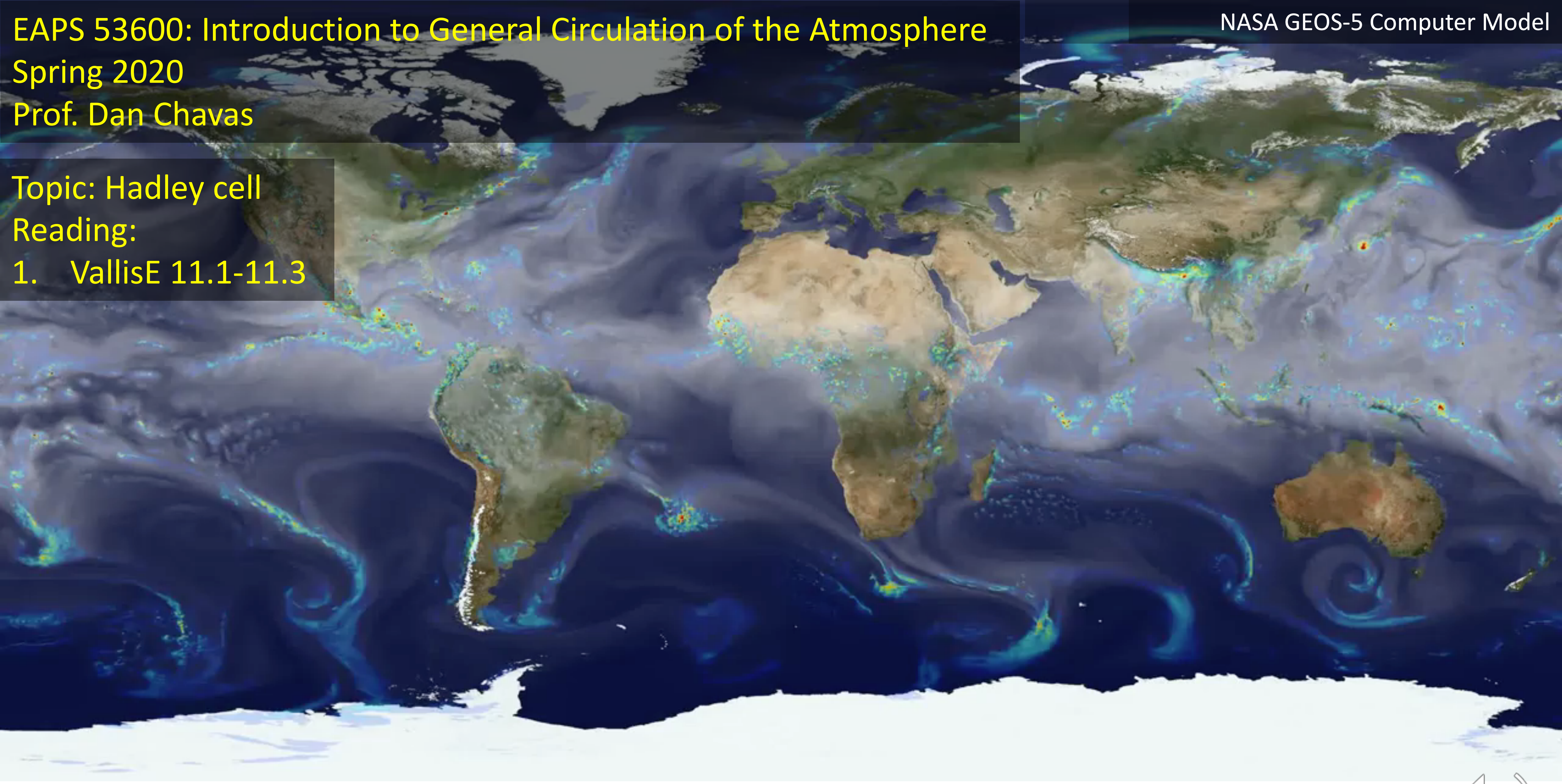
EAPS 53600: Introduction to General Circulation of the Atmosphere
Spring 2020
Prof. Dan Chavas

Topic: Hadley cell
Reading:
1. VallisE 11.1-11.3

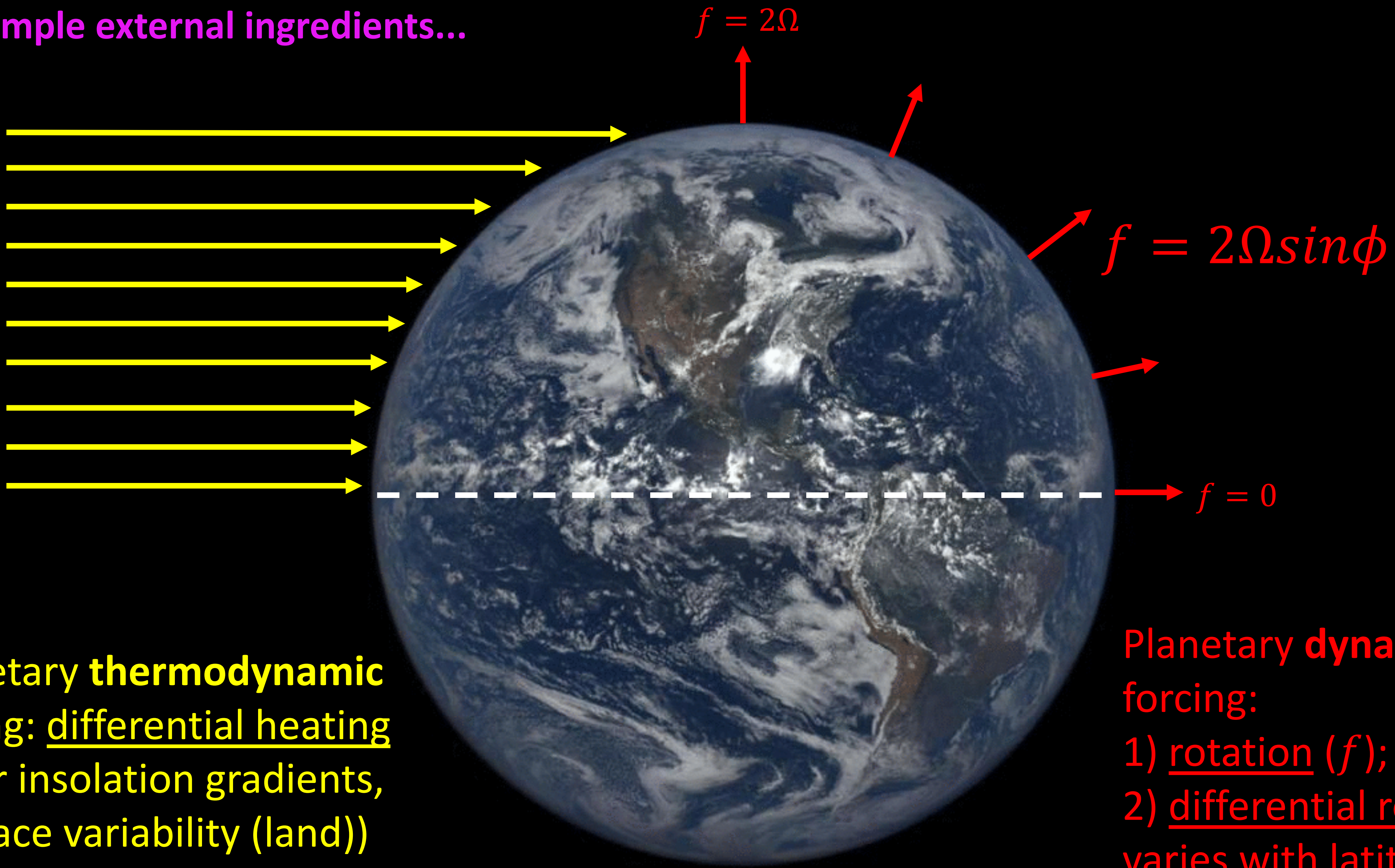


White: total precipitable water (brigher white = more water vapor in column)
Colors: precipitation rate ($0 - 15\frac{mm}{hr}$, red=highest)

Source: https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=30017

Back to the big picture...

These simple external ingredients...



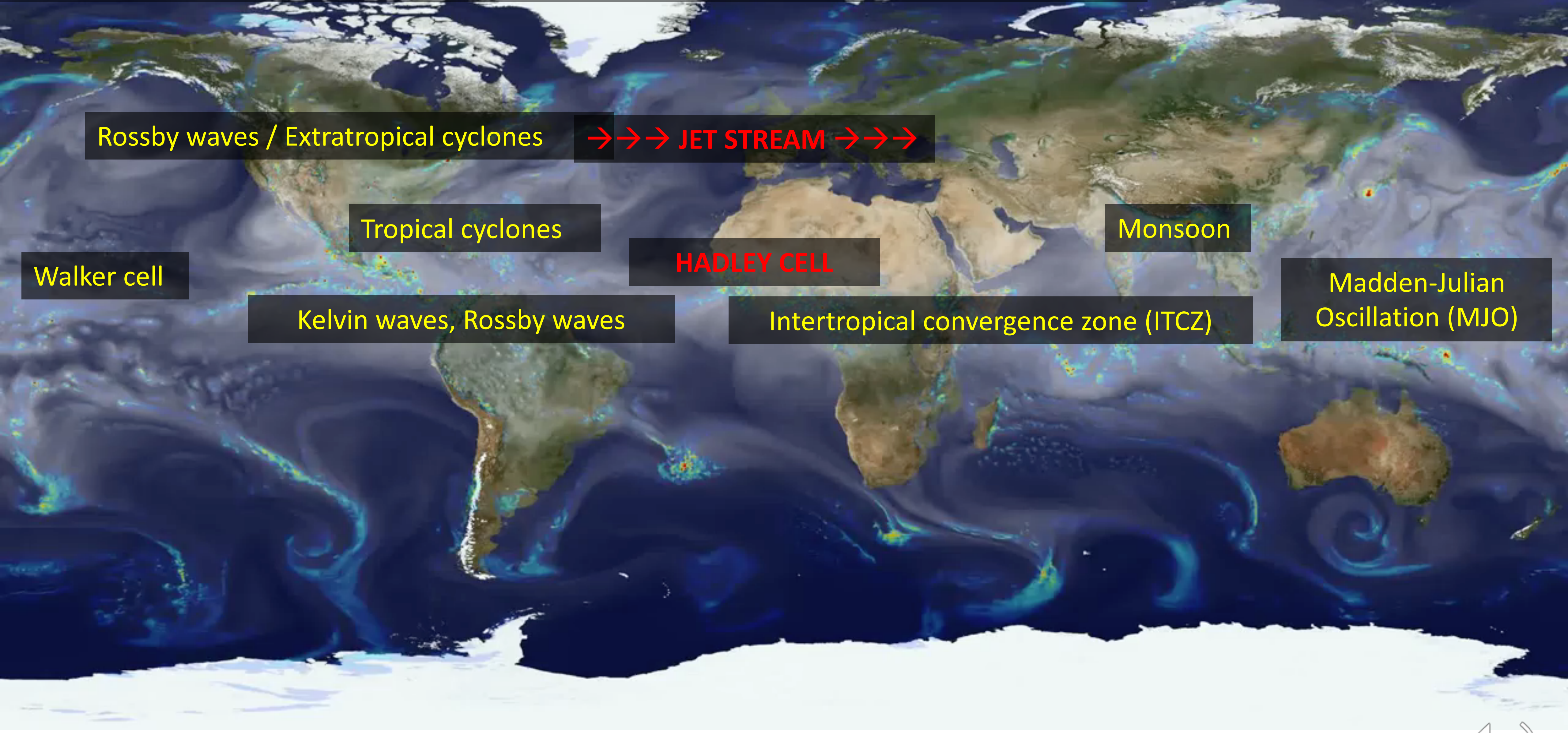
Planetary **thermodynamic** forcing: <u>differential heating</u> (solar insolation gradients, surface variability (land))

Planetary **dynamical** forcing:
1) <u>rotation</u> (f);
2) <u>differential rotation</u> (f varies with latitude)

https://media.giphy.com/media/o2XbUUi1CXKTe/

... generate many types of horizontal circulations!

