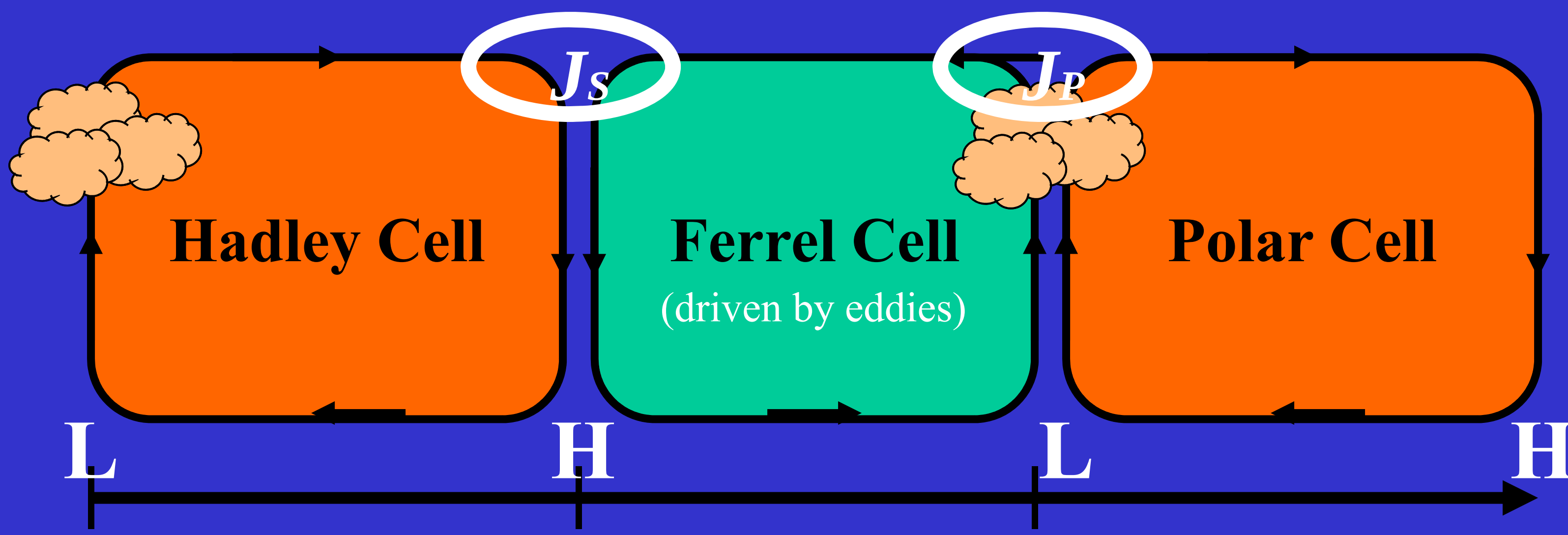
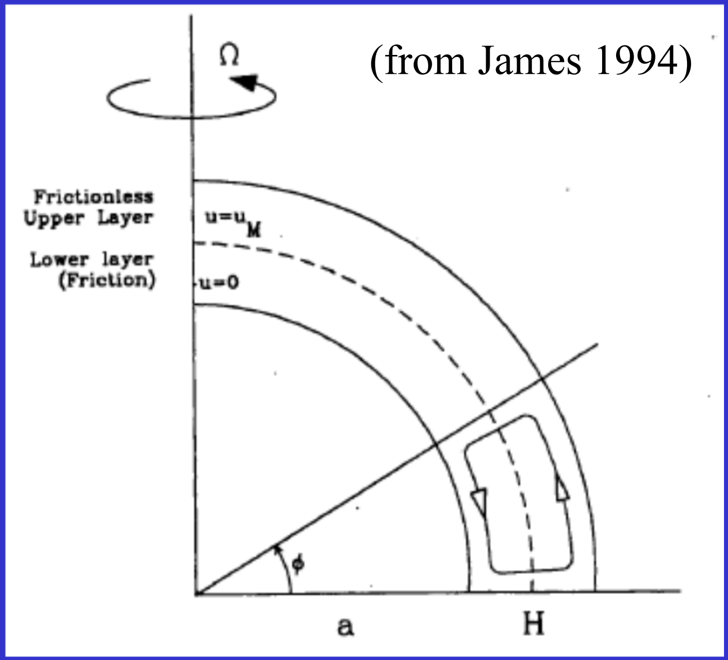
Lecture 11: Atmospheric General Circulation



- Hadley Cell – a thermal-driven circulation
- Farrell Cell – an eddy-driven circulation

The Held-Hou Model (1980) for Hadley Circulation



thermal wind balance

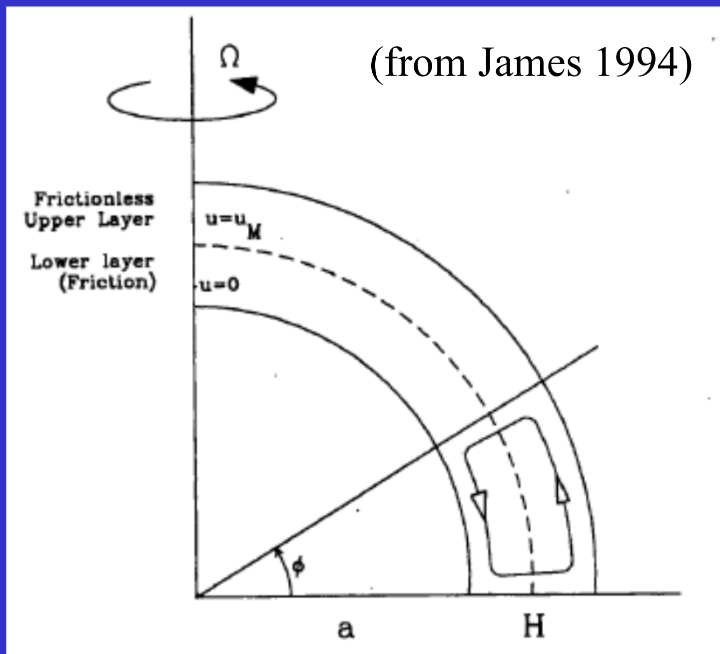
$$\partial U/\partial z \propto \partial T/\partial y$$

