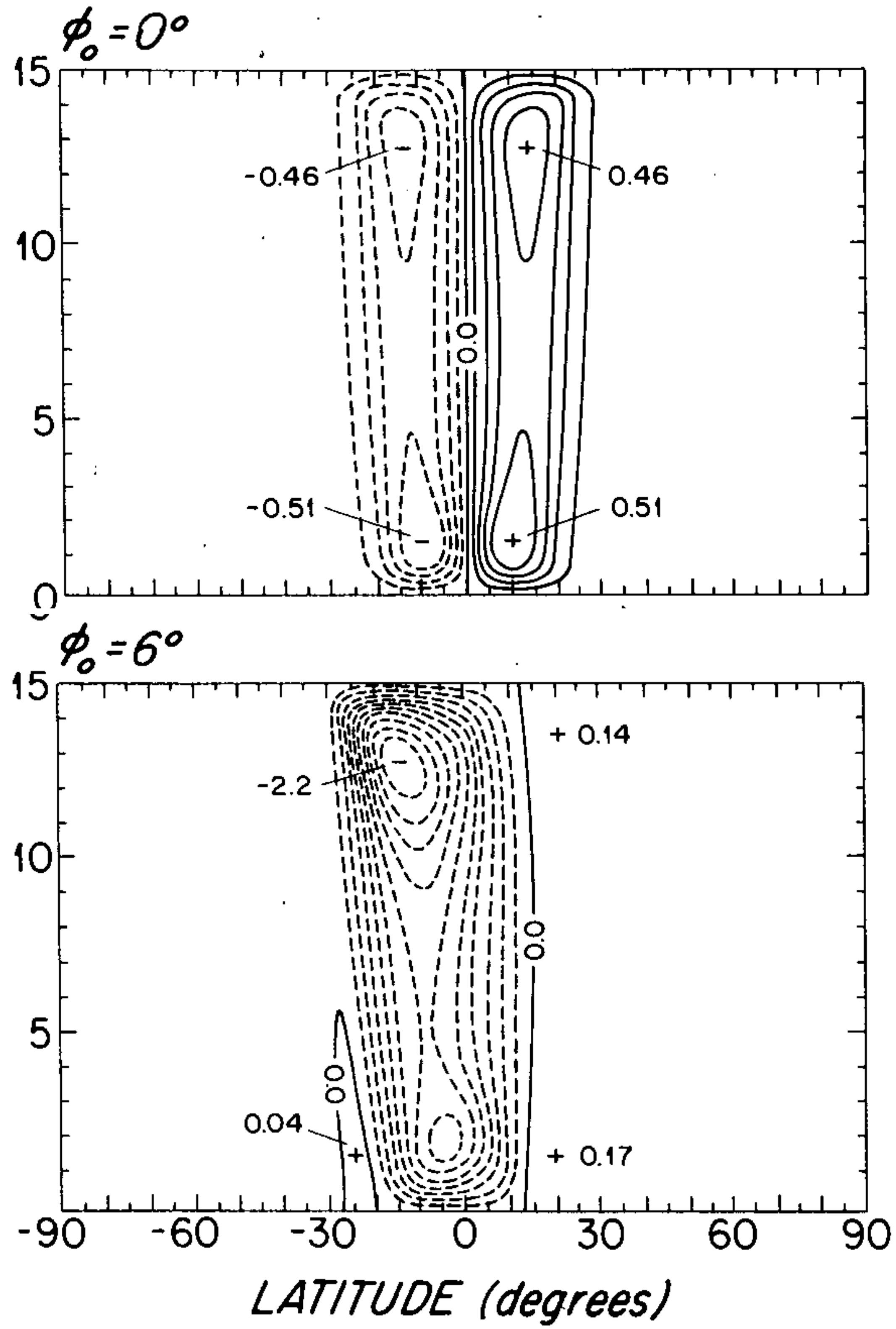
Max θ_E at equator (Φ_0=0)

Max θ_E off equator (Φ_0=6 degrees)

Streamfunction units of 10^{10}kg/s;
contour interval changes between panels

Lindzen and Hou, JAS, 1988

Fig 8b. Winter cell (cross-equatorial cell) is much stronger than summer cell



Max θ_E at equator (Φ_0=0)