NASA GEOS-5 Computer Model



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A couple of contrasts to think about

1) Tropics (**weakly-rotating**) vs. extra-tropics (**strongly-rotating**)

2) Waves vs. overturning circulations
   - **Waves** (gravity, Rossby…): require a **dynamical restoring force**
   - **Overturning circulations** (Hadley, Walker...): principally a response to **differential heating** (less dense fluids tend to rise...)

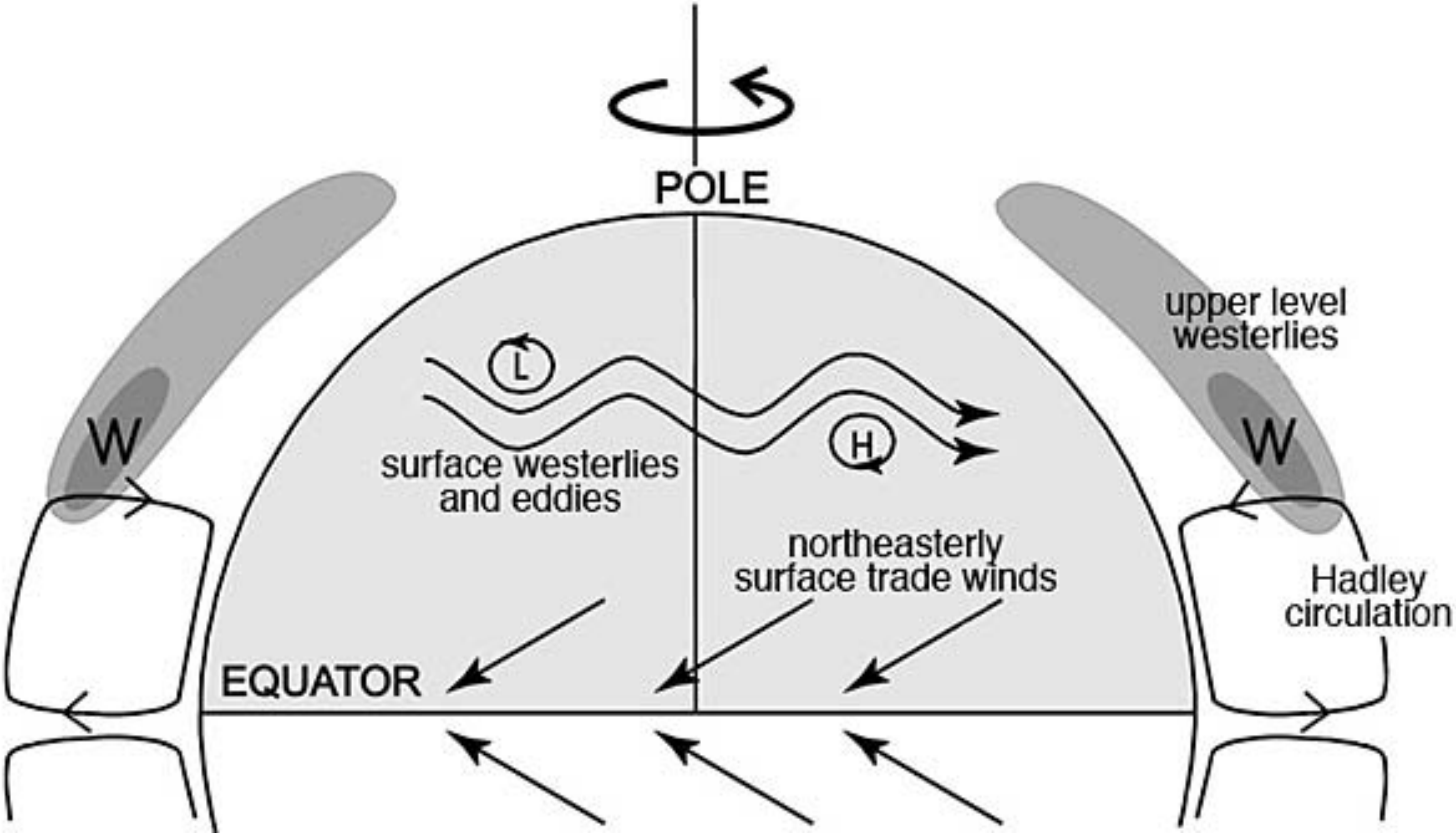

POLE
upper level westerlies
W
W
L
H
surface westerlies and eddies
northeasterly surface trade winds
Hadley circulation
EQUATOR

Fig 6.5

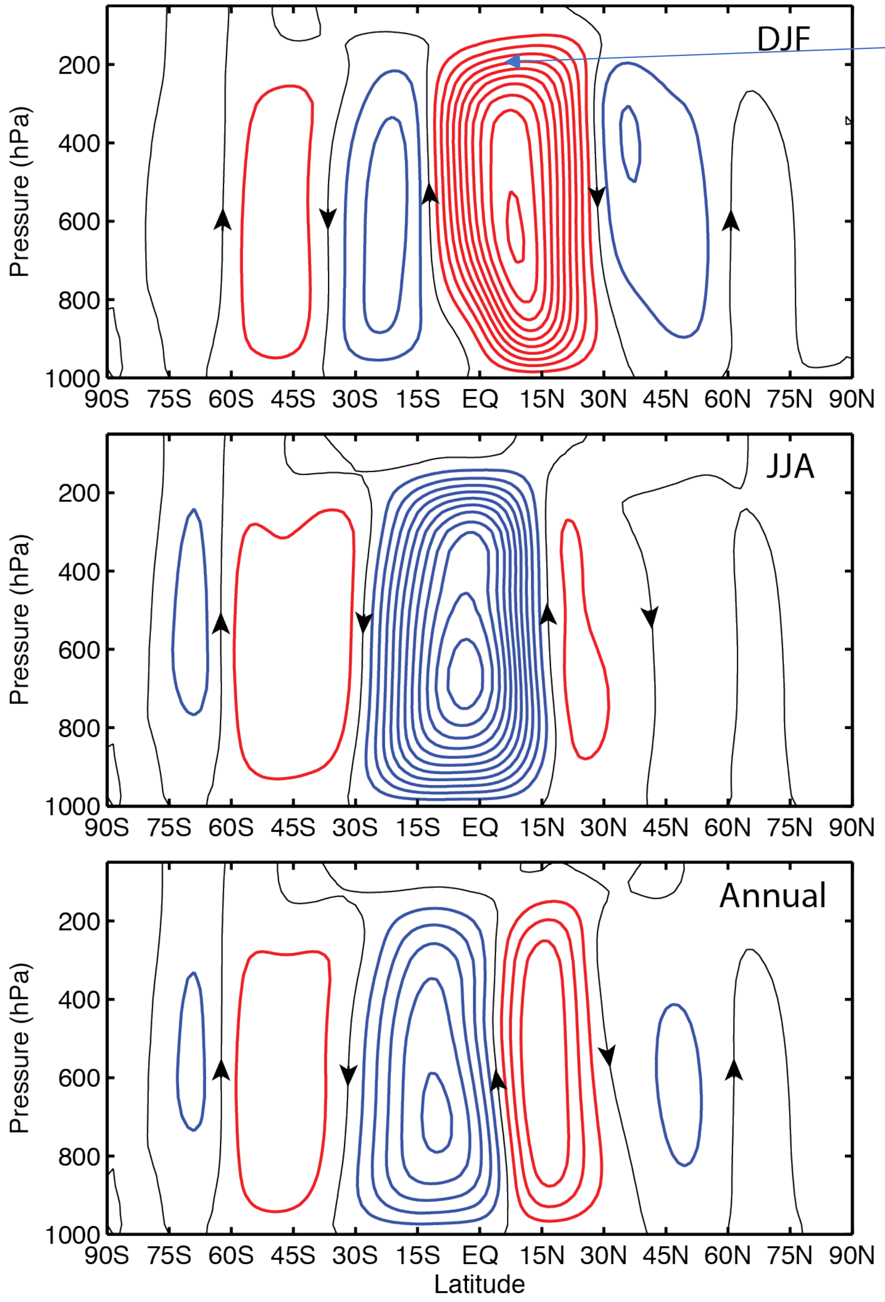
Zonal-mean meridonal/vertical overturning streamfunction

Solid = positive

Dashed = negative

Hadley cell:

- Confined to tropics (< 30 N/S)
- stronger in winter hemisphere
- thermally-direct overturning circulation (warmer fluid rises, colder fluid sinks)