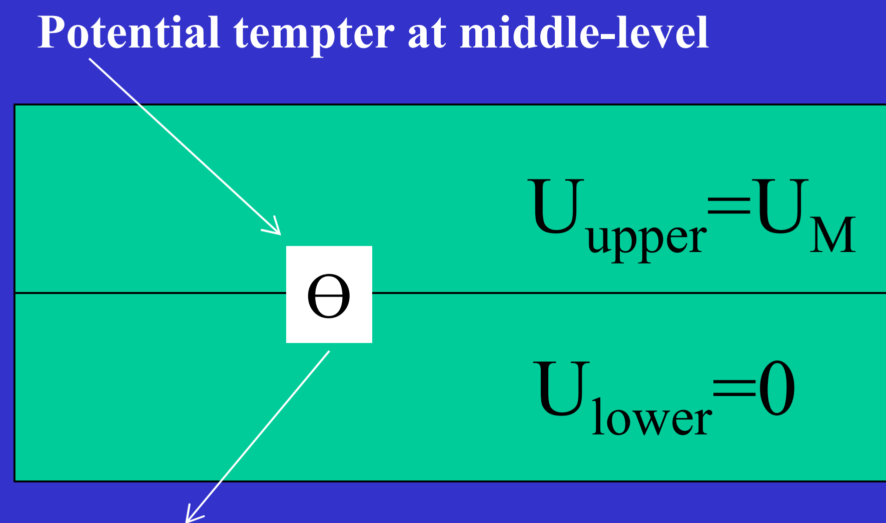
angular momentum conservation

radiative equilibrium

- The Held-Hou model is a two-level model on the sphere with equatorward flow at the surface and poleward flow at height H.
- The model uses angular momentum conservation and thermal wind balance to determine the width and strength of the Hadley circulation.

Held and Hou Model: ***Radiative Forcing***





$$\frac{D\theta}{Dt} = \frac{\theta_E - \theta}{\tau_E},$$

$$\theta_E(\varphi) = \theta_0 - \frac{1}{3}\Delta\theta\left(3\sin^2\varphi - 1\right).$$

$$\varphi \approx \sin\varphi \approx y/a$$

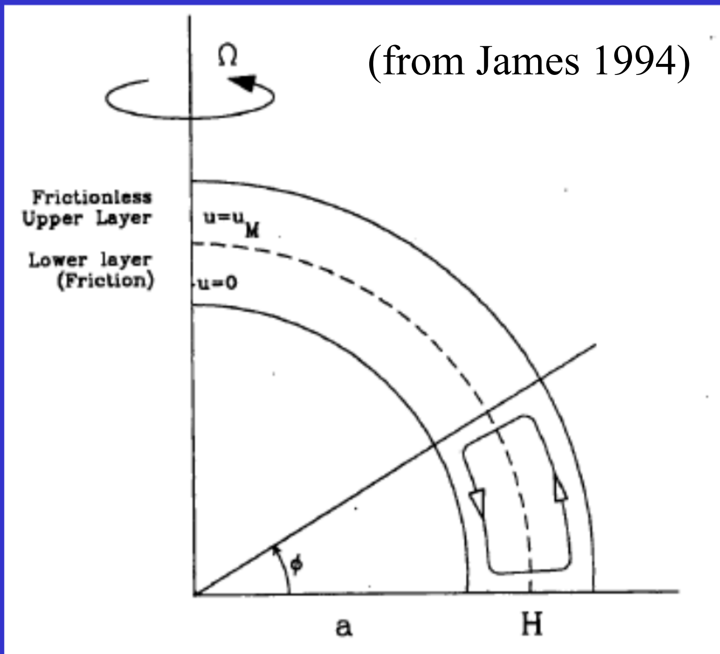
$$\theta_E(y) = \theta_{E0} - \Delta\theta\frac{y^2}{a^2},$$

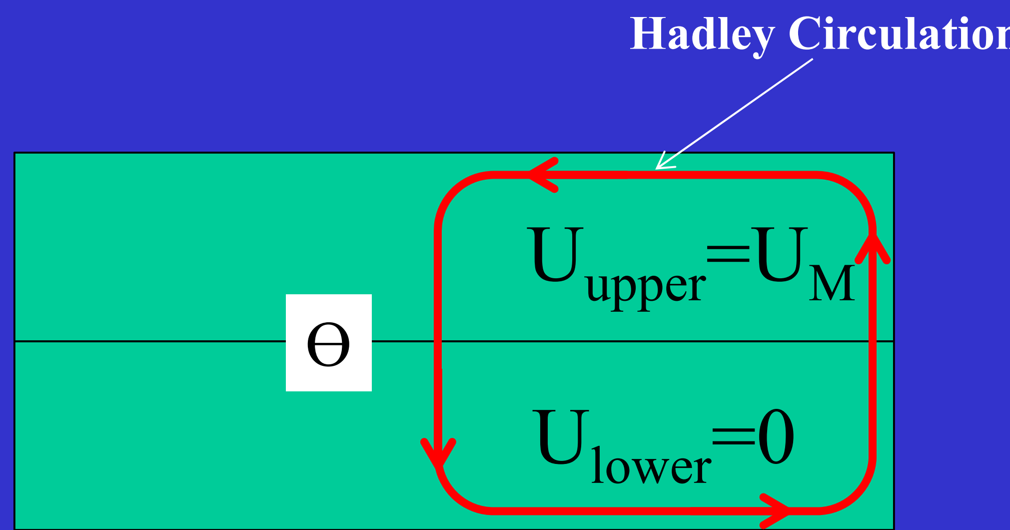
where $\theta_{E0} = \theta_0 + \Delta\theta/3$

$\Theta_{E:}$ global mean radiative equilibrium temperature
$\Delta\Theta$: pole-to-equator temperature deference

- Radiative processes are represented in the model using a Newtonian cooling formulation.

