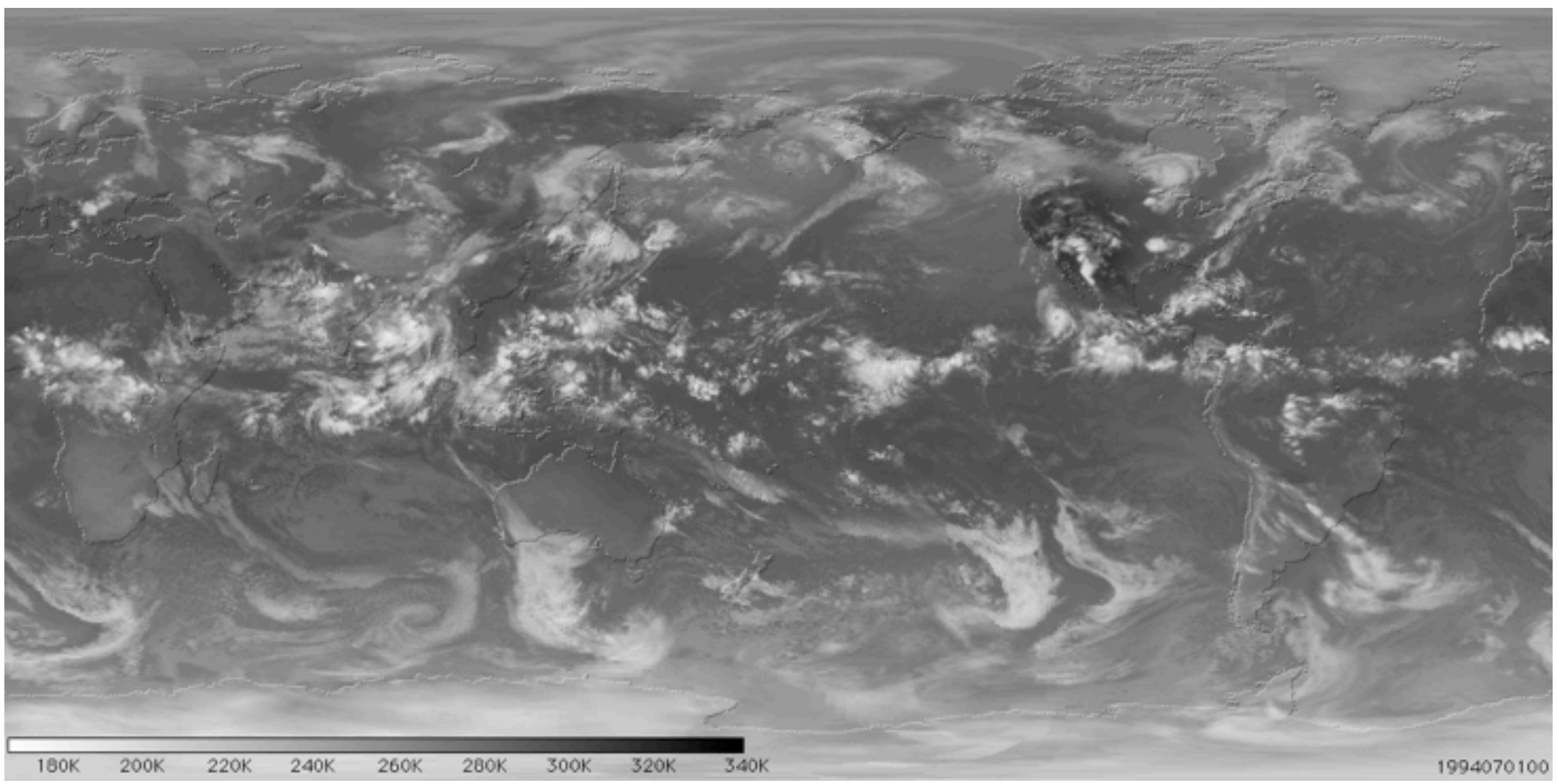
Grand Challenges in Global Circulation Dynamics

Tapio Schneider

ETH Zurich, Caltech



(*Source:* CLAUS, http://badc.nerc.ac.uk/data/claus/)

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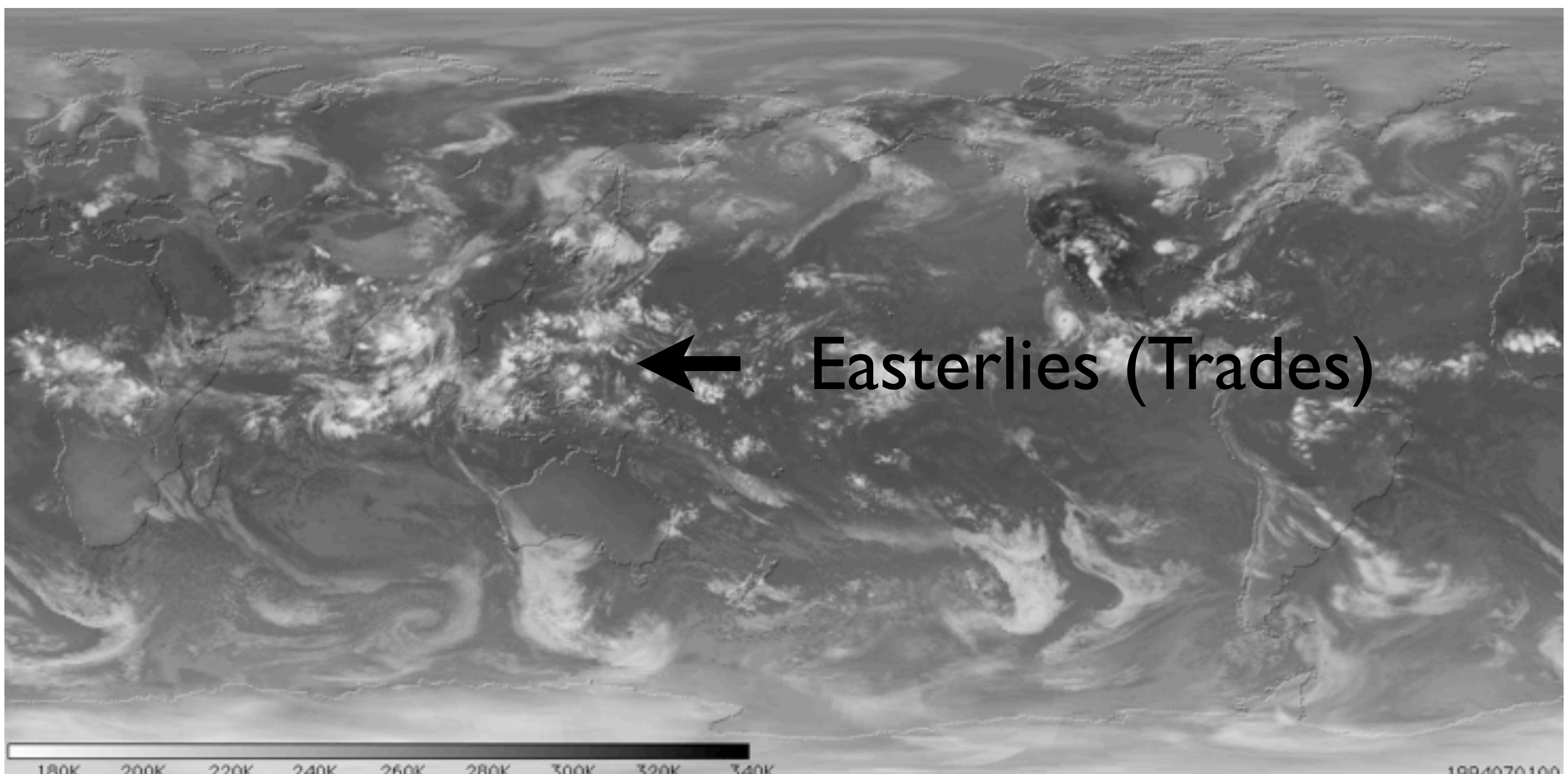