$\overline{v} \sim 1$ m/s

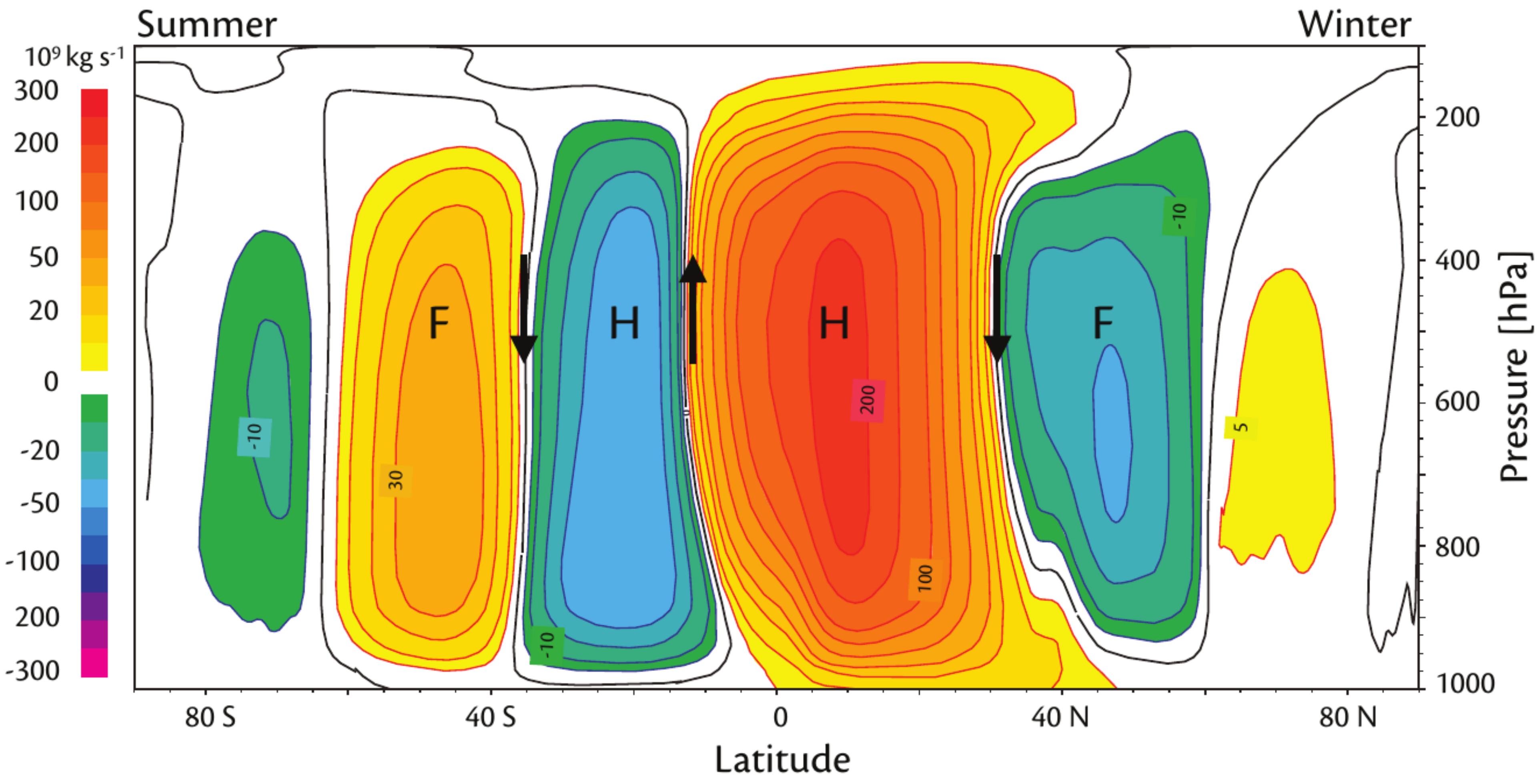
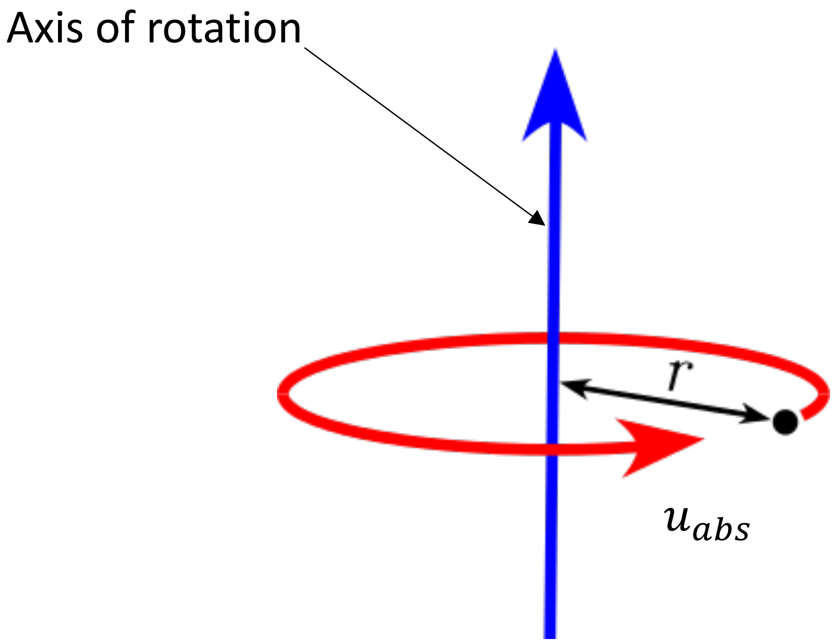

Summer
Winter
10^9 kg s^-1
300
200
100
50
20
0
-20
-50
-100
200
-300
F
H
H
F
-10
30
-10
200
100
-10
5
200
400
600
800
1000
Pressure [hPa]
80 S
40 S
0
40 N
80 N
Latitude

Fig. 11.3:

Air motion transports things poleward:

1) Energy (heat, water vapor)
2) **Angular momentum**



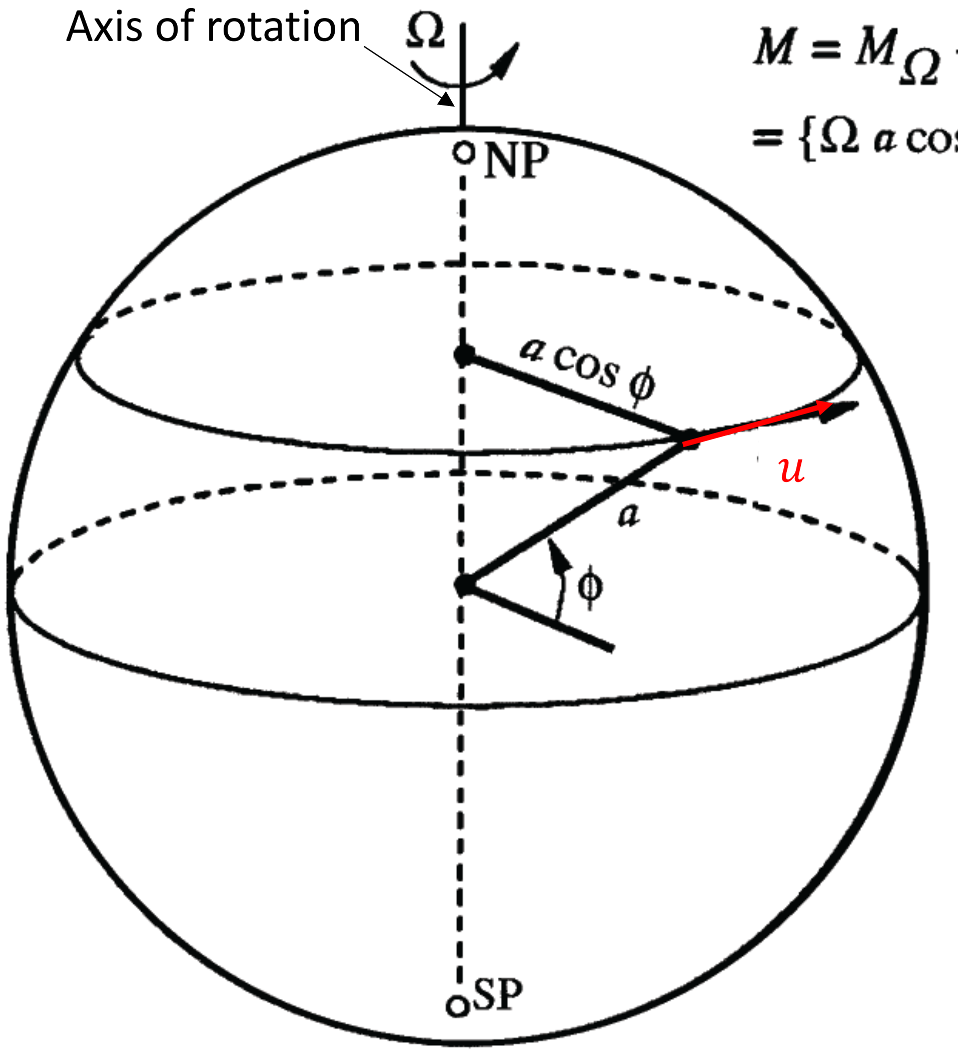
Angular momentum per unit mass:
a point mass

$$M = ru_{abs} \qquad \text{Units: } \left[\frac{m^2}{s}\right]$$

r: distance from axis of rotation
u_{abs}: absolute tangential speed

https://upload.wikimedia.org/wikipedia/commons/thumb/e/e8/PointInertia.svg/272px-PointInertia.svg.png

Angular momentum of an air parcel



$M = M_\Omega + M_r$

$= \{\Omega a \cos\phi + u) a \cos\phi$

Angular momentum of an air parcel per unit mass

$$\boxed{\boldsymbol{M} = \underbrace{\boldsymbol{a\cos\phi}}_{r}\underbrace{(\boldsymbol{\Omega a\cos\phi} + \boldsymbol{u})}_{u_{abs}}}$$

Units: $\left[\frac{m^2}{s}\right]$

r Distance from axis of rotation

u_{abs} Absolute tangential speed

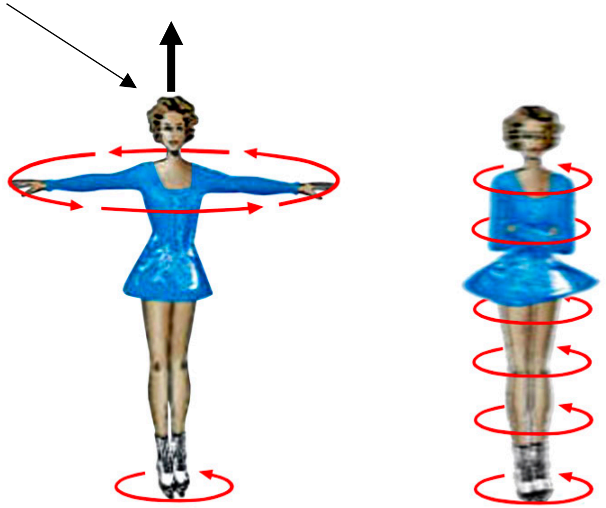
Tangential speed of Earth (solid-body rotation)

zonal wind speed (relative to Earth's motion)

IMPORTANT: this defines **positive angular momentum** to be **westerly** (this is the direction of the Earth's rotation!)

Conservation of angular momentum: M is constant unless acted on by a torque.

Axis of rotation



Mass is moved to smaller radius,
so the skater spins faster.

Angular momentum per unit mass:
a point mass

$$M = ru_{abs} \qquad \text{Units: } \left[\frac{m^2}{s}\right]$$

r: distance from axis of rotation
u_{abs}: absolute tangential speed

https://upload.wikimedia.org/wikipedia/commons/thumb/e/e8/PointInertia.svg/272px-PointInertia.svg.png

In the atmosphere, air **above the boundary layer** is nearly ***inviscid*** – i.e. frictionless. Thus it nearly **conserves its angular momentum** as it moves.

(In the boundary layer, surface friction acts acts as a torque that weakens zonal motion.)