Held and Hou Model: *Dynamics*





$(\Omega a \cos\varphi + u) a \cos\varphi$ absolute angular momentum

$$u(\varphi) = \Omega a \frac{\sin^2 \varphi}{\cos \varphi}.$$

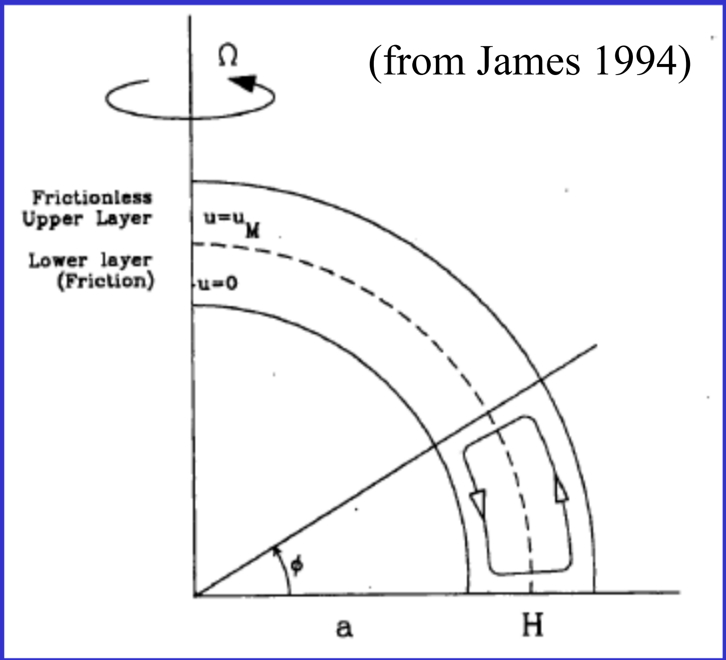
angular momentum conservation from equator to a latitude φ

$\varphi \approx \sin\varphi \approx y/a$

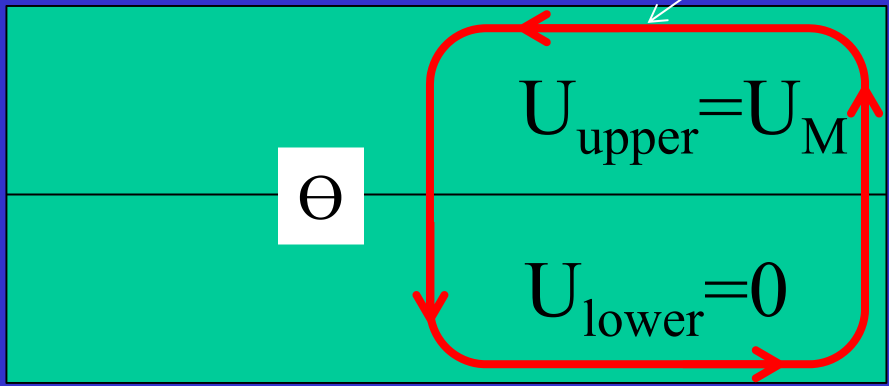
$$U_M = \frac{\Omega}{a} y^2.$$

- The zonal-mean zonal wind (U) is determined by the conservation of absolute angular momentum.

Held and Hou Model: *Thermal Wind Balance*



Hadley Circulation



$$\frac{\partial u}{\partial z} = \frac{U_M}{H} = \frac{\Omega}{aH} y^2 .$$

$$\frac{\partial \theta}{\partial y} = -\frac{2\Omega^2 \theta_0}{a^2 g H} y^3 .$$

$$\theta_M = \theta_{M0} - \frac{\Omega^2 \theta_0}{2a^2 g H} y^4 ,$$

based on thermal wind balance

$$\frac{\partial \mathbf{V}_g}{\partial \ln p} = -\frac{R}{f} \mathbf{k} \times \nabla_p T$$

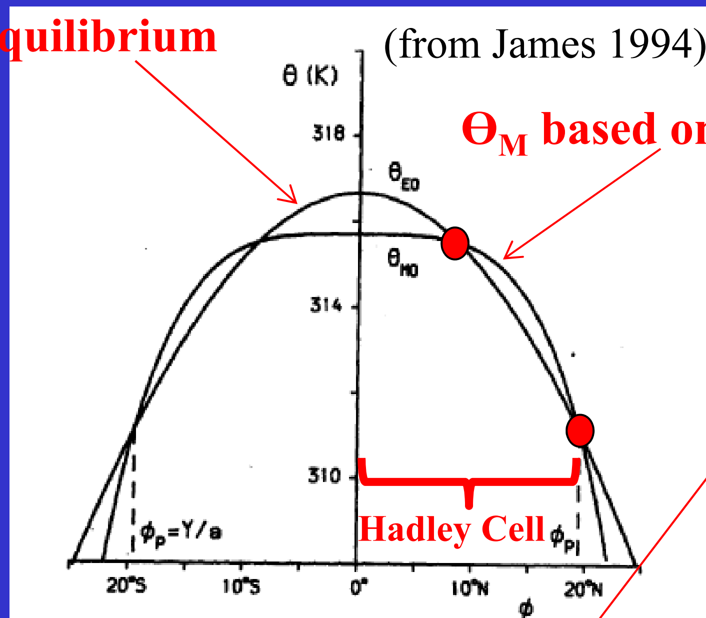
$\Theta_{M:}$ potential temperature derived based on conservation of angular momentum

- The potential temperature structure at the middle level of the model is calculated from thermal wind balance.