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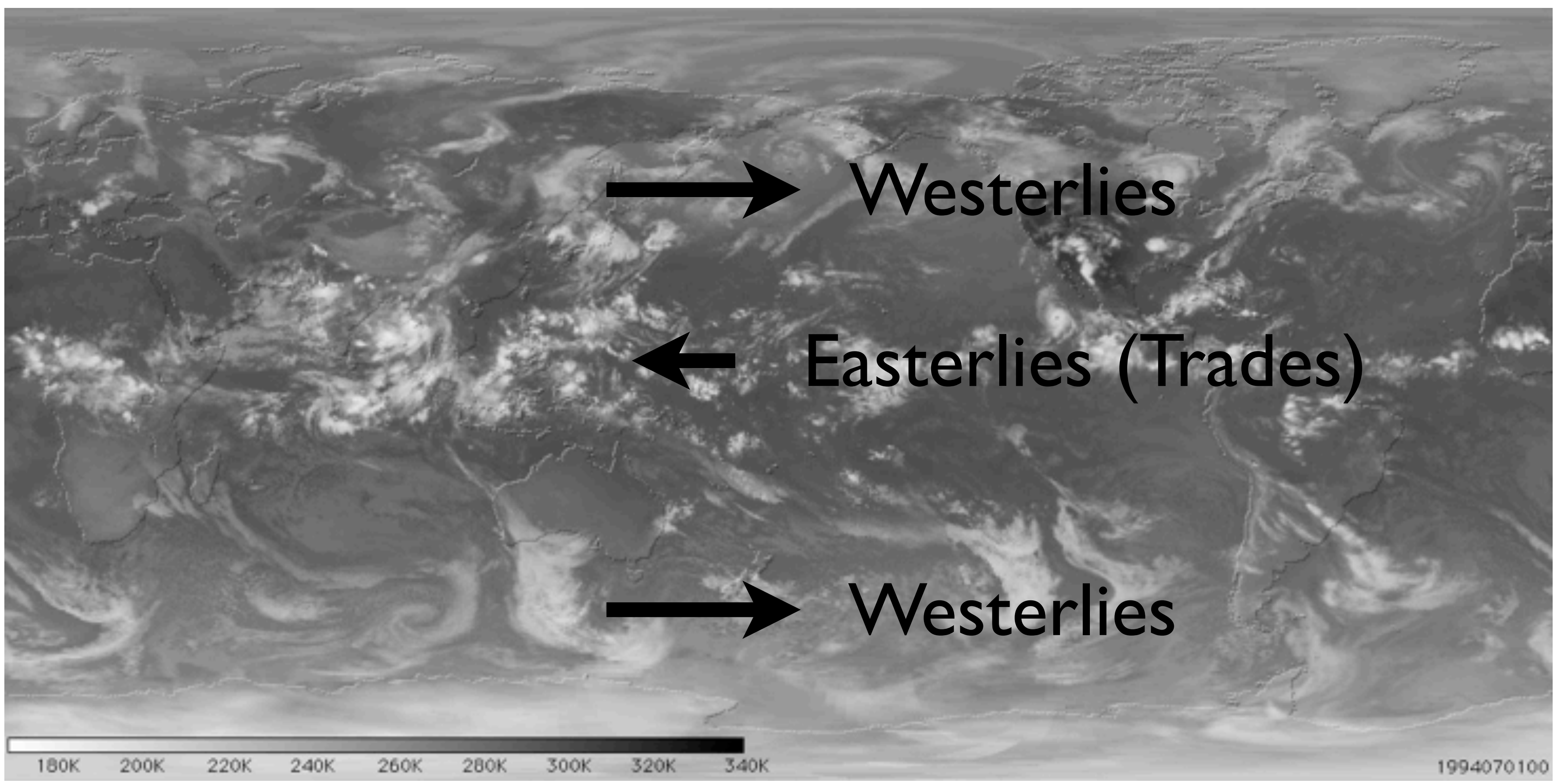

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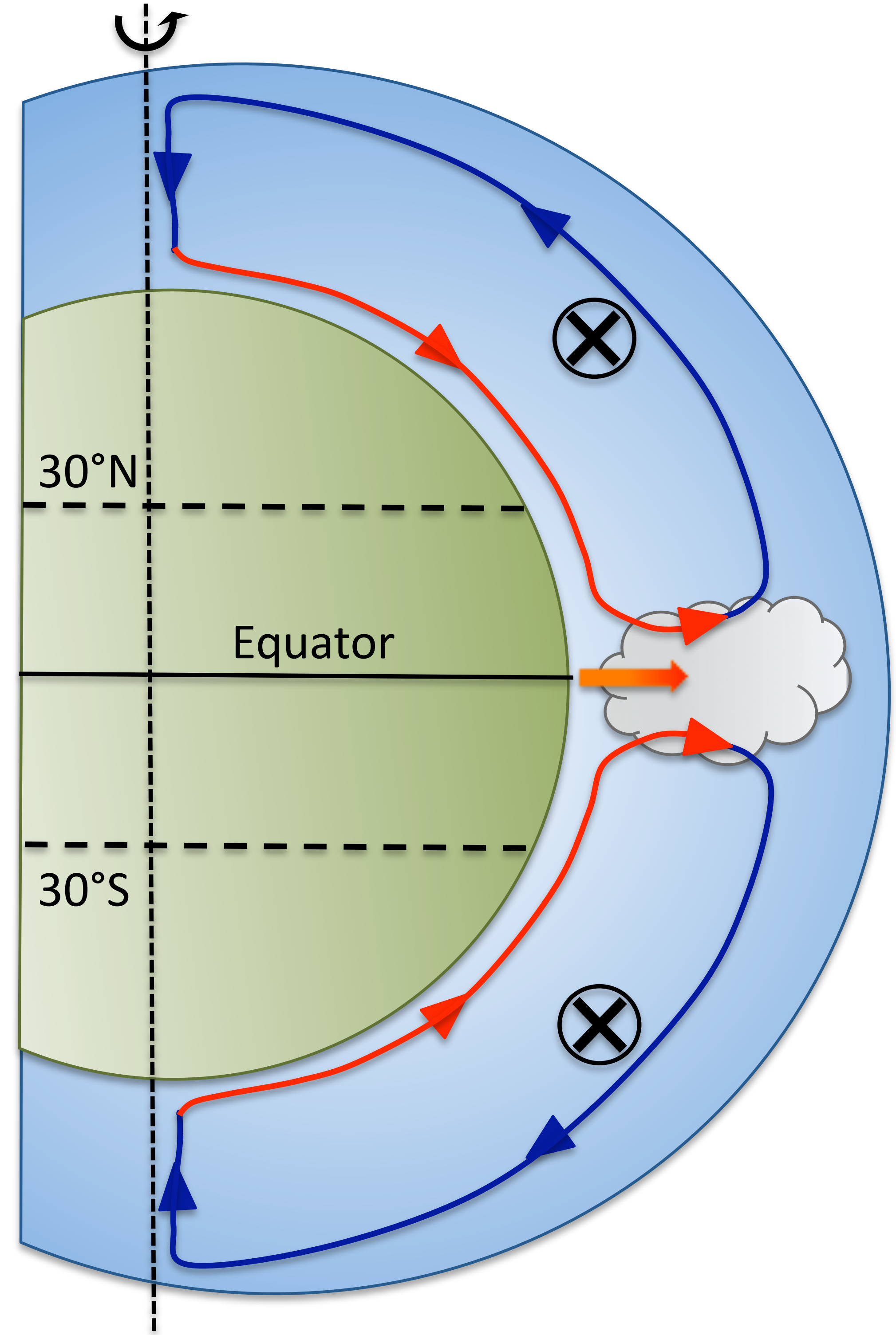
VI. *Concerning* the Caufe *of the* General Trade-Winds: *By* Geo. Hadley, *Efq;* *F. R. S.*

I Think the Caufes of the General Trade-Winds have not been fully explained by any of thofe who have wrote on that Subject, for want of more particularly and diftinctly confidering the Share the diurnal Motion of the Earth has in the Production of them: For although this has been mention'd by

(Hadley 1735)