Air moving **poleward** will be **accelerated toward the east**. (this is just the zonal component of the Coriolis force)

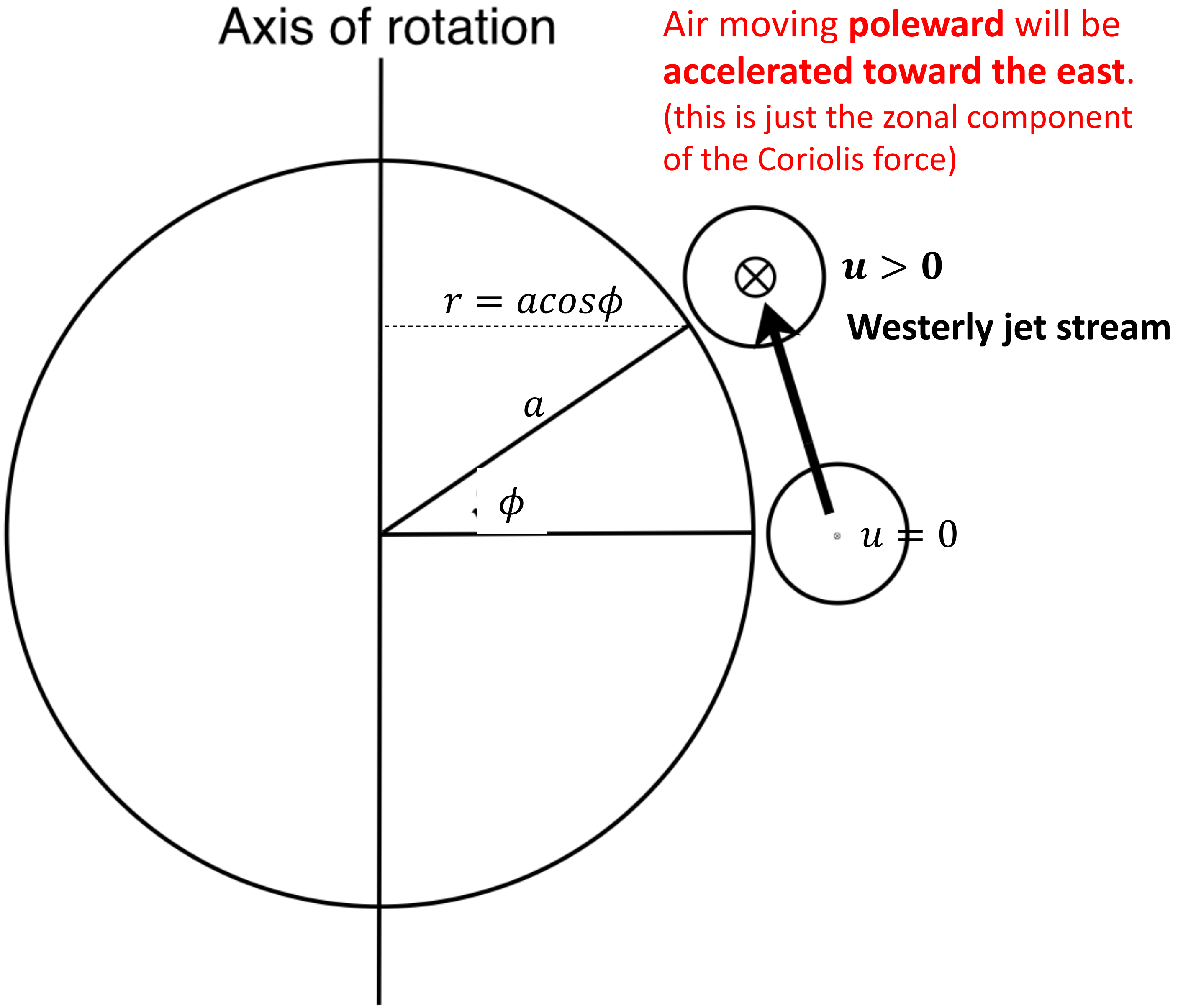
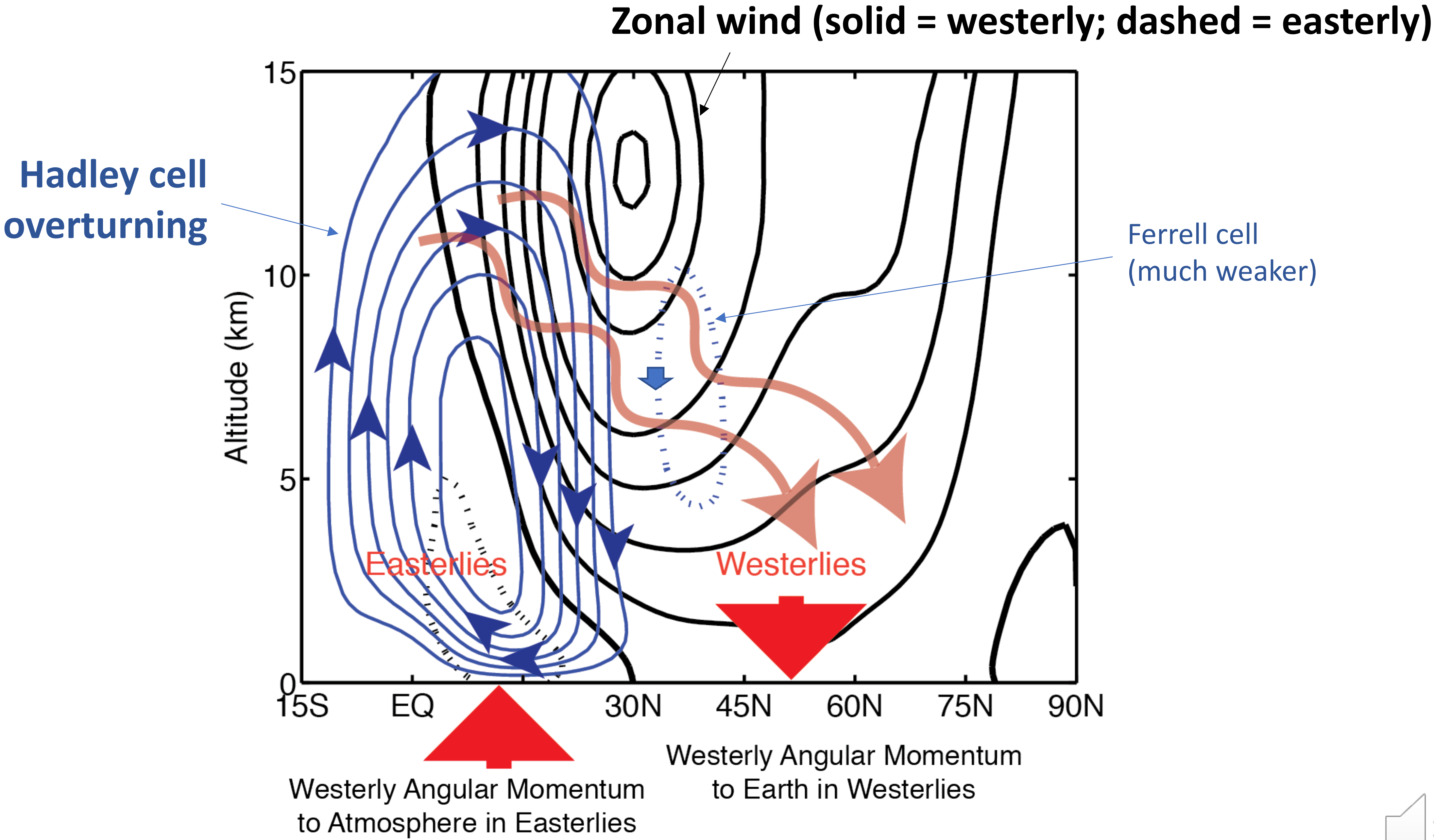


Fig. 14.5

Fig 6.17



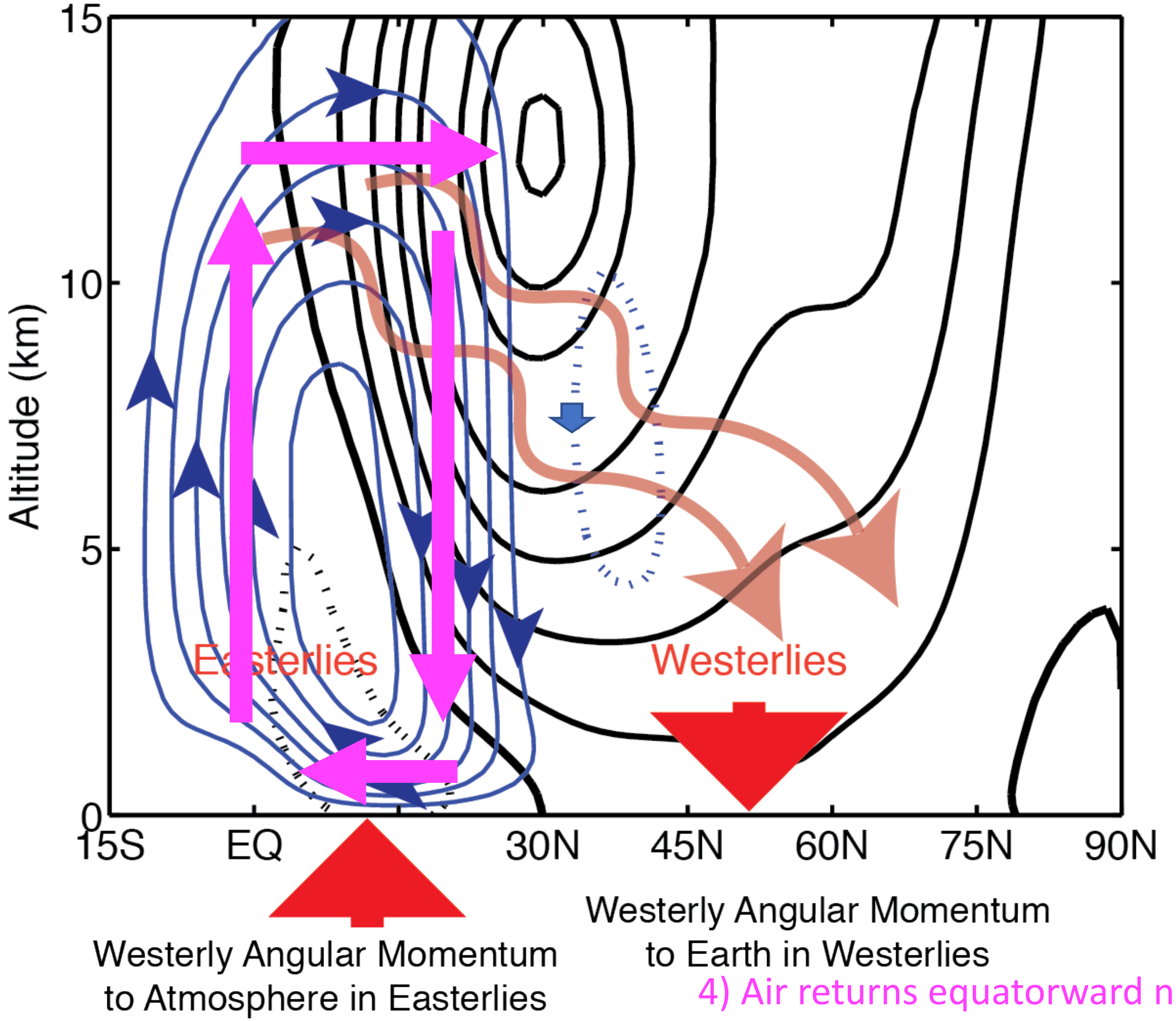
Zonal wind (solid = westerly; dashed = easterly)
Hadley cell overturning
Ferrell cell (much weaker)
15
10
5
0
Altitude (km)
Easterlies
Westerlies
15S
EQ
30N
45N
60N
75N
90N
Westerly Angular Momentum to Atmosphere in Easterlies
Westerly Angular Momentum to Earth in Westerlies

Fig 6.17

2) Air then moves poleward while conserving its angular momentum. The result is a **westerly jet stream** (solid black contours; out of the page).