Held and Hou Model: *Hadley Circulation*

Θ_E based on radiative equilibrium

$$\theta_E(y) = \theta_{E0} - \Delta\theta\frac{y^2}{a^2},$$



Θ_M based on momentum conservation

$$\theta_M = \theta_{M0} - \frac{\Omega^2\theta_0}{2a^2gH}y^4,$$

$$\frac{D\theta}{Dt} = \frac{\theta_E - \theta}{\tau_E};$$

- The steady state solution to the above equation can be found from the cross points of Θ_E and Θ_M.
- Zone 1 (Equator to the first crossing point): $\Theta_E > \Theta_M$ ➔ radiative heating
- Zone 2 (first to second crossing point): $\Theta_E < \Theta_M$ ➔ radiative cooling
- Hadley cell is driven by radiative heating to move from equator to Y while conserving angular momentum.

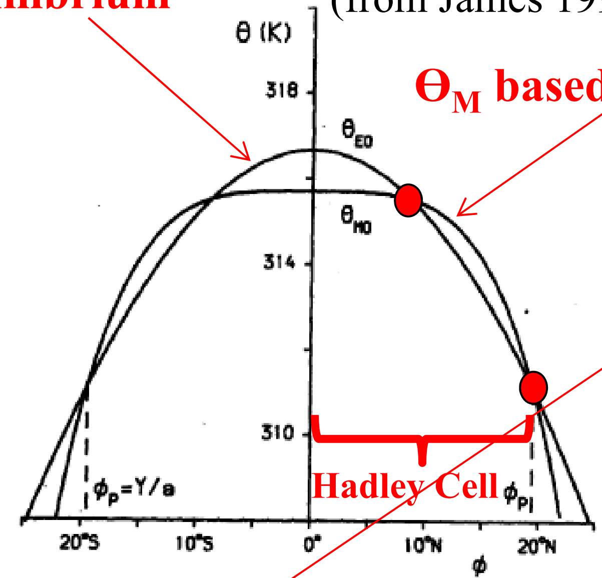
Held and Hou Model: ***HC Width Y***

Θ_E based on radiative equilibrium

$$\theta_E(y) = \theta_{E0} - \Delta\theta \frac{y^2}{a^2},$$

$$\theta_{E0} = \theta_0 + \Delta\theta/3$$

(from James 1994)



Θ_M based on momentum conservation

$$\theta_M = \theta_{M0} - \frac{\Omega^2 \theta_0}{2a^2 gH} y^4,$$

$$\frac{D\theta}{Dt} = \frac{\theta_E - \theta}{\tau_E},$$

$$\int_0^Y \frac{D\theta}{Dt} dy = 0,$$

Since the model assumes a steady state, there can be no net heating of an air parcel when it completes a circuit of the Hadley cell

$$\int_0^Y \theta_M \, dy = \int_0^Y \theta_E \, dy.$$

$$\theta_{M0} - \frac{\Omega^2 \theta_0}{10a^2 gH} Y^4 = \theta_{E0} - \frac{\Delta\theta}{3a^2} Y^2.$$

Assume continuity of potential temperature at y = Y

➔ $\Theta_E(Y) = \Theta_M(Y)$

$$\theta_{M0} - \frac{\Omega^2 \theta_0}{2a^2 gH} Y^4 = \theta_{E0} - \frac{\Delta\theta}{a^2} Y^2.$$

$$Y = \left(\frac{5 \Delta\theta g H}{3 \Omega^2 \theta_0} \right)^{1/2},$$

HC Width

$$\theta_{M0} = \theta_{E0} - \frac{5 \Delta\theta^2 g H}{18 a^2 \Omega^2 \theta_0}.$$

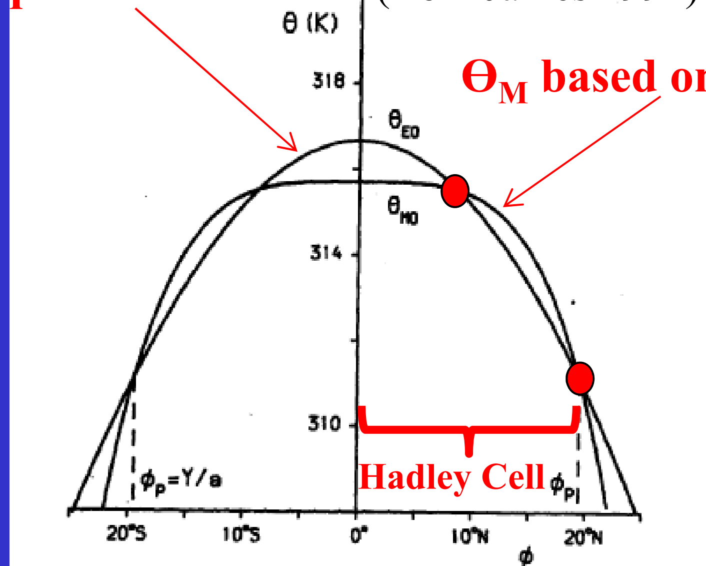
HC Strength

Held and Hou Model: *Hadley Circulation*

Θ_E based on radiative equilibrium

$$\theta_E(y) = \theta_{E0} - \Delta\theta \frac{y^2}{a^2},$$

$$\theta_{E0} = \theta_0 + \Delta\theta/3$$



(from James 1994)