Post Newton: Hadley's (1735) view of the winds



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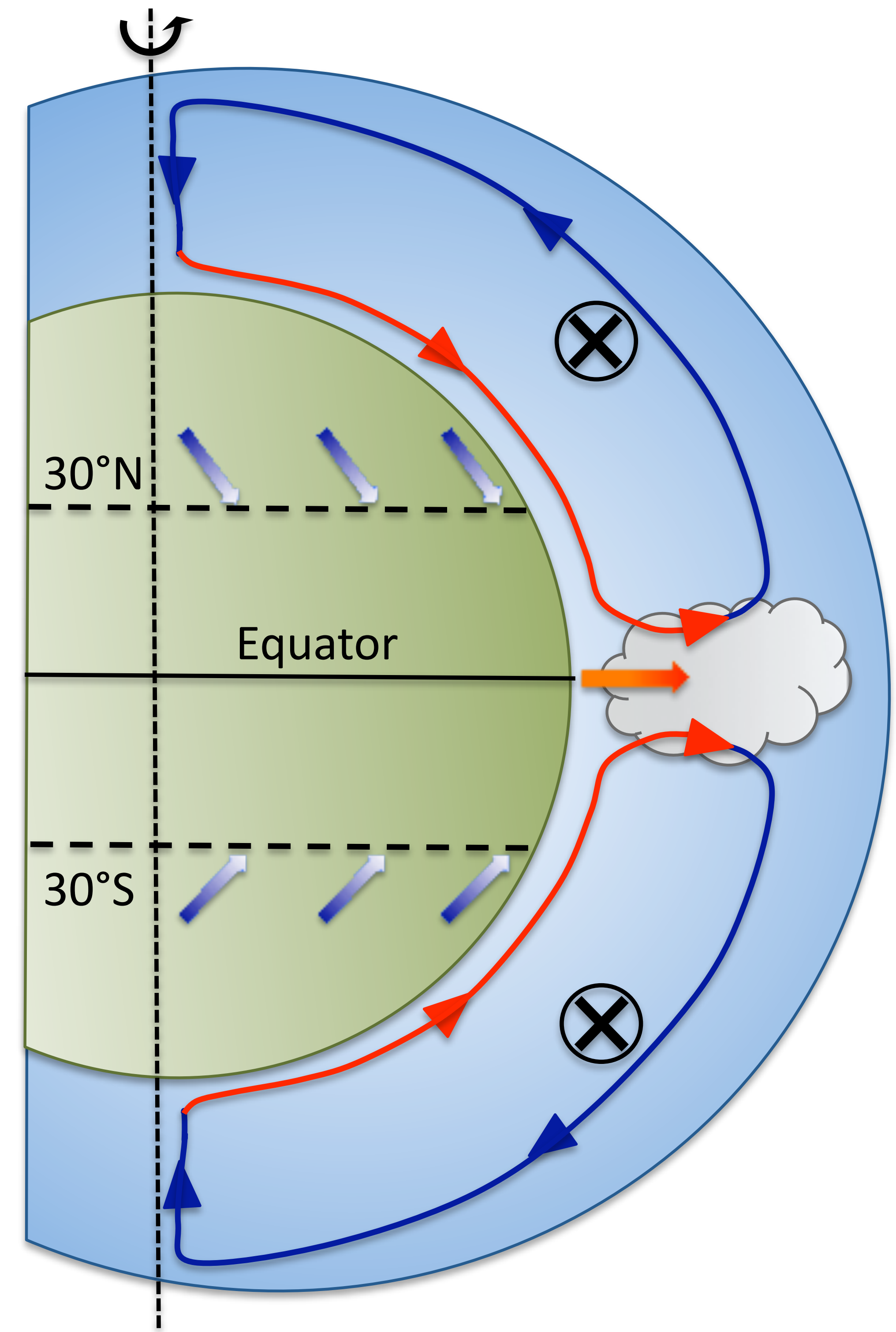

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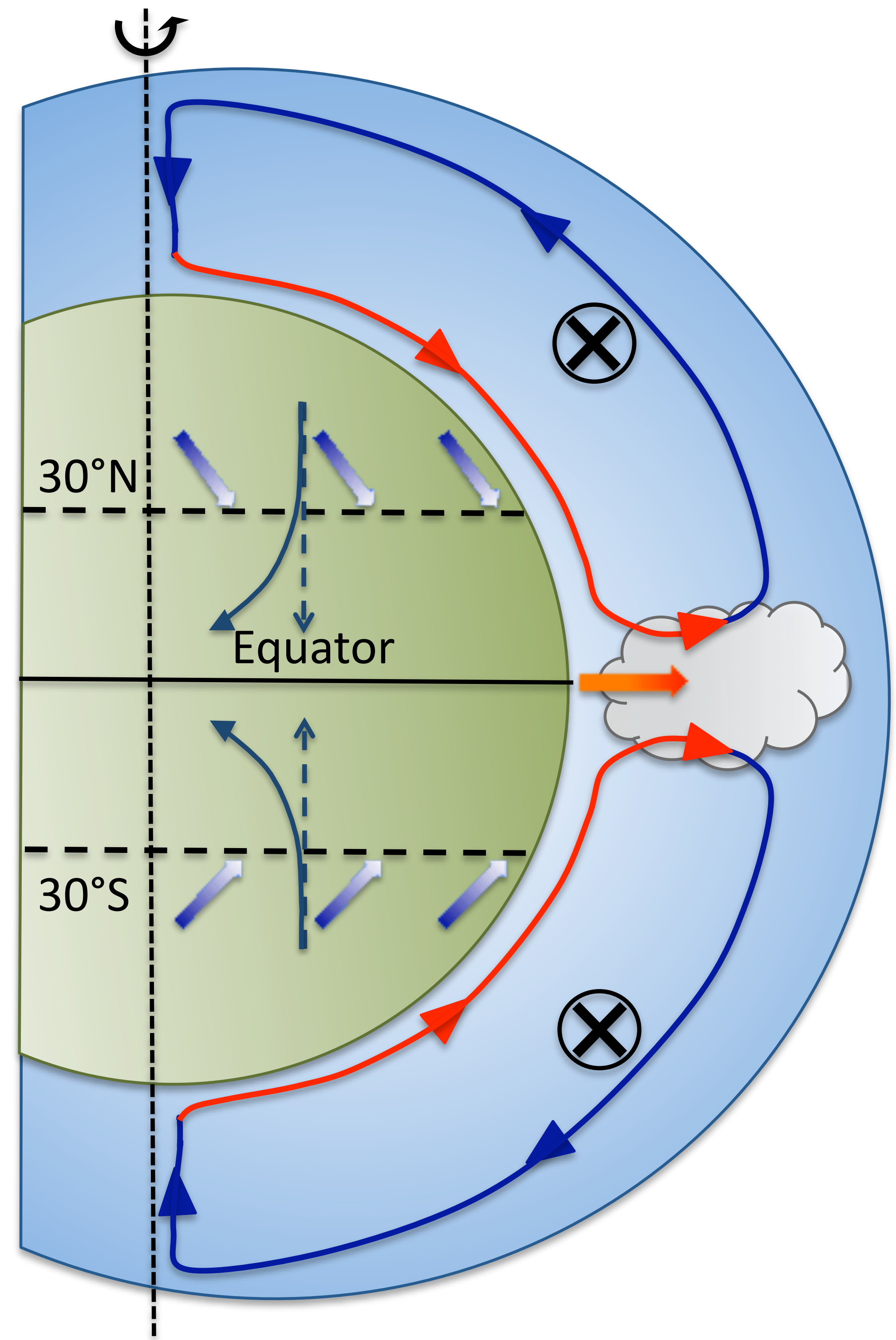