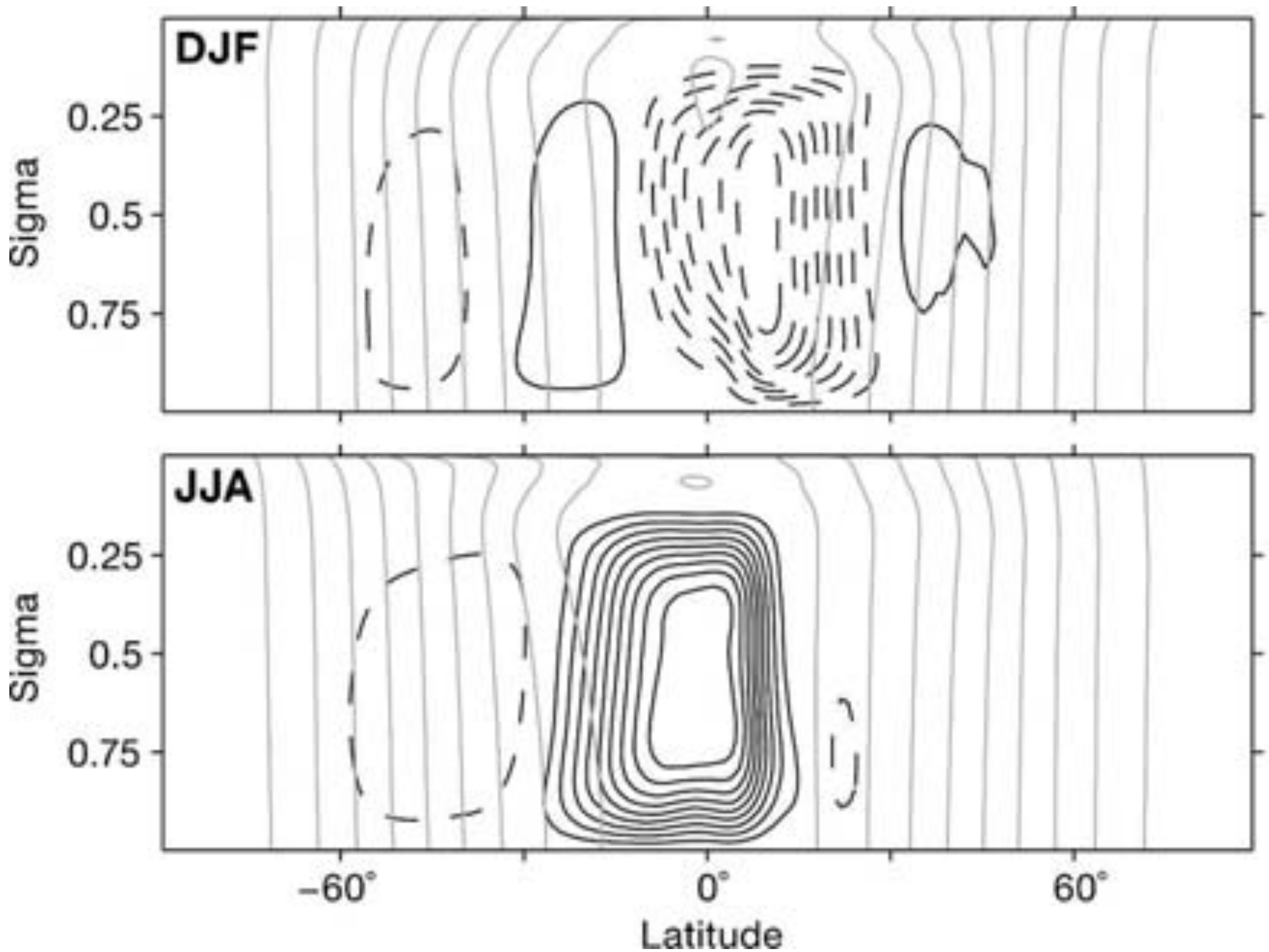
Max θ_E off equator (Φ_0=6 degrees)