Θ_M based on momentum conservation

$$\theta_M = \theta_{M0} - \frac{\Omega^2\theta_0}{2a^2gH} y^4,$$

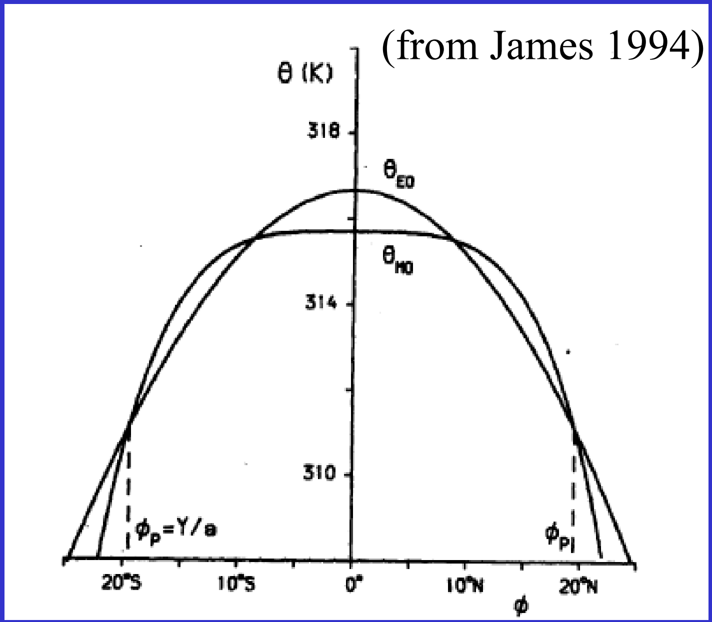
$$Y = \left(\frac{5\Delta\theta g H}{3\Omega^2\theta_0}\right)^{1/2},$$

HC Width ⟵ **Come close to the observations (too narrow)**

$$\theta_{M0} = \theta_{E0} - \frac{5\Delta\theta^2 g H}{18a^2\Omega^2\theta_0}.$$

HC Strength ⟵ **Too weak!**

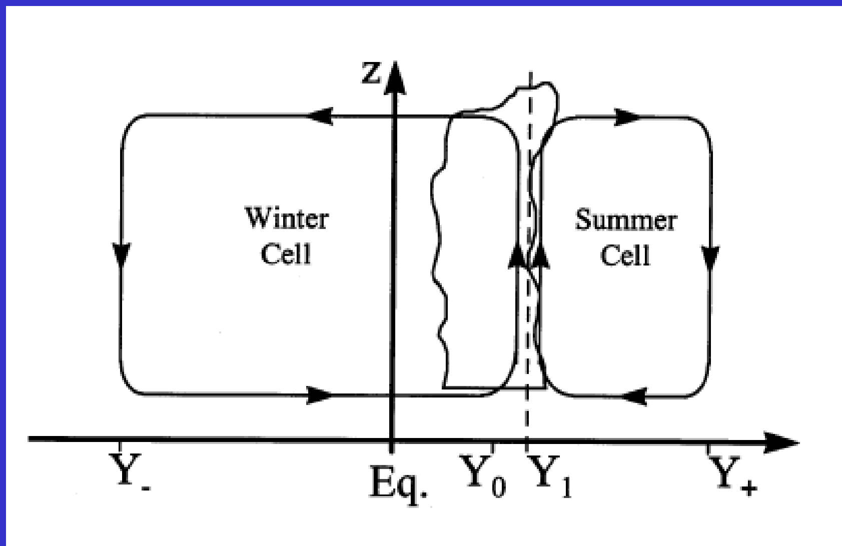
Factors Affect the Hadley Circulation Width

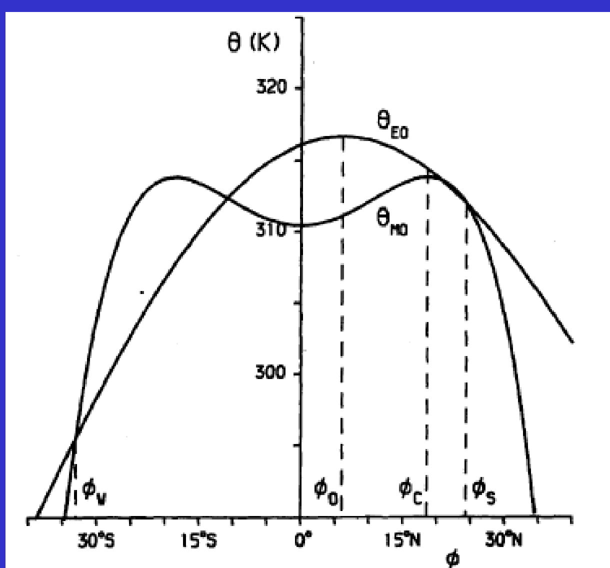


$$Y = \left(\frac{5 \Delta \theta g H}{3 \Omega^2 \theta_0} \right)^{1/2},$$

- The Held-Hou model predicts that the width of the Hadley cell is inversely proportional to the planetary rotation rate.
- At low rotation rates the Hadley cells extend far poleward and account for most of the heat transport from equator to pole.
- At high rotation rates the Hadley cells are conned near the equator and baroclinic waves poleward of the Hadley circulations are responsible for a significant proportion of the heat transport.