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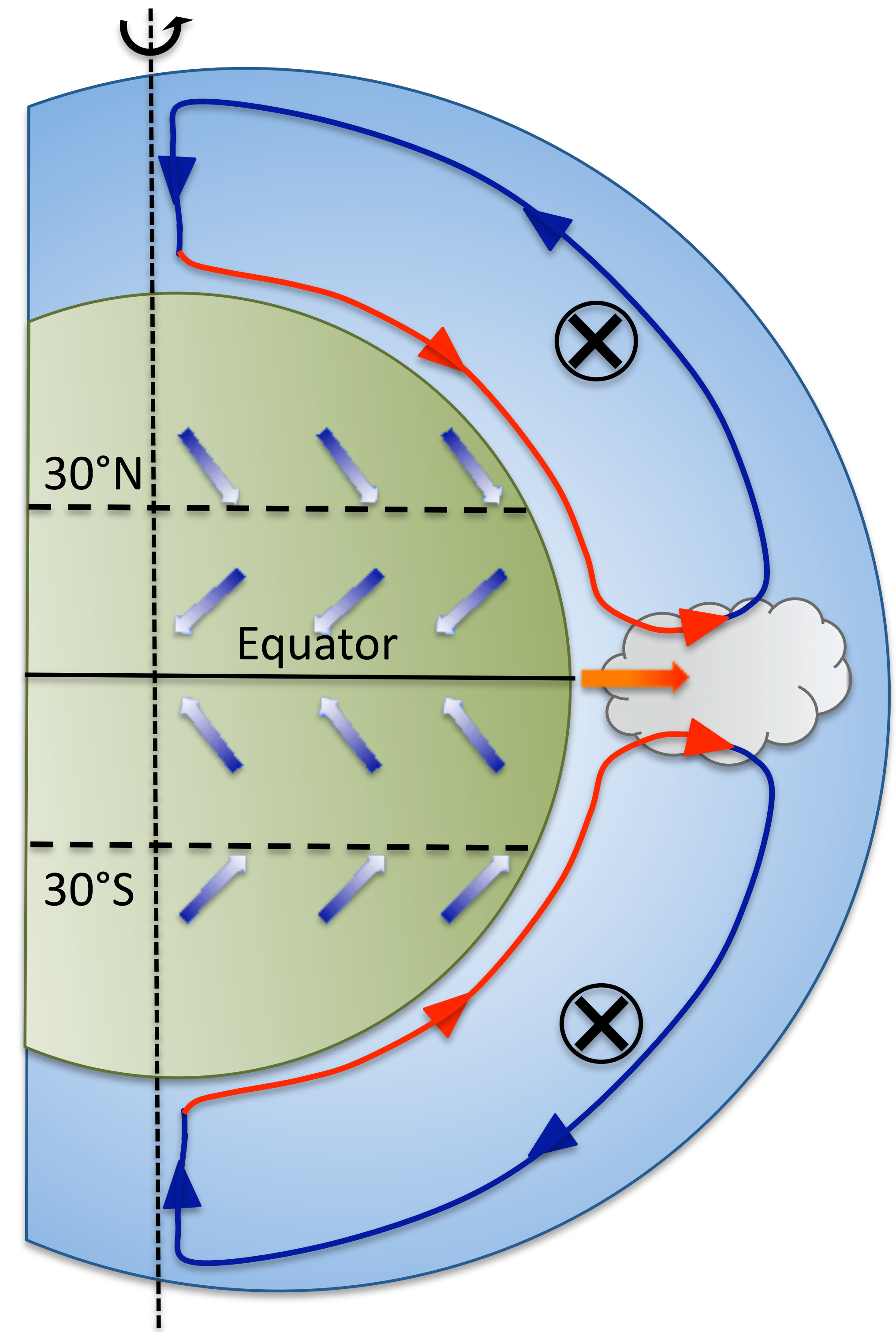
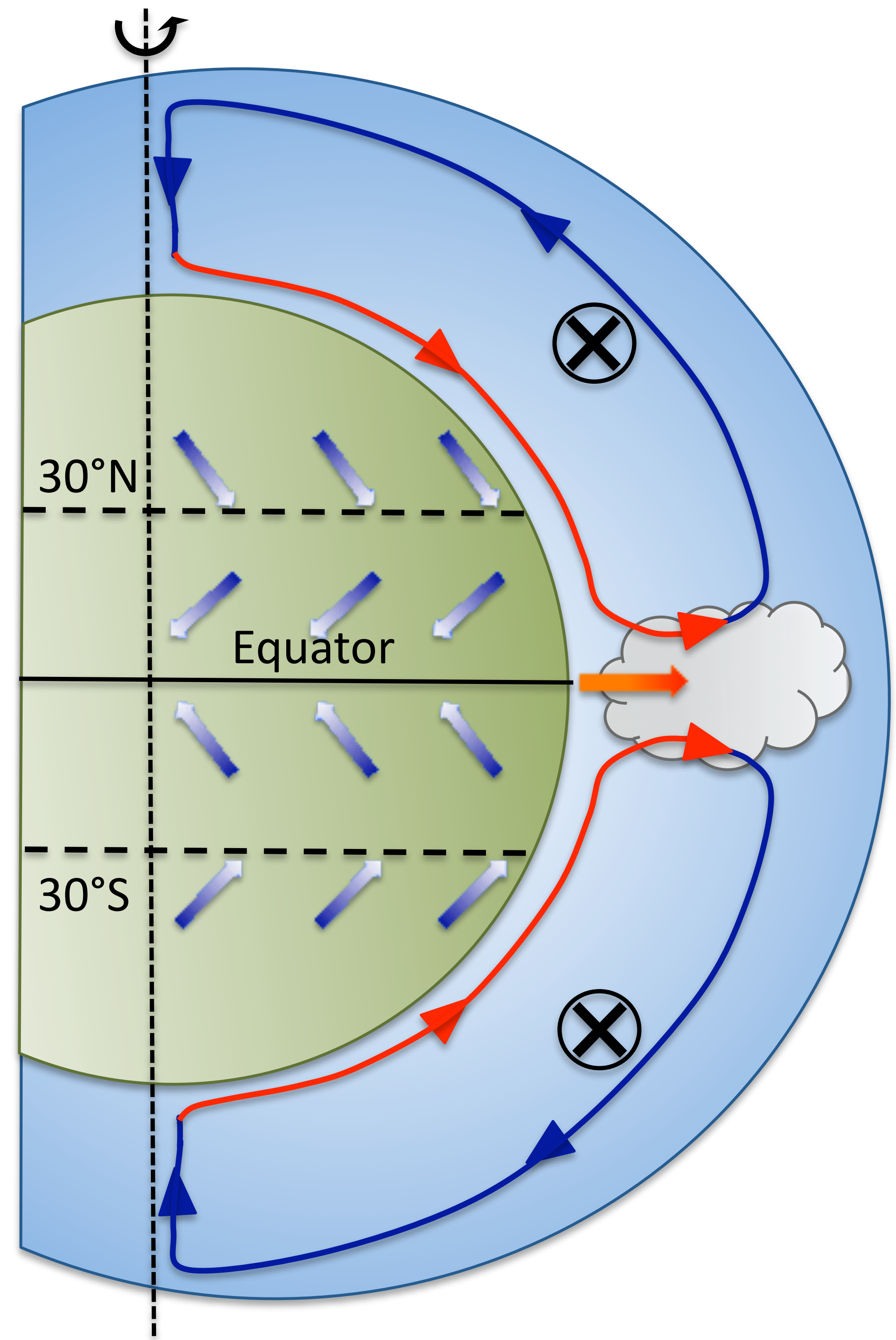
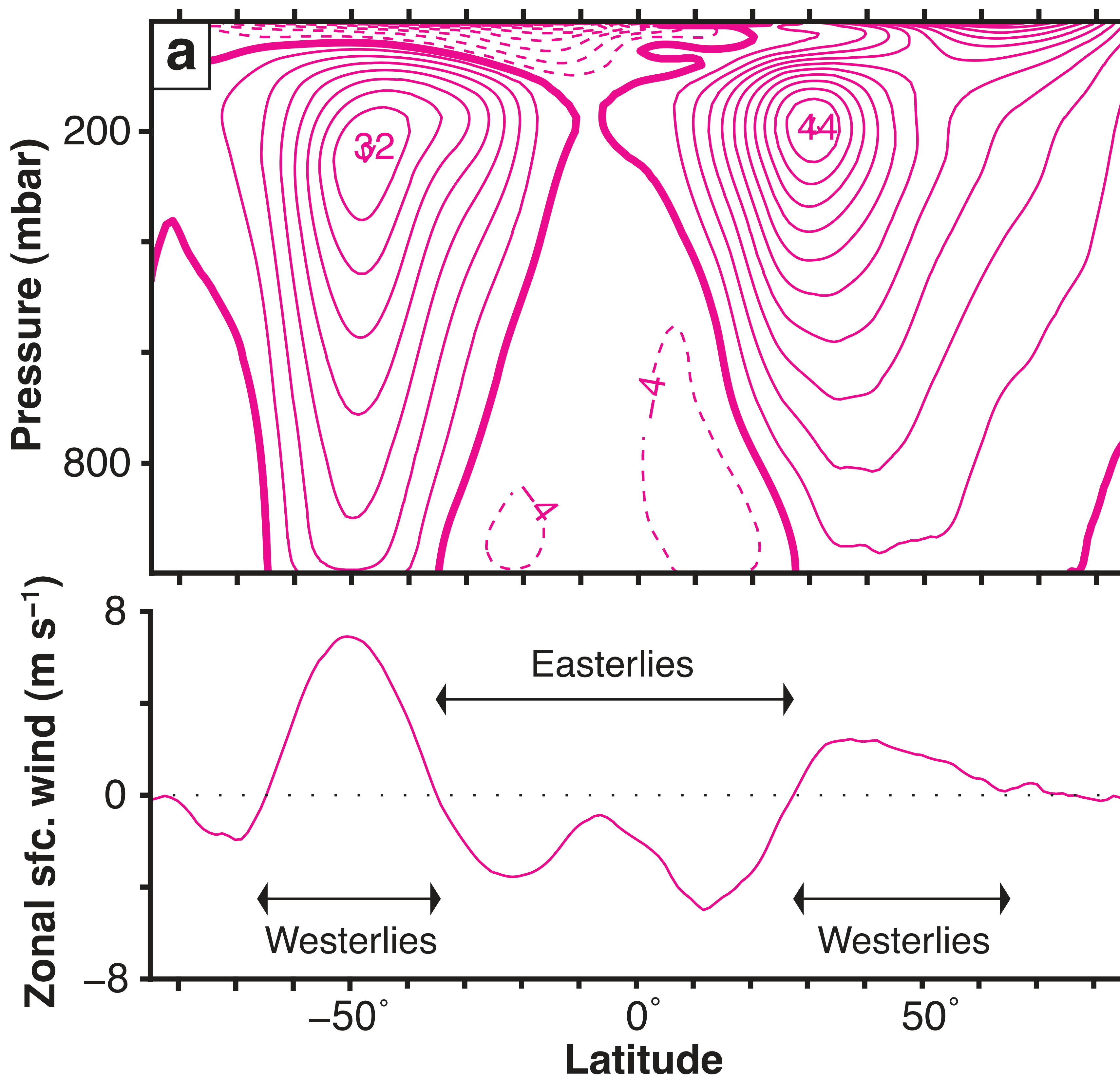


Post Newton: Hadley's (1735) view of the winds

Surface easterlies in the tropics must be compensated by westerlies elsewhere; otherwise Earth's rotation rate would change.