Streamfunction units of 10^{10}kg/s; contour interval changes between panels

Lindzen and Hou, JAS, 1988

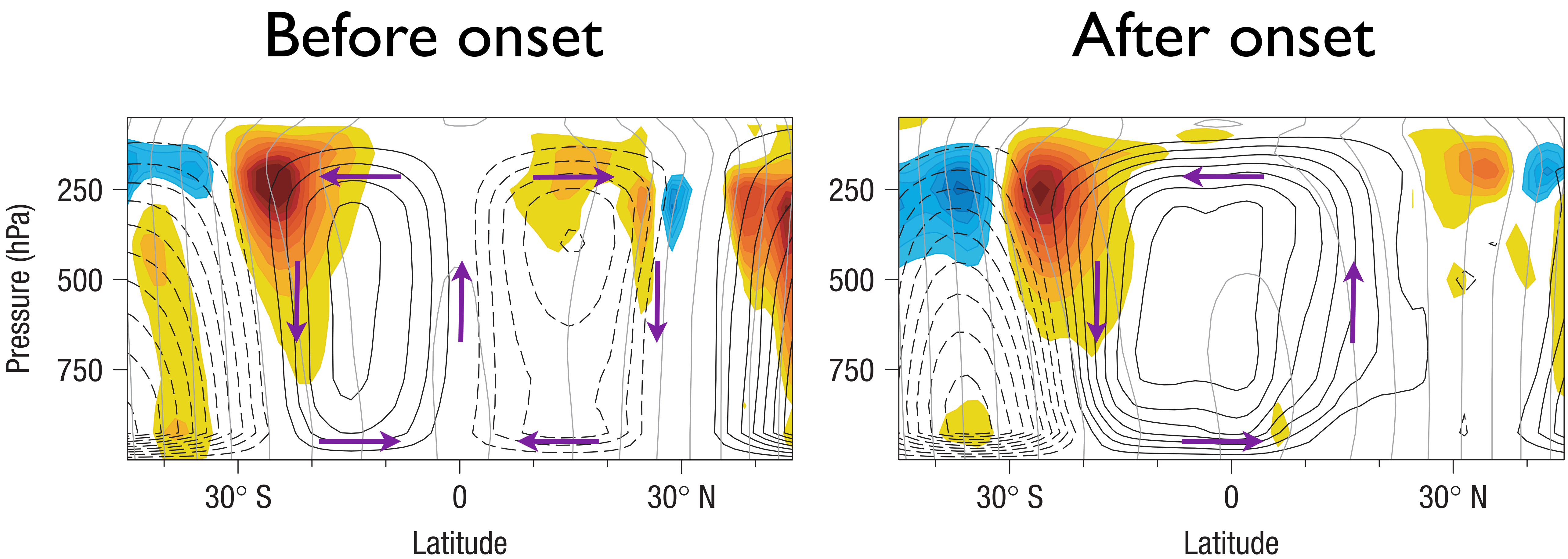
Hadley circulation crosses angular momentum contours in summer cell (eddies important), but much less so in cross-equatorial winter cell (e.g. monsoons)

Fig. 9



Mass flux streamfunctions (black contours) and angular momentum (gray contours) Streamfunction contour interval is $25\text{x}10^9$ kg/s. Contour interval for angular momentum is $0.1\Omega a^2$, with values decreasing monotonically away from the equator.

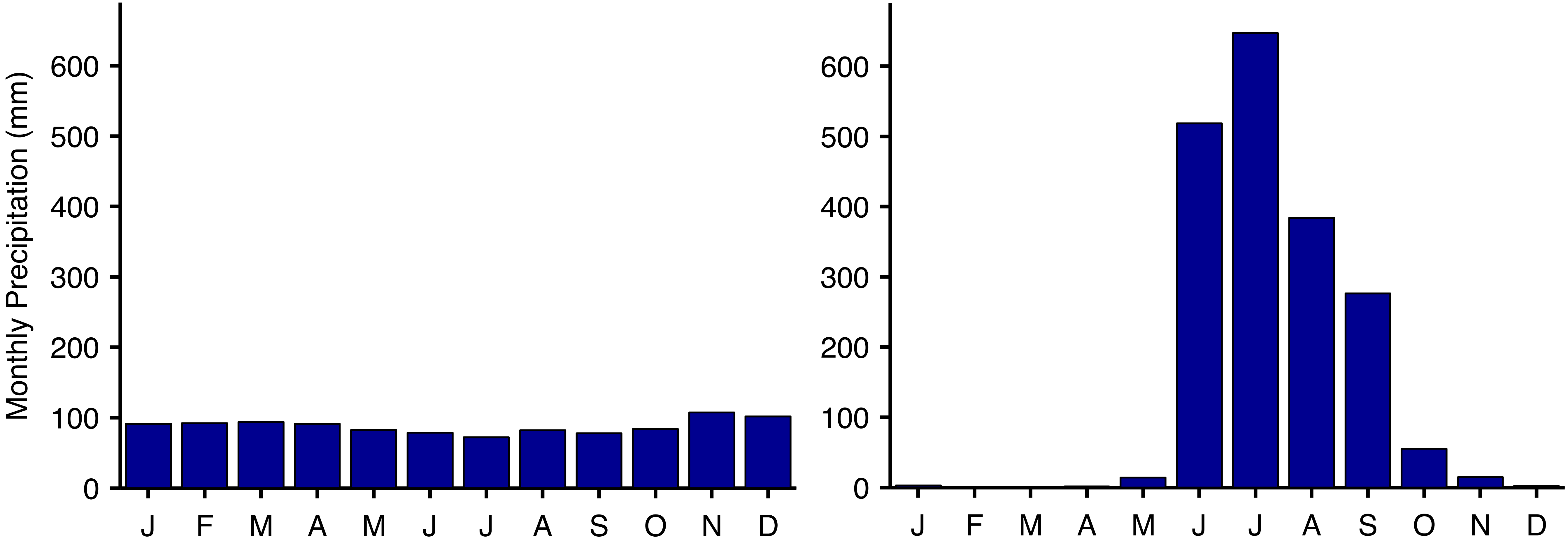
Relevance to Monsoons: Meridional overturning in South Asian Monsoon sector (streamfunction in black contours)