Held and Hou Model: *Asymmetric to Equator*





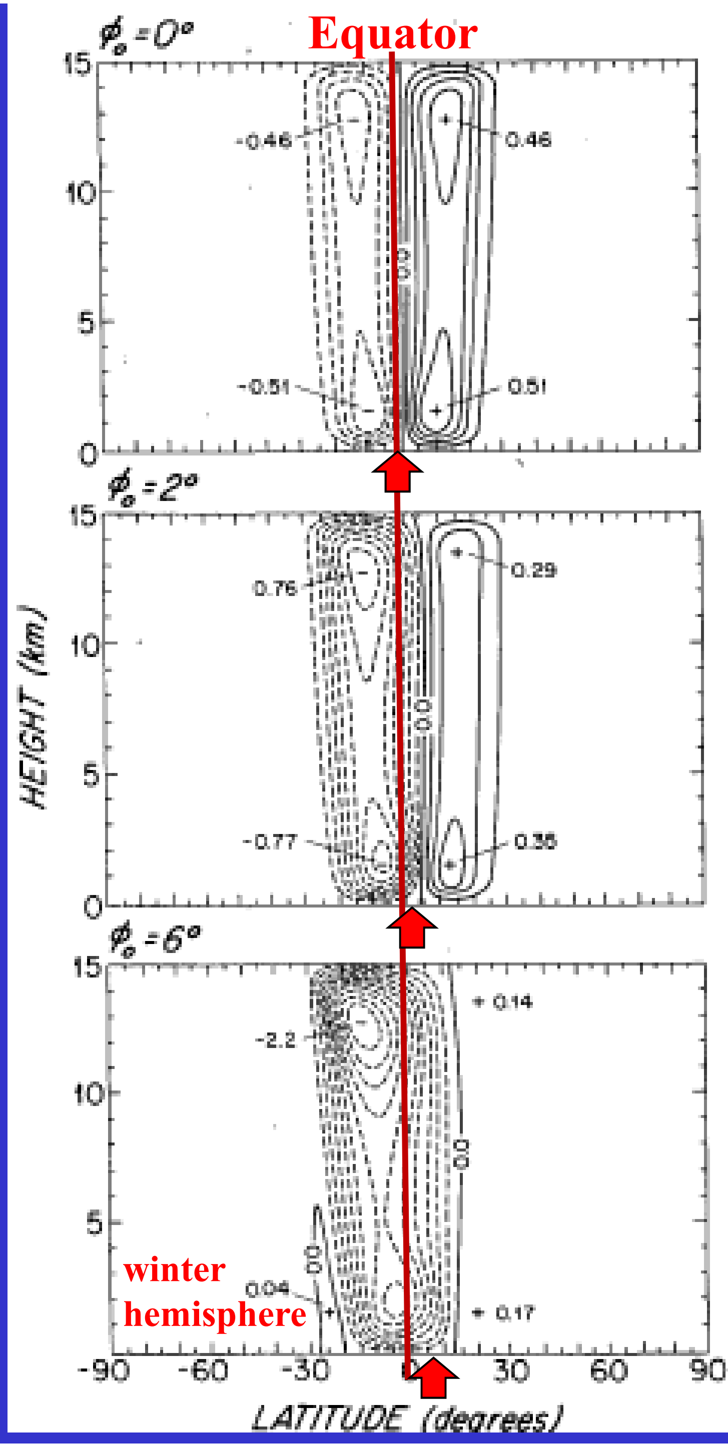
(from James 1994)

For maximum heating only 2-degree away from the equator, the winter cell is over three times as wide as the summer cell.

Off-Equatorial Heating

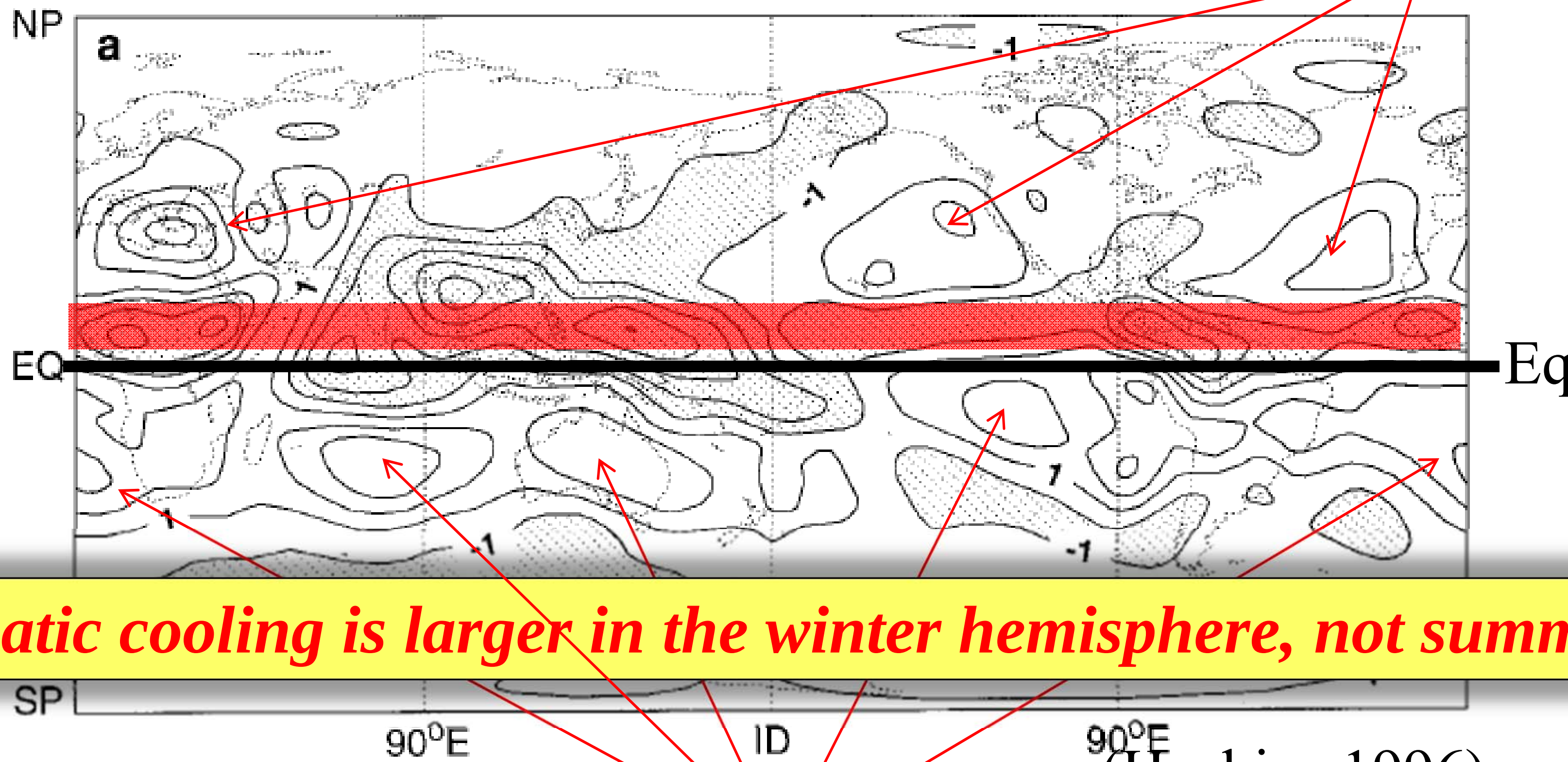
" .. We find that moving peak heating even 2 degree off the equator leads to profound asymmetries in the Hadley circulation, *with the winter cell amplifying greatly and the summer cell becoming negligible*."