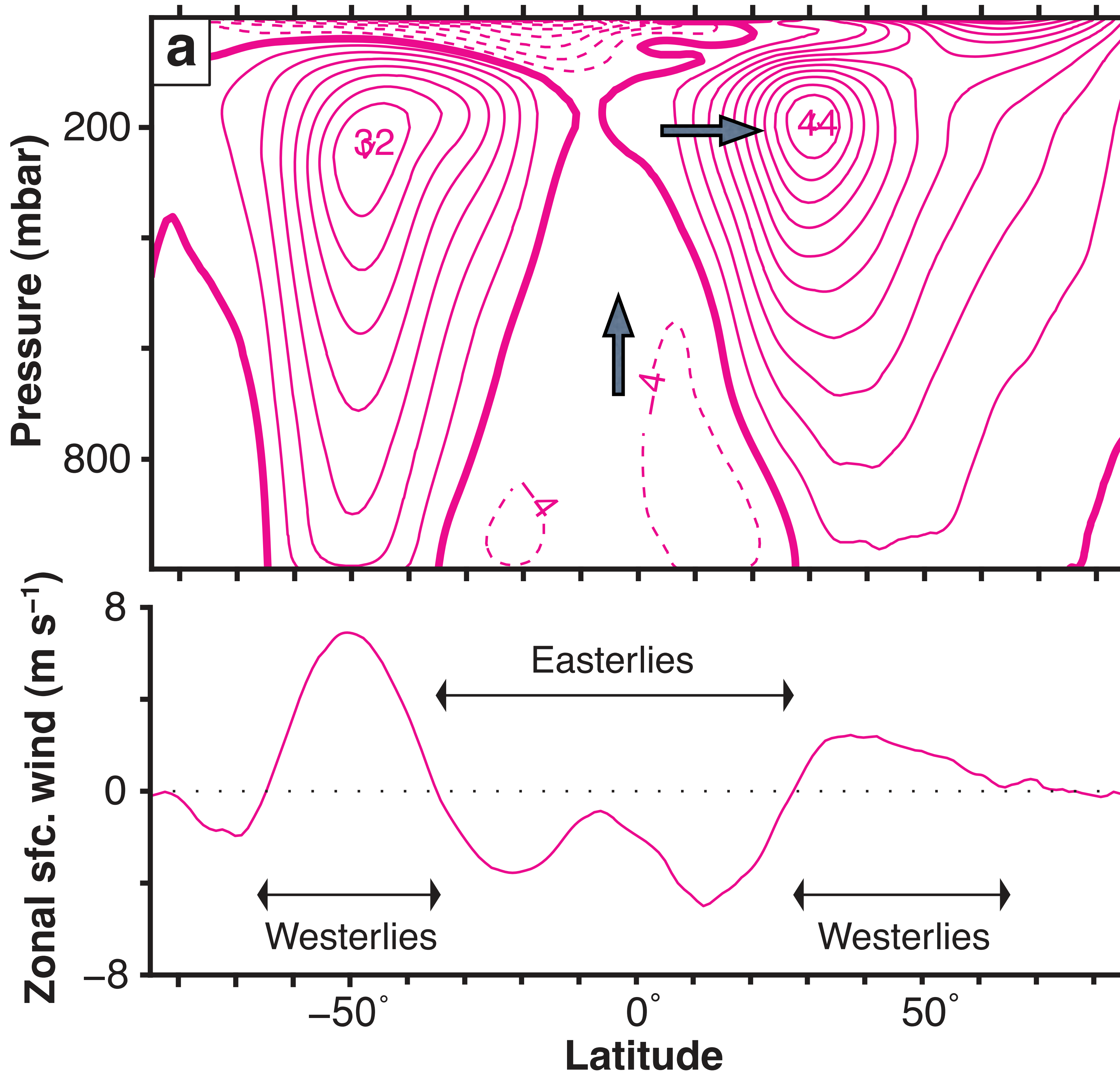


Eastward wind (January)



(Schneider, *Ann. Rev. Earth Planet. Sci.*, 2006)

Eastward wind (January)



(Schneider, *Ann. Rev. Earth Planet. Sci.*, 2006)

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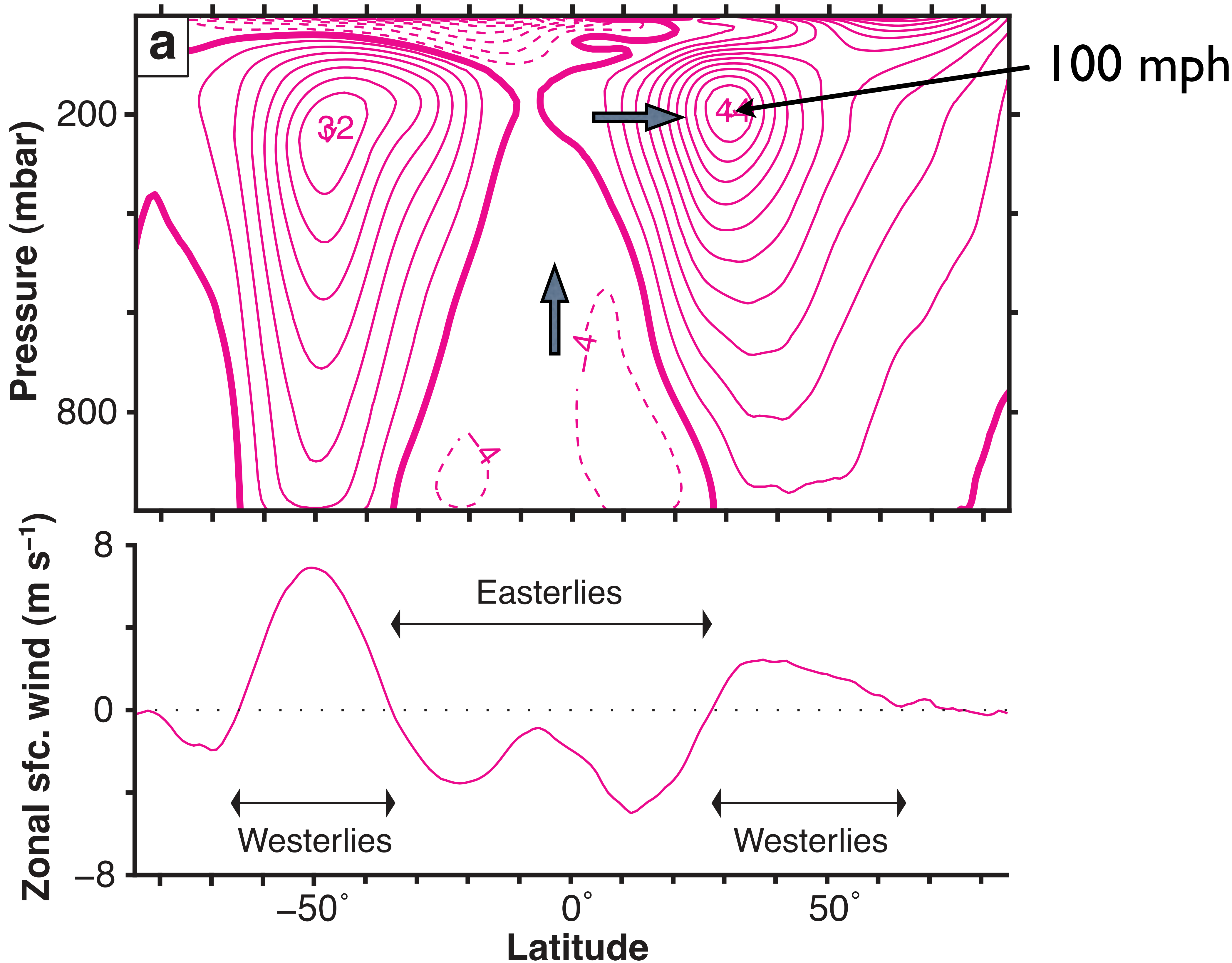