1) Warm, moist air rises near the equator within the ITCZ.

Much of the moisture is rained out within the ITCZ.



Formally this is the subtropical jet stream. Though it is typically merged with the mid-latitude jet stream.

3) Air then gradually subsides in the descending region over the subtropics.

This suppresses convection/precipitation. Thus the subtropics are often deserts.

4) Air returns equatorward near the surface. Angular momentum is <u>not</u> conserved; **surface friction** weakens the flow. The result is weak easterly **trade winds**.

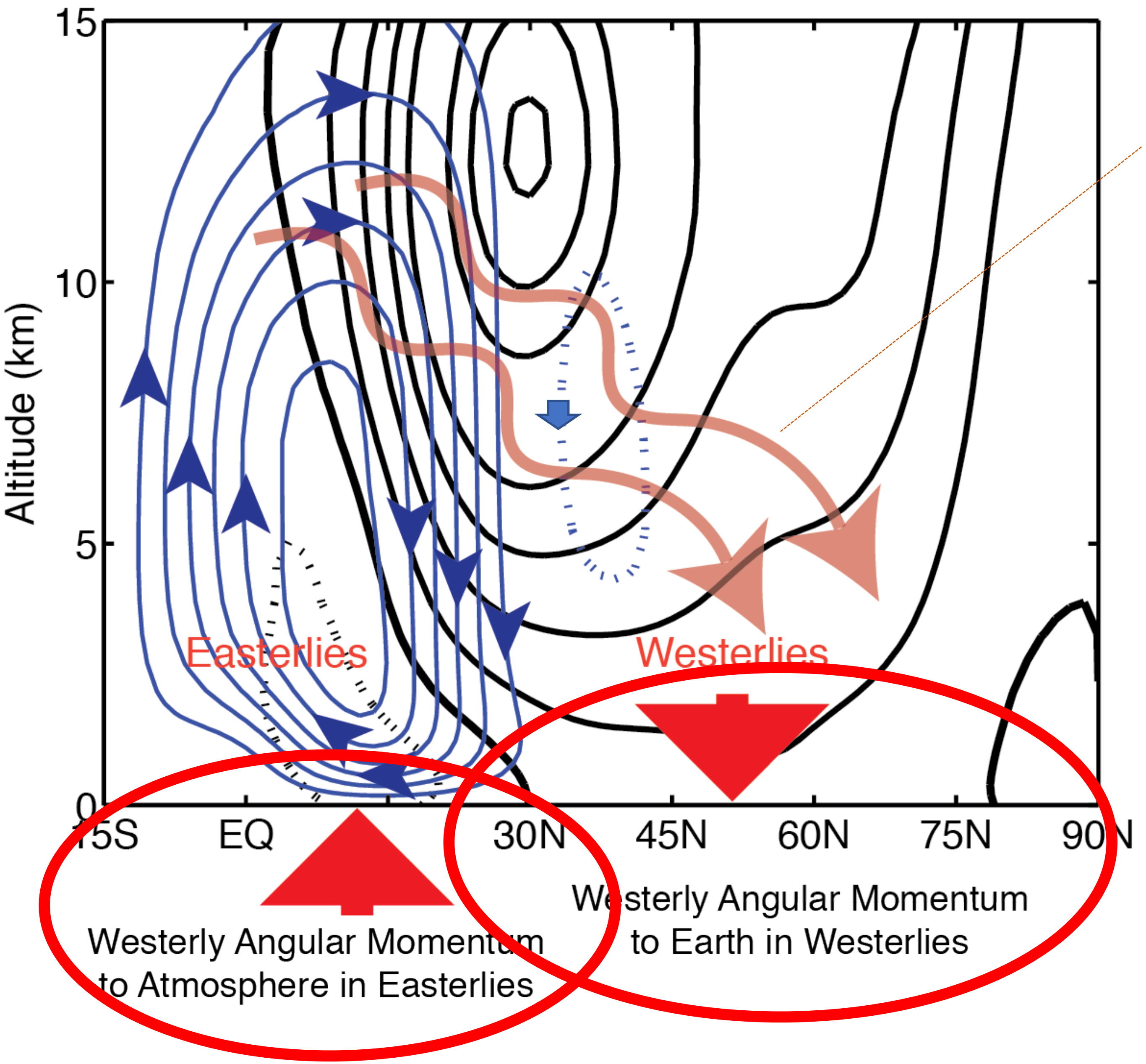
Fig 6.17

In the time-mean, global-mean, **angular momentum balance** must hold.

$$\frac{\partial M_{global}}{\partial t} = 0 = sources - sinks$$

Surface friction acting on:

- **Easterly flow** is a **source** of angular momentum
- **Westerly flow** is a **sink** of angular momentum



Something must **move this westerly angular momentum poleward and down to the surface**!

The Eulerian mean circulation can't do it. Instead **eddies/waves do this transport.**

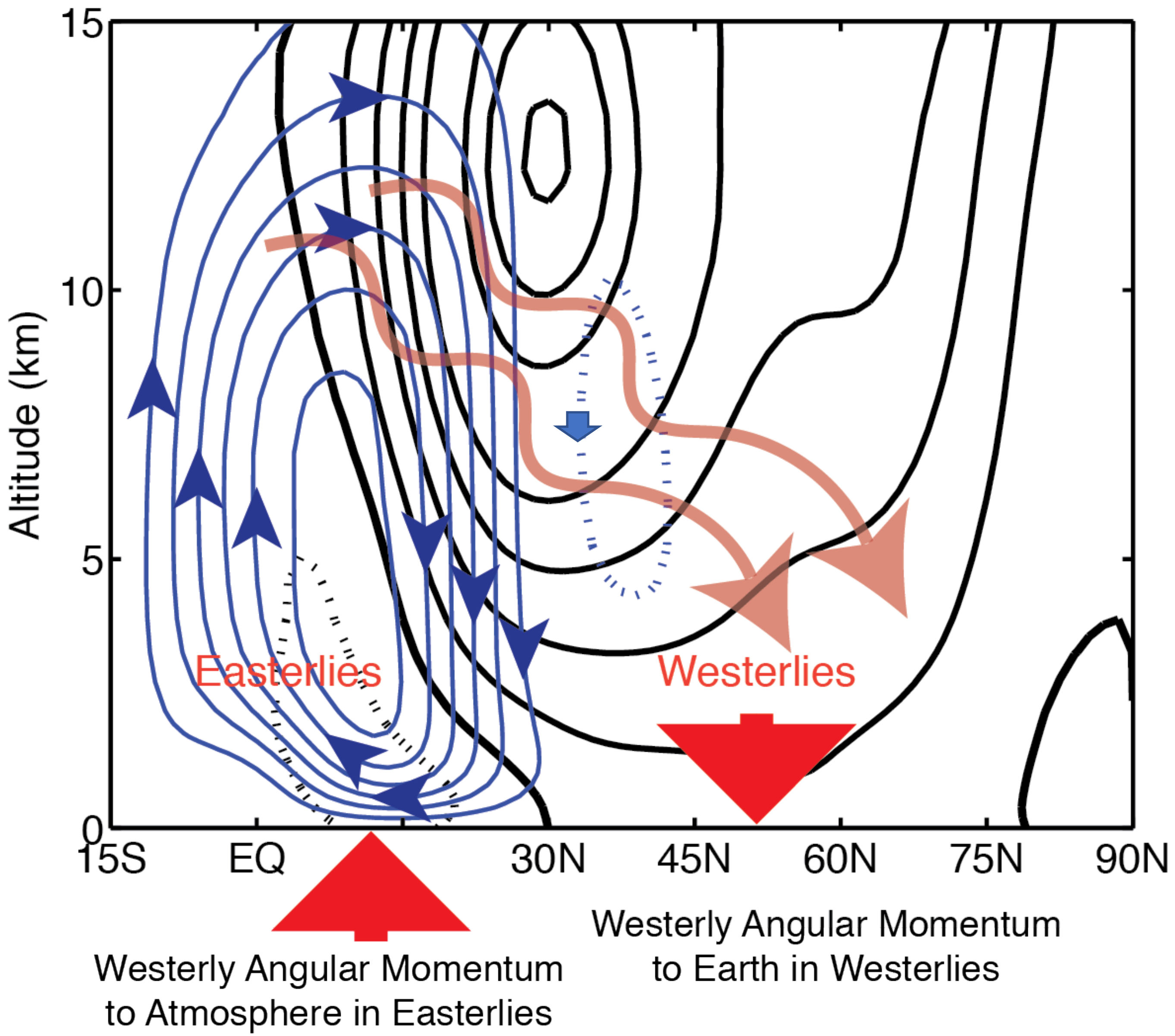
This is really important!

Fig 6.17

The **mean state depends on** transport of energy and angular momentum by **circulations and eddies**.

However, the properties of these **circulations and eddies also *depend* on the mean state**.

So there is a mutual interaction – **"eddy-mean flow interaction"** – that is fundamental, but is hard to deconvolve.



Hadley cell theory: symmetric about the equator

The logic:

1. **As air moves poleward**, the zonal wind (u) increases with latitude (angular momentum conservation).
2. Since near-surface flow is weak, this means the **vertical shear of the zonal wind** $\left(\frac{\partial u}{\partial z}\right)$ **also increases with latitude.**
3. At steady state (**thermal wind balance**), this shear must also have a **meridional temperature gradient** $\left(\frac{\partial \theta}{\partial \phi}\right)$ that increases with latitude.

What stops this from continuing all the way to the poles?

(i.e. what sets the poleward edge of the Hadley cell?)