--- Lindzen and Hou (1988; JAS)



Vertical Velocity ω_{500mb} (June-August 1994)

Northern (summer) subtropical descent



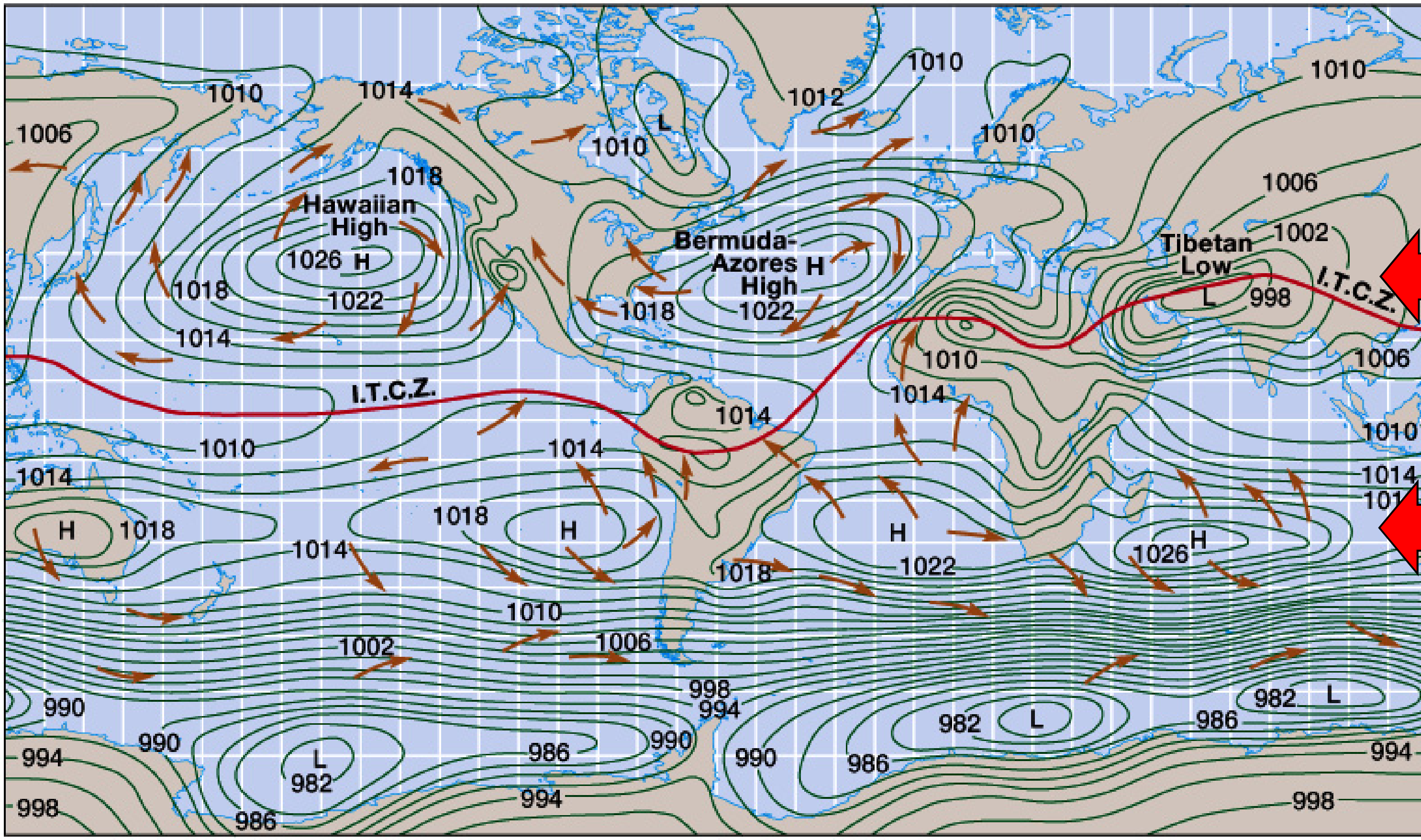
Diabatic cooling is larger in the winter hemisphere, not summer

(Hoskins 1996)

Southern (winter) subtropical descent

Subtropical Highs

July (northern summer)



Localized Highs (summer)

A Belt of Highs (winter)

- *Winter subtropical highs can be explained by the Hadley circulation*
- *Summer subtropical highs has to be explained in the contect of planetary waves*

Possible Mechanisms - Summer

The underlying mechanisms are still disputed:

(1) Monsoon-desert mechanism (Rodwell and Hoskins 1996, 2001)

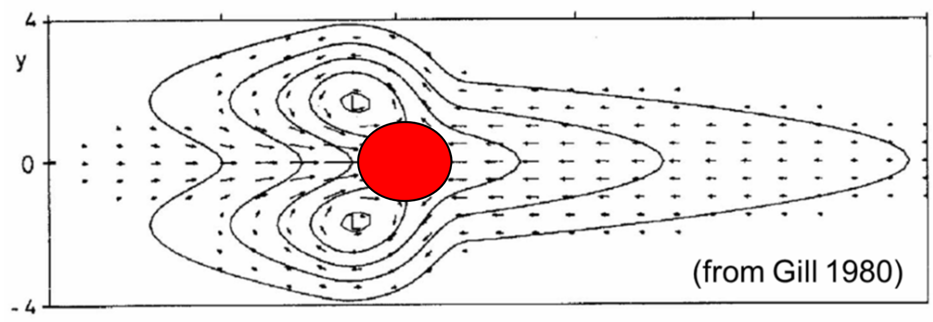
(2) Local land-sea thermal contrast (Miyasaka and Nakamura 2005)