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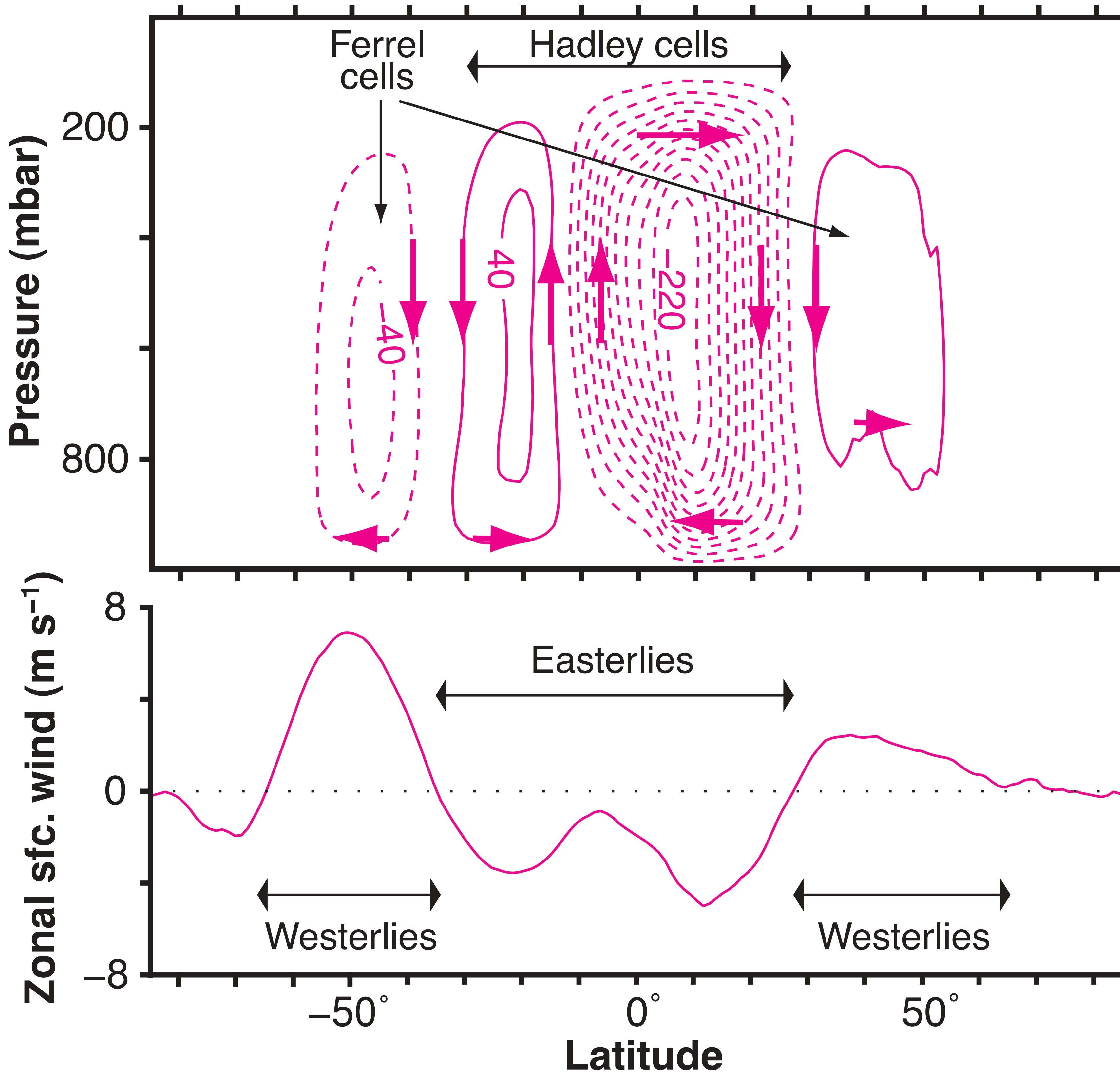
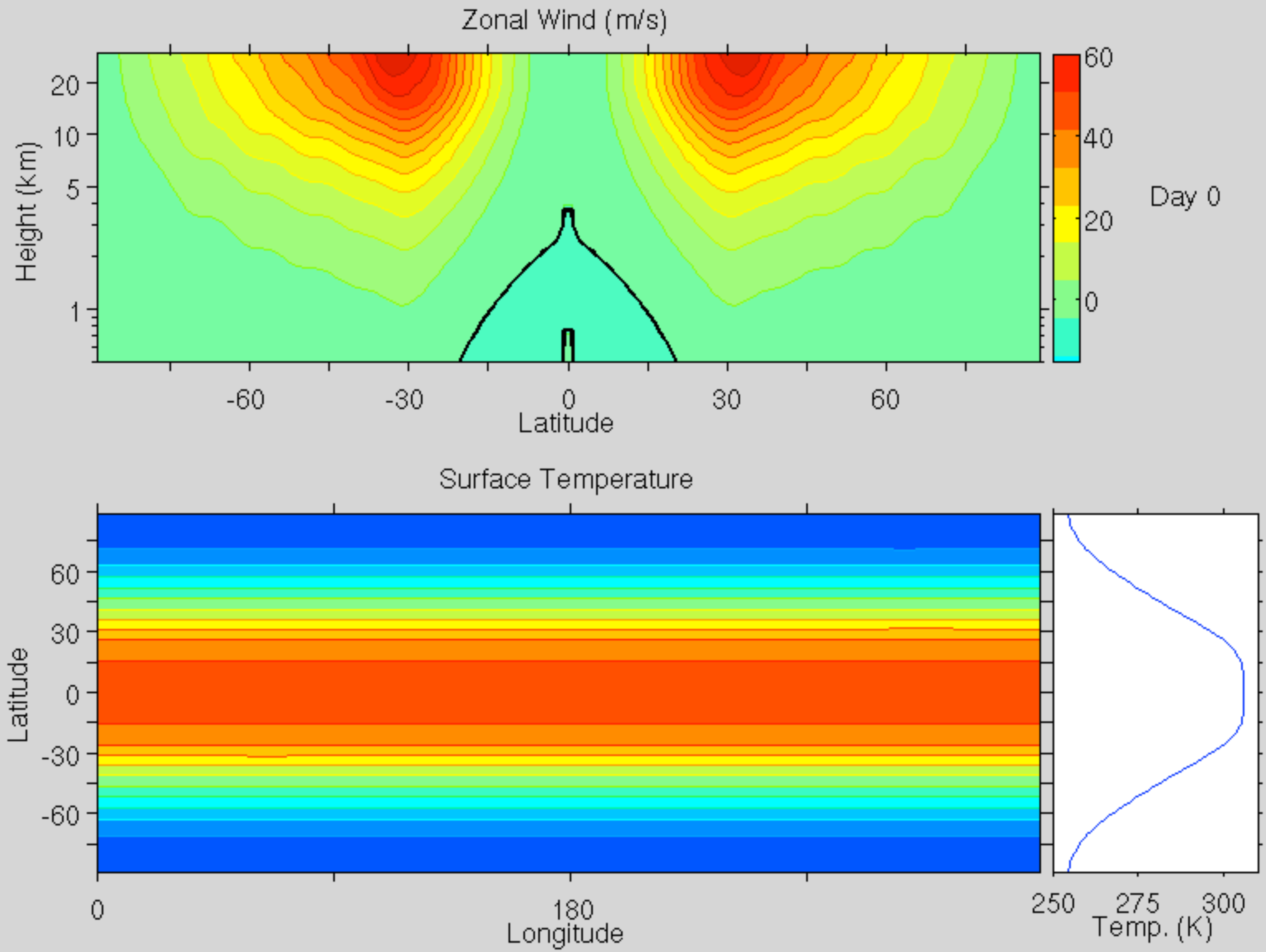
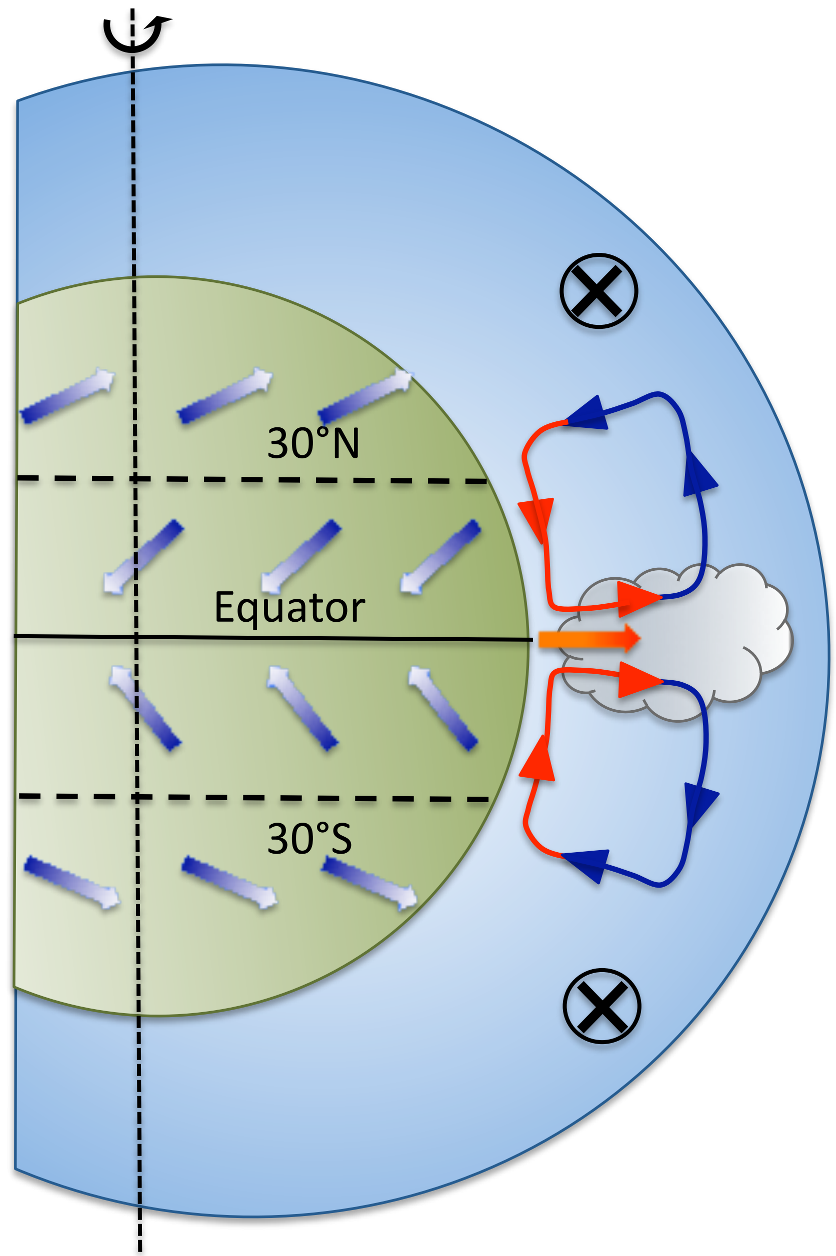
Eastward wind (January)