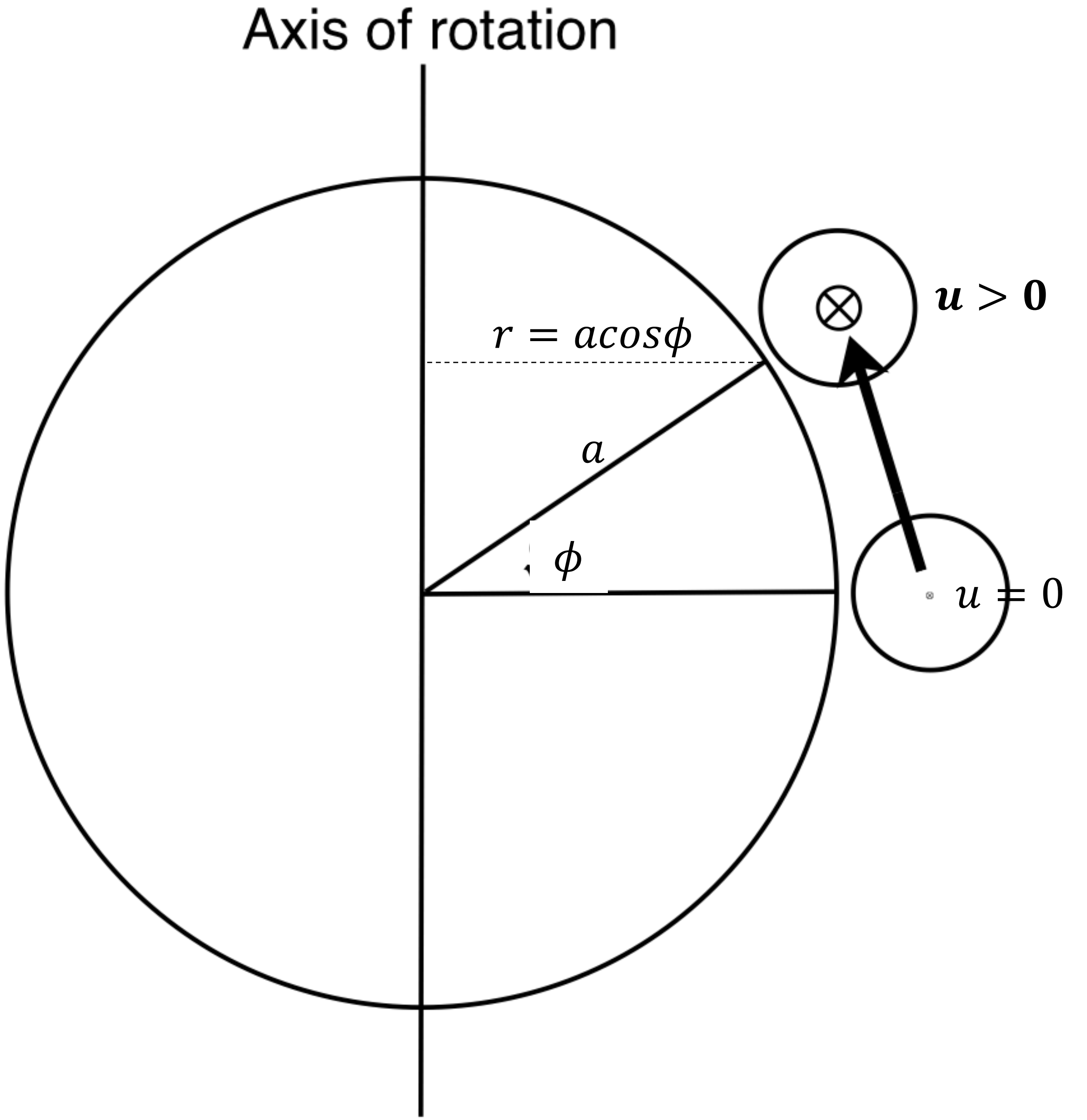


Fig. 14.5

Angular momentum conserving (AMC) solution

$$M(\phi) = M(0)$$

$$a\cos\phi(\Omega a\cos\phi + u) = \Omega a^2$$

$$\boxed{u_{AMC}(\phi) = \Omega a \frac{\sin^2\phi}{\cos\phi}}$$

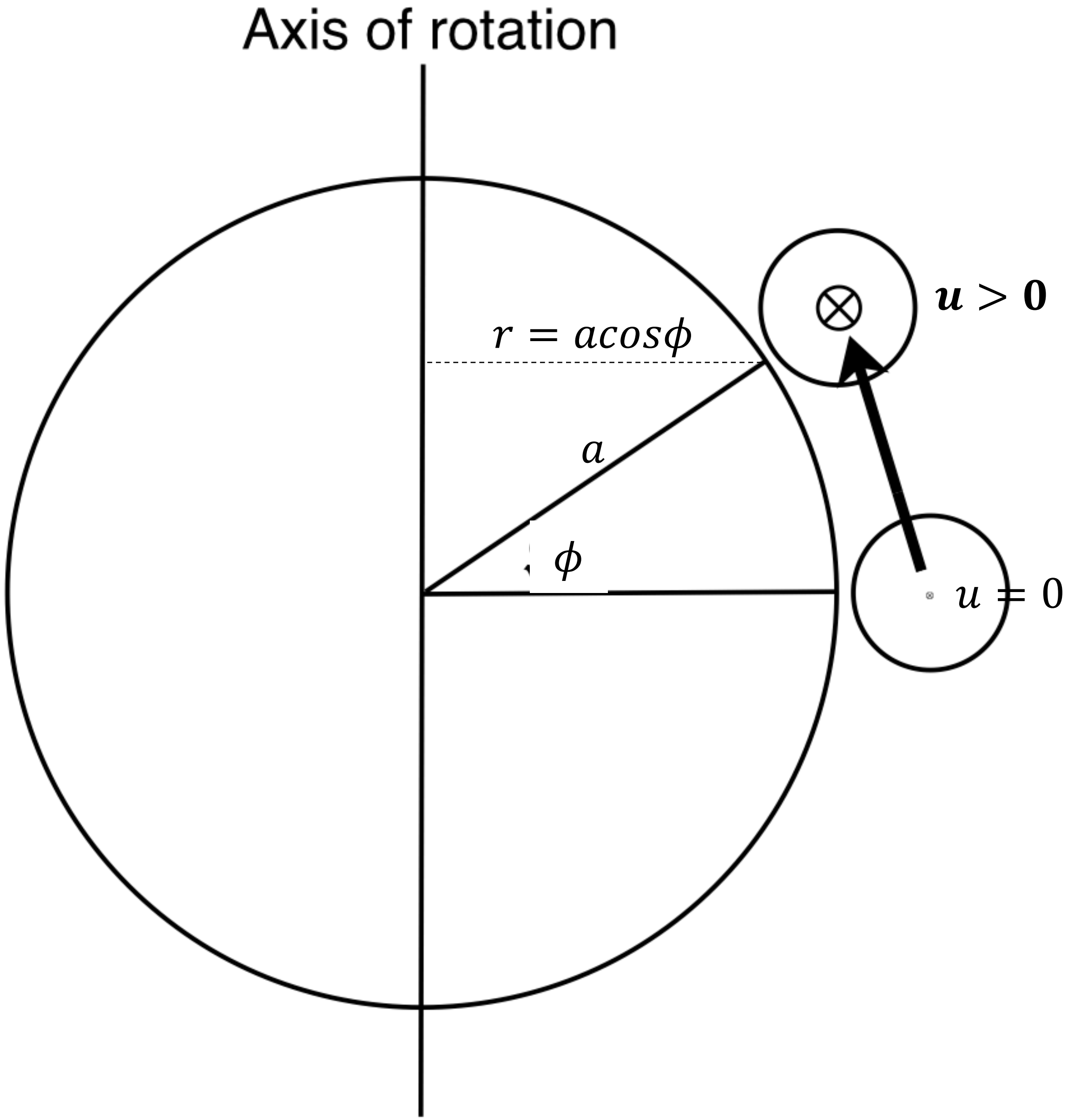


Fig. 14.5

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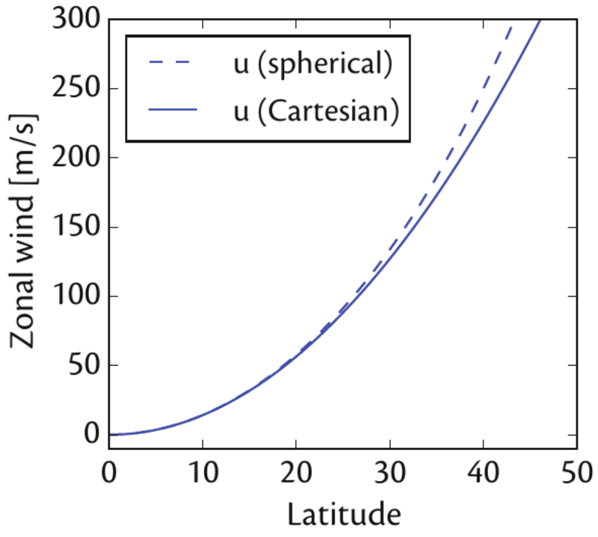
$$\boxed{u_{AMC}(\phi) = \Omega a \frac{\sin^2 \phi}{cos\phi}}$$

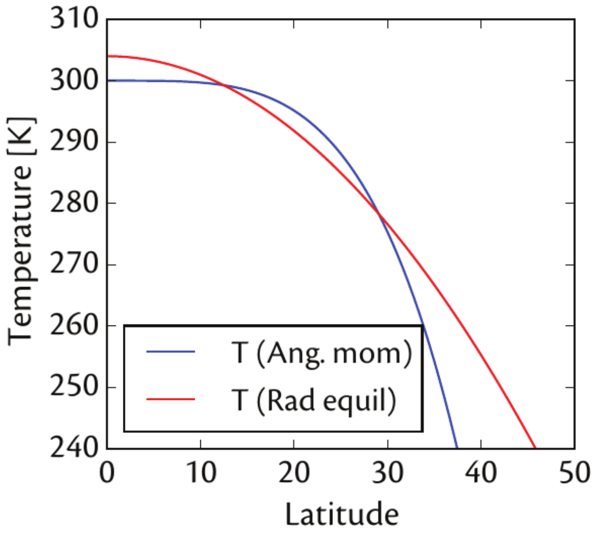
Thermal wind balance:

$$2\Omega sin\phi \frac{\partial u}{\partial z} = -\frac{g}{a\theta_0}\frac{\partial \theta}{\partial \phi}$$

Vertical-mean potential temperature:

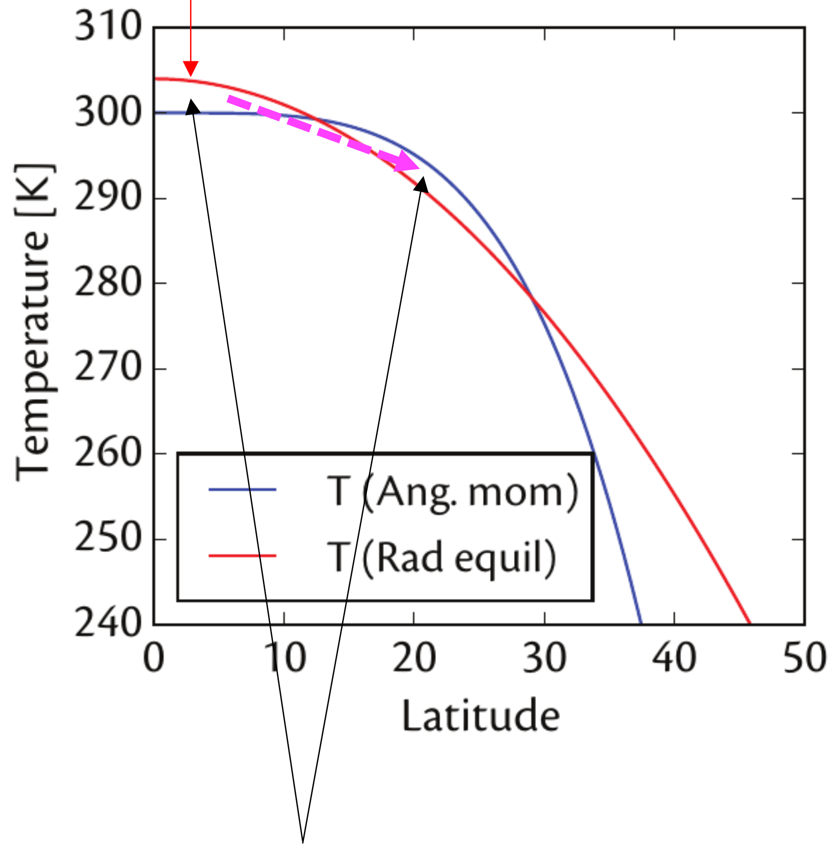
$$\boxed{\overline{\theta}_{AMC}(\phi) = \theta(0) - \frac{\theta_0 \Omega^2 a^2 \phi^2}{2gH}}$$





“Held-Hou” theory (Held and Hou 1980)

If the atmosphere *didn’t* move – no Hadley cell (radiative equilibrium)



Eddy heat transport is given by: $-v'\frac{dT'}{dy}$

$v' > 0$

$\frac{dT'}{dy} < 0$

This is positive – i.e. **poleward!**

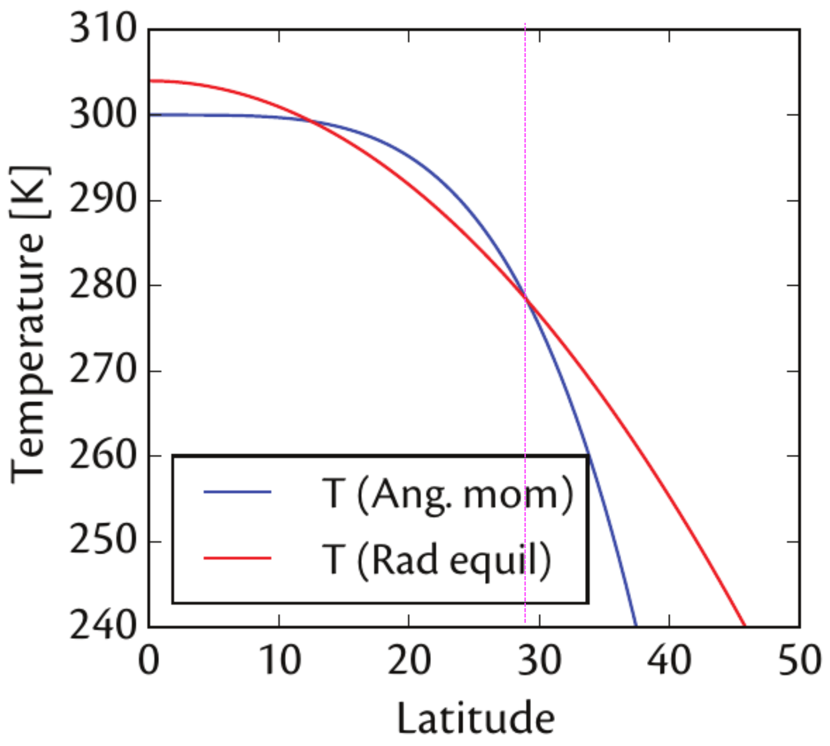
Our Hadley solution, if true, must transport heat polewards!

Low latitudes: $\overline{\theta}_{AMC} < \overline{\theta}_{RE}$ -- Hadley cell causes **cooling**

HIgh latitudes: $\overline{\theta}_{AMC} > \overline{\theta}_{RE}$ -- Hadley cell causes **warming**

This theory says that the Hadley cell strength depends on $\boldsymbol{\overline{\theta}_{AMC}}$ - $\boldsymbol{\overline{\theta}_{RE}}$

"Held-Hou" theory (Held and Hou 1980)



A thermodynamic constraint! Conservation of energy

"Equal area":

total heat removed from low latitudes

=

total heat added to high latitudes

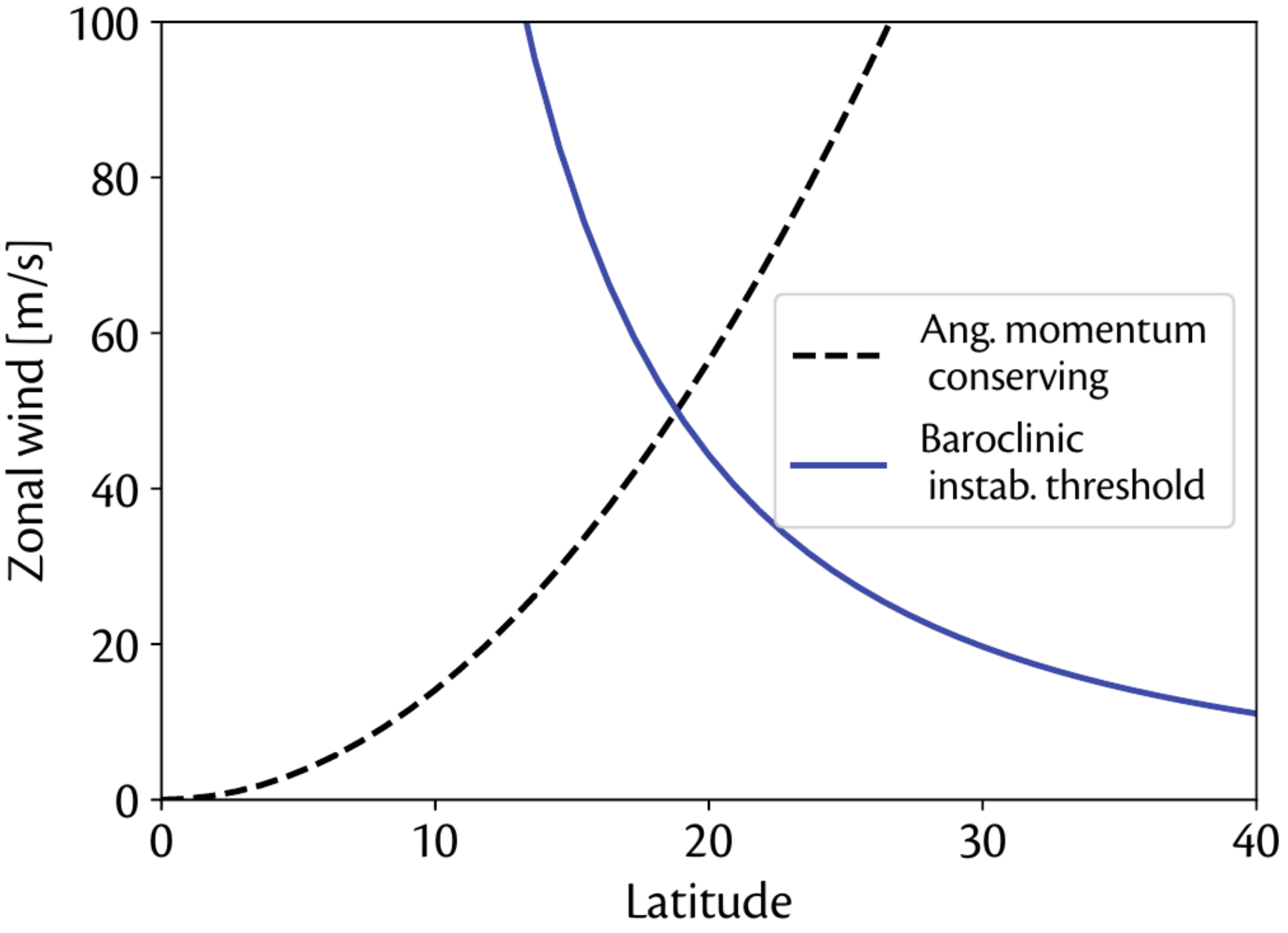
$$\boxed{\phi_{max} = \sqrt{\frac{2\Delta\theta g H}{\Omega^2 a^2 \theta_0}}}$$

$\Delta\theta$: equator-pole temperature difference

This theory predicts the poleward edge of the Hadley cell to be around 30°

(Note: the answer is sensitive to assumption of how quickly $\overline{\theta}_{RE}$ decreases with latitude)

A dynamical constraint: baroclinic instability



As the **vertical wind shear** increases, eventually the system becomes baroclinically unstable and the jet will break down into eddies.