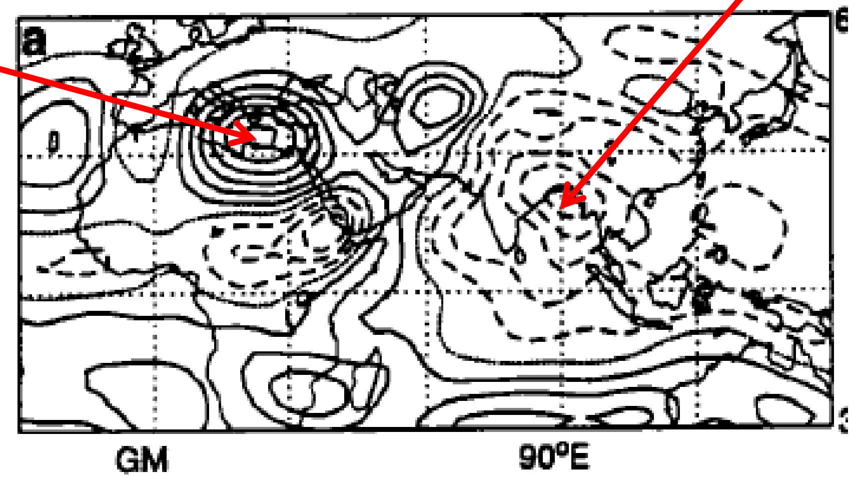
(3) Diabatic amplification of cloud-reduced radiative cooling

(4) Air-sea interaction

Monsoon-Desert Mechanism

(Rodwell and Hoskins 1996)





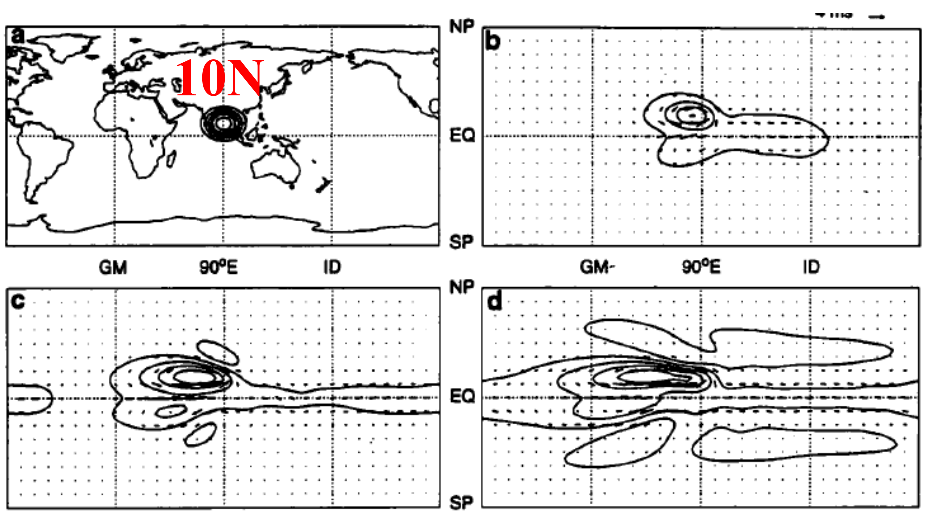


Figure 6. (a) Column-mean diabatic heating centred at 90°E, 10°N. The contour interval is 50 W m^{-2}; the zero contour is not shown. (b), (c) and (d) show the corresponding perturbation surface pressure and 887 hPa horizontal winds for an integration linearized about a resting basic-state at (b) day 3, (c) day 7 and (d) day 11. The contour interval is 1 hPa.

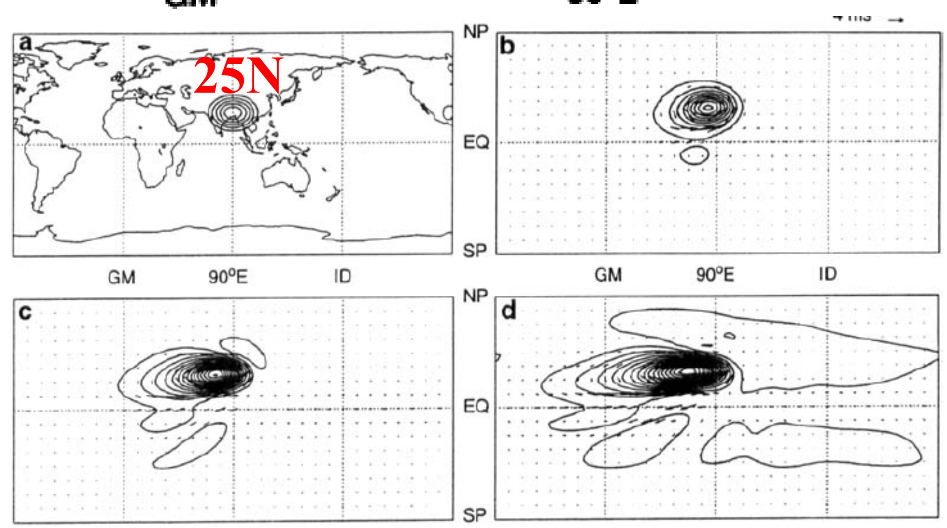


Figure 7. (a) Column-mean diabatic heating centred at 90°E, 25°N. The contour interval is 50 W m^{-2}; the zero contour is not shown. (b), (c) and (d) show the corresponding perturbation surface pressure and 887 hPa horizontal winds for an integration linearized about a resting basic-state at (b) day 3, (c) day 7 and (d) day 11. The contour interval is 1 hPa.