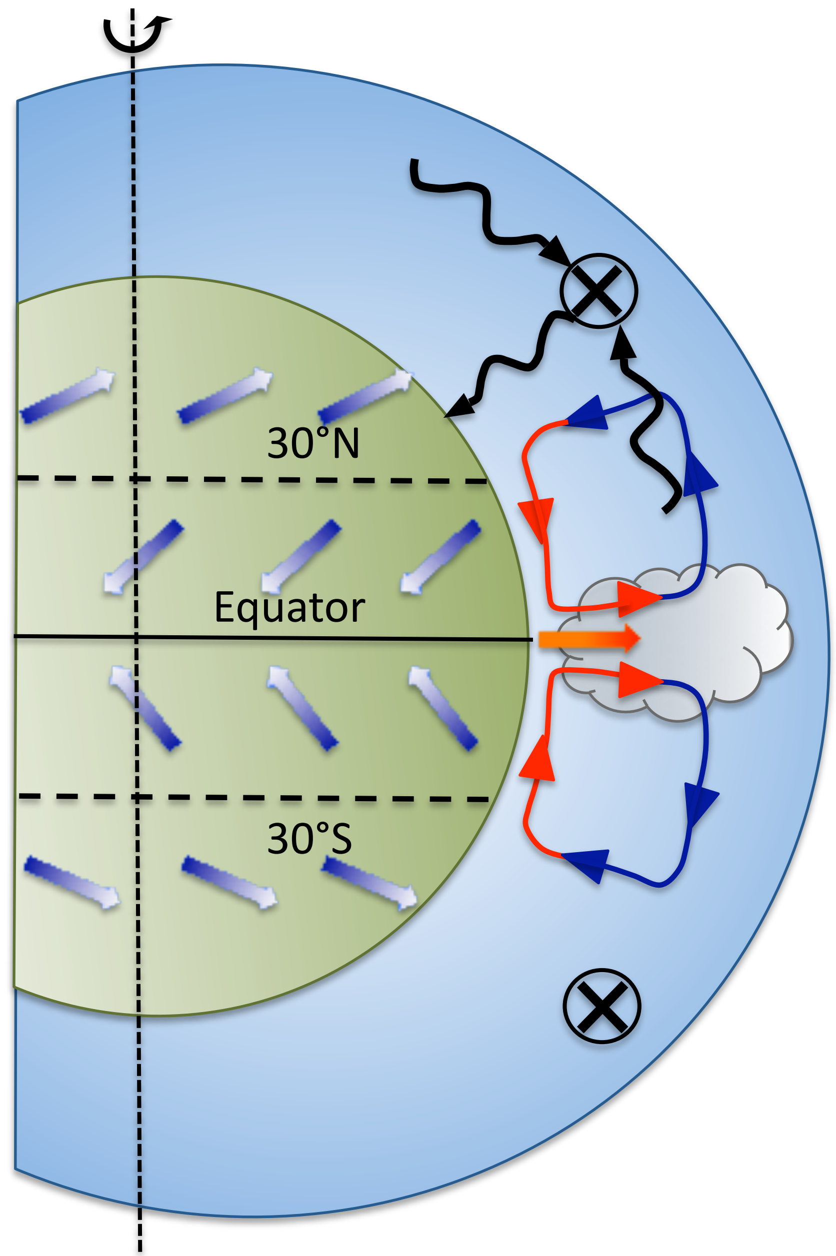
(Schneider, *Ann. Rev. Earth Planet. Sci.*, 2006)


Zonal Wind (m/s)
Height (km)
20
10
5
1
-60
-30
0
30
60
Latitude
60
40
20
0
Day 0
Surface Temperature
Latitude
60
30
0
-30
-60
0
180
Longitude
250
275
300
Temp. (K)

20th century: Hadley circulation only in tropics



20th century: Hadley circulation only in tropics



Extratropical macroturbulence transports angular momentum out of tropics into extratropics

Macroturbulence in control

Any theory of atmospheric circulations and of climate must be based on a theory of atmospheric macroturbulence.

Because we have no complete theory of macroturbulence, "the causes of the General Winds still *have not been fully explained by any of those who have written on that Subject" (Hadley).*

The Hadley circulation was generally thought not to depend strongly on atmospheric macroturbulence. But that is not the case.

The ideal Hadley circulation...

- Conserves angular momentum *m* in upper branch

$$\bar{v}\partial_y \bar{m} \approx 0$$

Since $\partial_y \bar{m} \propto f + \bar{\zeta}$, this implies

$$(f + \bar{\zeta})\bar{v} = f(1 - \mathrm{Ro})\bar{v} \approx 0$$

with *local Rossby number* $\mathrm{Ro} = -\bar{\zeta}/f \to 1$

- Is energetically closed (no heat export)

- Responds *directly* to variations in thermal driving

- Result: $\phi_h \sim \left(\frac{gH_t'}{\Omega^2 a^2}\Delta_h'\right)^{1/2}$ $\Psi_{\max} \sim \frac{(H_t'\Delta_h')^{5/2}}{\Omega^3 a}$

(Schneider 1977; Schneider & Lindzen 1976, 1977; Held & Hou 1980)

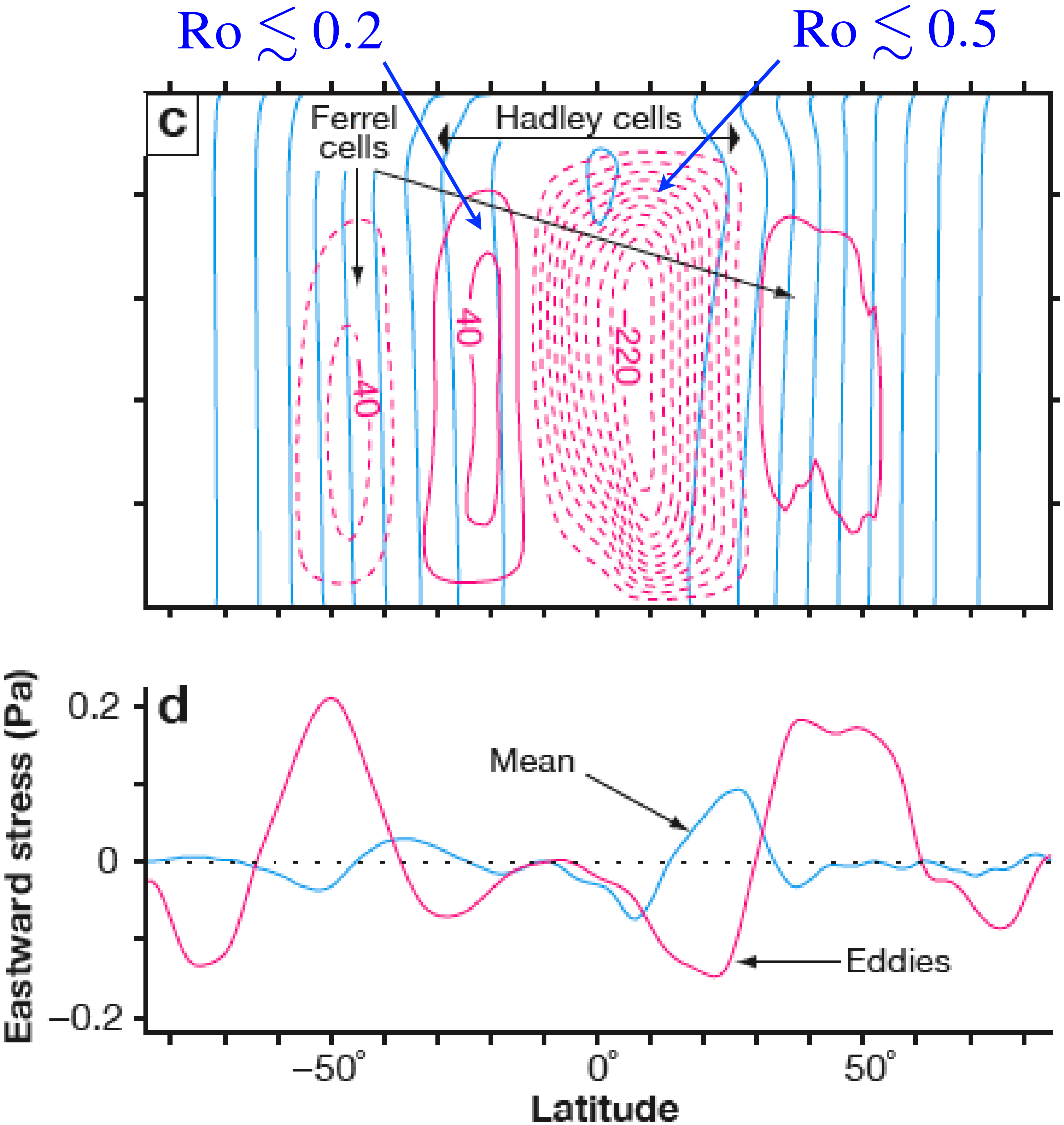
Ideal Hadley circulation theory...