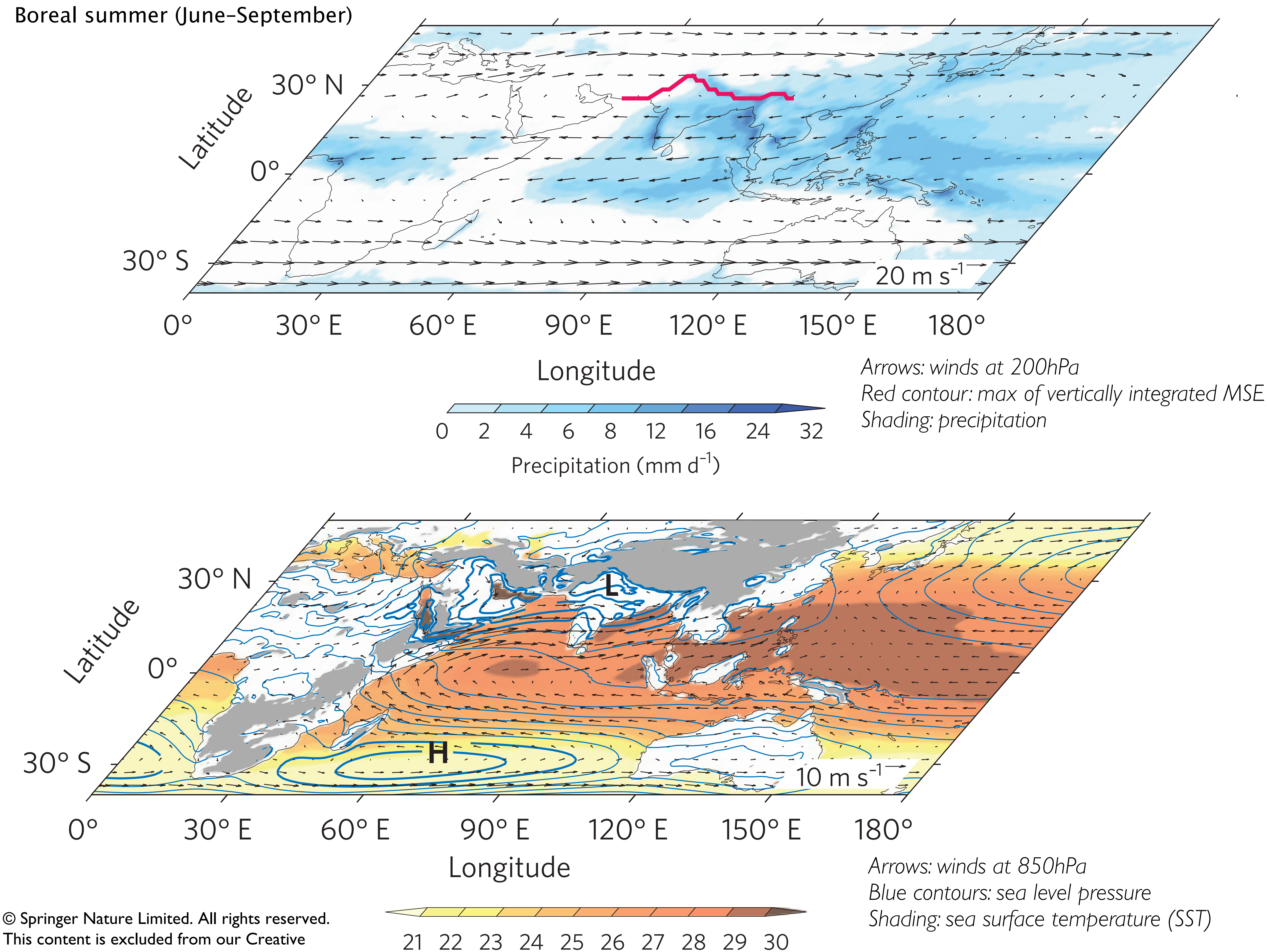


Contours: streamfunction (CI 50×10^9 kg s^{-1})
Gray lines: angular momentum
Color shading: eddy mom. flux div.
Sector defined as 70E-100E

Bordoni and Schneider, Nature Geoscience, 2008

Dramatic contrast in the seasonal cycle of precipitation in two cities

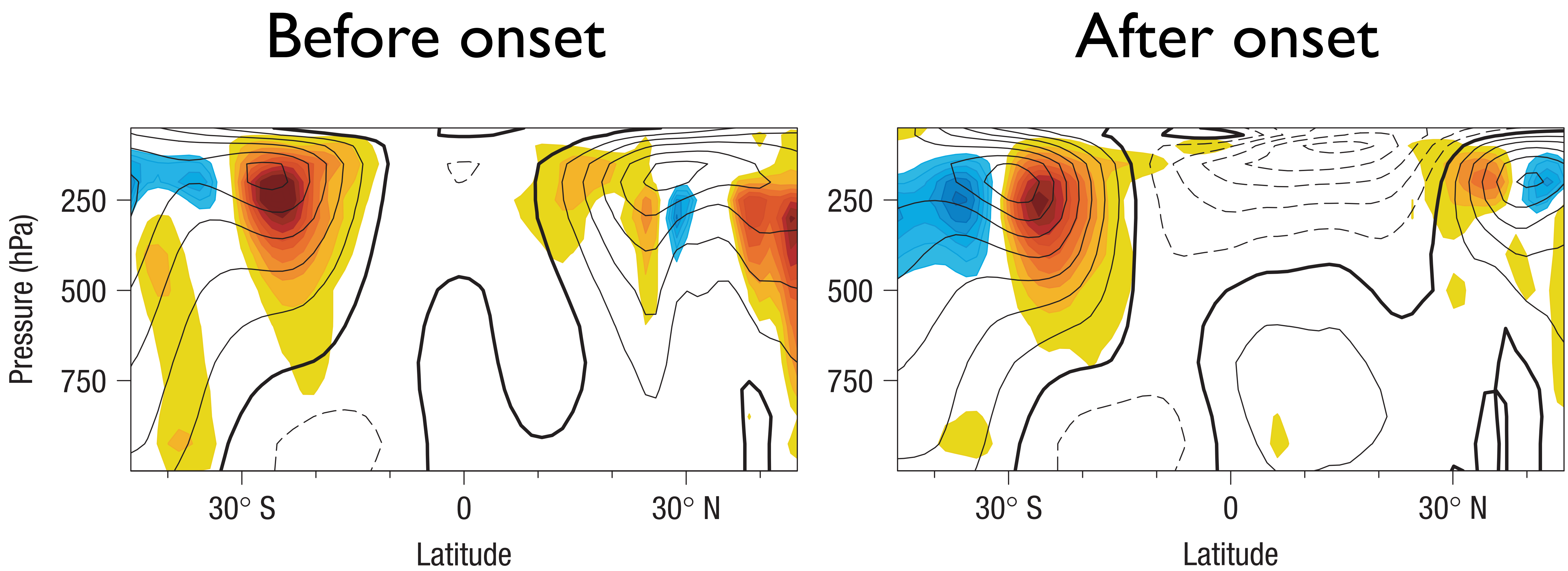




Turner and Annamalai, Nature Climate Change, 2012

Fig. 11

Zonal wind in South Asian Monsoon sector (black contours)



Contours: zonal wind (CI 6 m s^{-1}) with dashed for easterly
Color shading: eddy mom. flux div.
Sector defined as 70E-100E

Bordoni and Schneider, Nature Geoscience, 2008

12.810 Dynamics of the Atmosphere
Spring 2023