$$\boxed{\phi_{max} = \sqrt{\frac{NH}{2\Omega a}}}$$

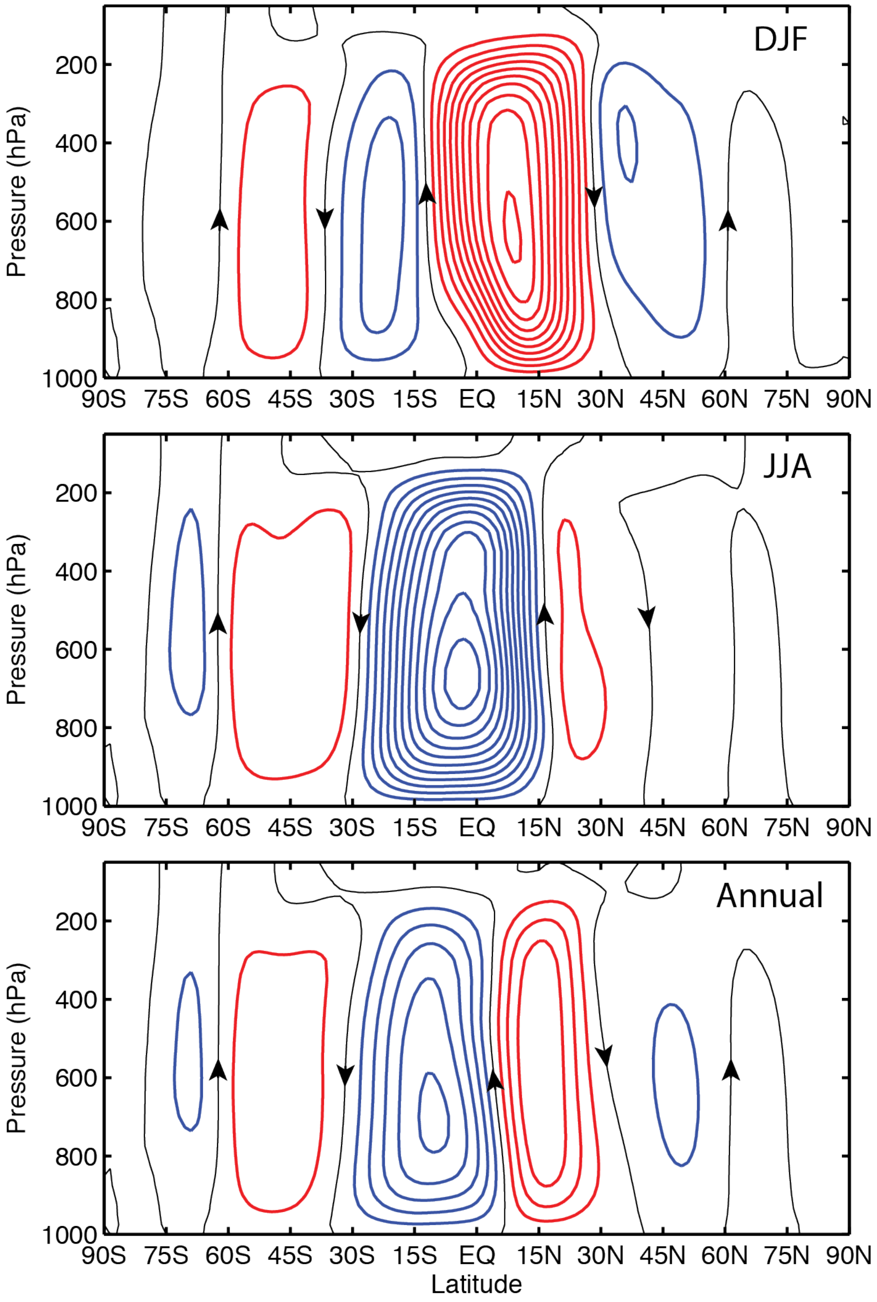
This theory predicts the poleward edge of the Hadley cell to be around 20^o

Both of these constraints are likely important for limiting the meridional extent of the Hadley cell to within 30^o.

Fig 6.5

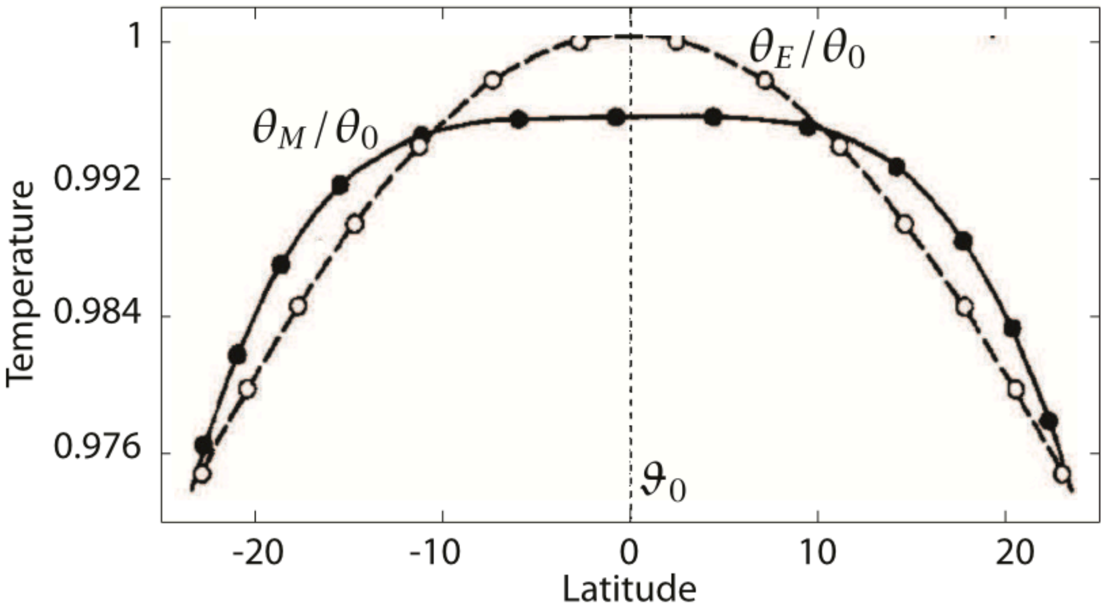
But why is the **seasonal cycle** of the Hadley cell **so strong**?

And why is the Hadley cell so much stronger in the *winter* hemisphere?



Peak temperature at equator
(Held Hou 1980)

Peak temperature off equator
(Lindzen Hou 1988)



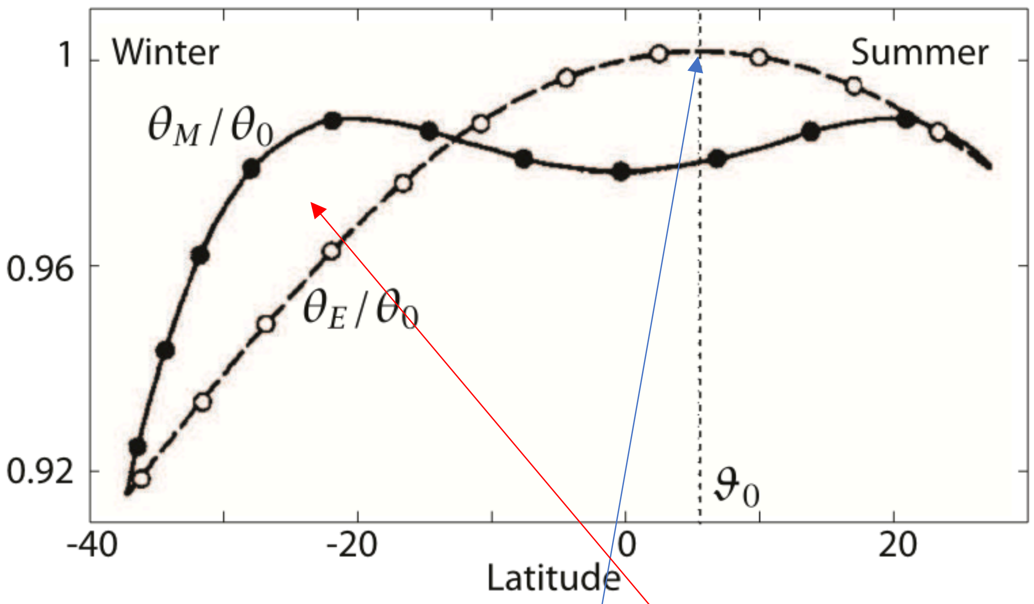


Fig. 14.10

Based on the thermodynamic constraint (Held-Hou):

Hadley cell strength ($\overline{\psi}$ or $\overline{v}$) depends on $\overline{\boldsymbol{\theta}}_{AMC}$ - $\overline{\boldsymbol{\theta}}_{RE}$

In the Summer, the peak radiative-equilibrium temperature is shifted towards the summer hemisphere.

Now $\overline{\boldsymbol{\theta}}_{AMC}$ - $\overline{\boldsymbol{\theta}}_{RE}$ is much larger in the *Winter* hemisphere!

Thus, this correctly predicts that the Hadley cell should be much stronger in the winter hemisphere.

Theory: Lindzen and Hou (1988)

Lindzen and Hou (1988) JAS
Figure 9

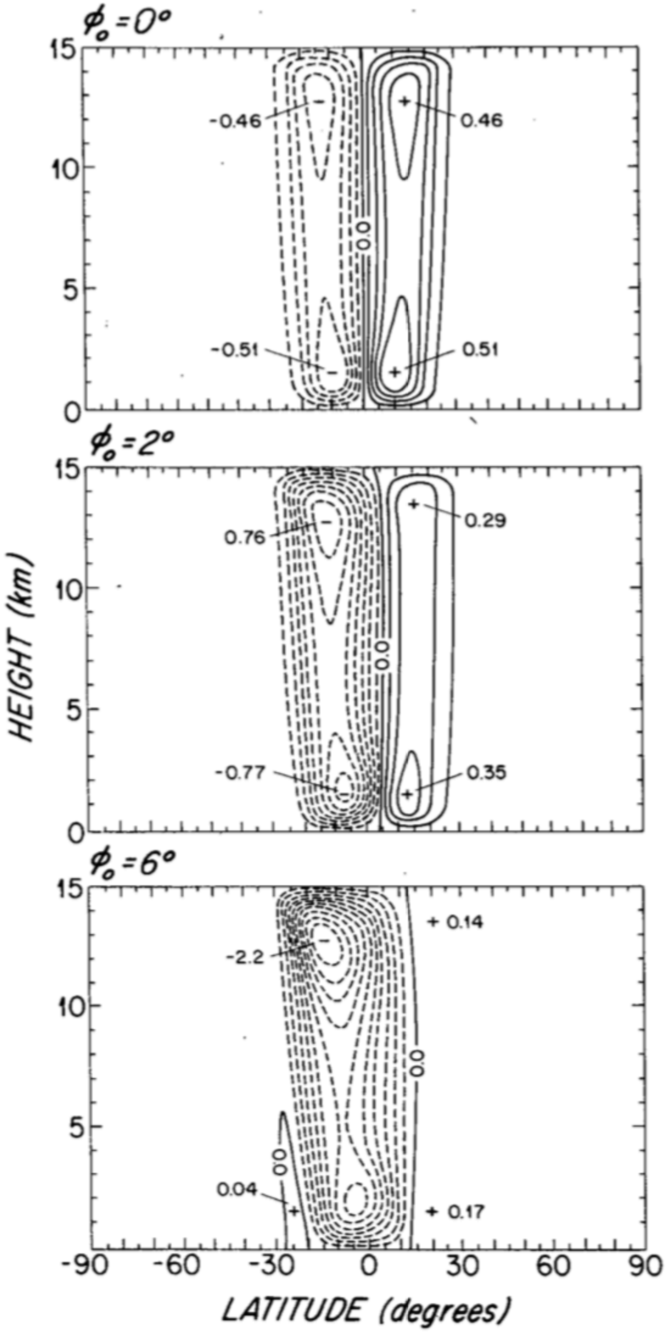


FIG. 9. Numerical model results for ψ for (a) $\phi_0 = 0°$, (b) $\phi_0 = 2°$, and (c) $\phi_0 = 6°$. Units are in 10^{10} kg s^{-1} and the contour interval is 0.1×10^{10} kg s^{-1} for (a) and (b); twice this value for (c).

Now go to Blackboard to answer a few questions about this topic!