- Is intuitively appealing (direct reponse to thermal driving)

- Appears to account for extent of circulation in Earth's atmosphere

But does it account for variations in Hadley circulation as climate varies?

January streamfunction and angular momentum



(Schneider 2006)

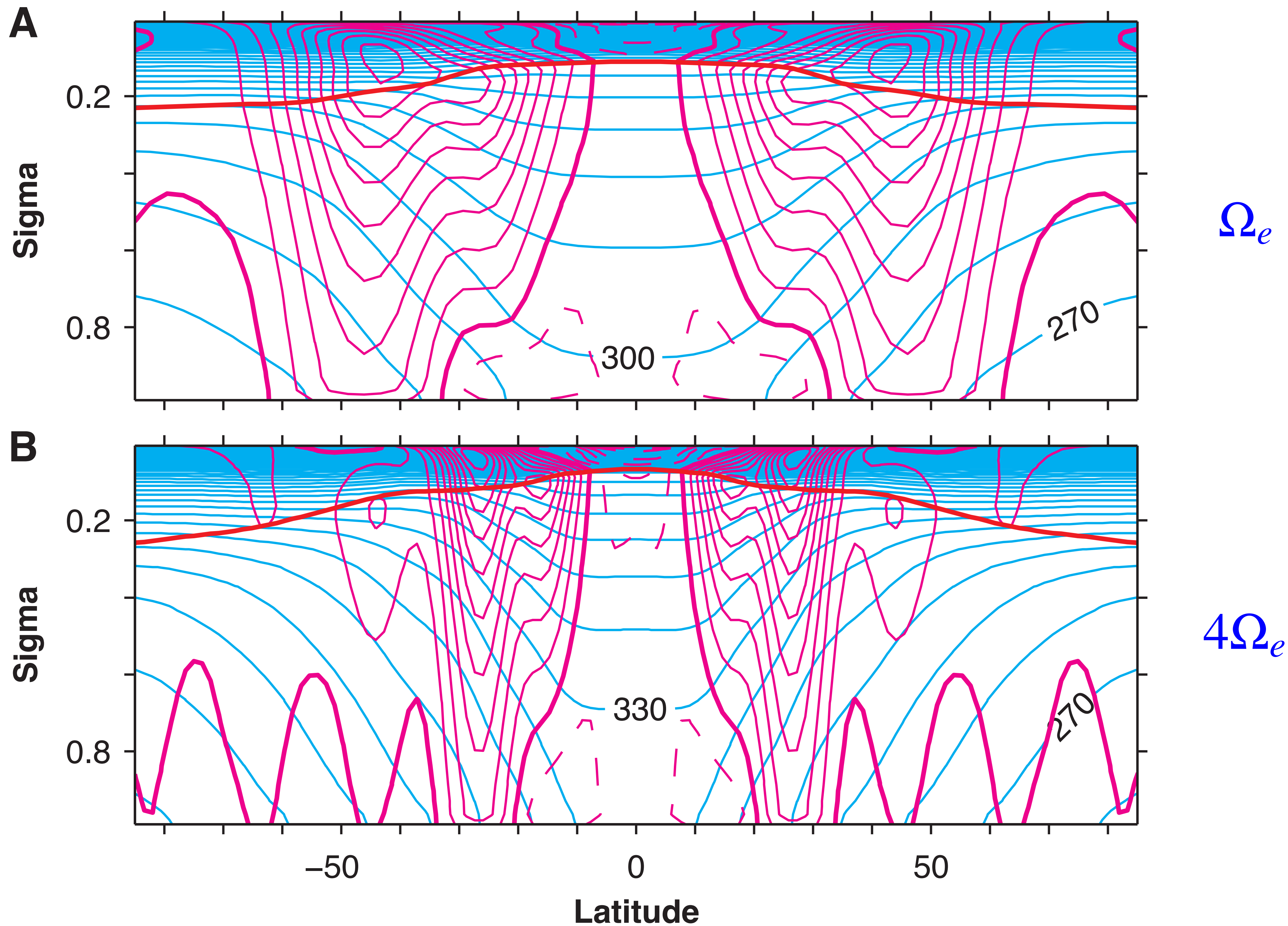
Earth-like Hadley circulations...

- In the annual mean or during equinox are close to limit $\mathrm{Ro} \to 0$

- Do not respond directly to variations in thermal driving but respond via changes in eddy fluxes

We need to rethink Hadley circulation response, for example, to ENSO and global warming

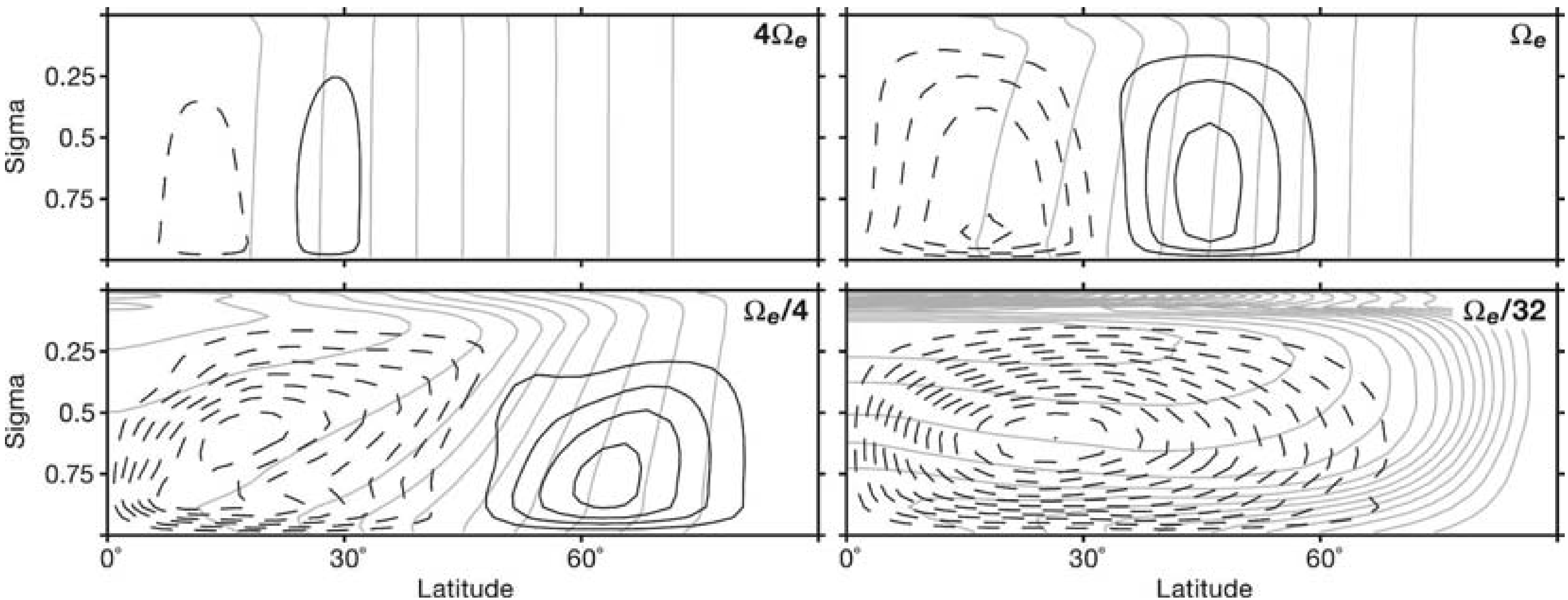
Simulate circulations with idealized GCM ...



Zonal wind (magenta) and potential temperature (blue)

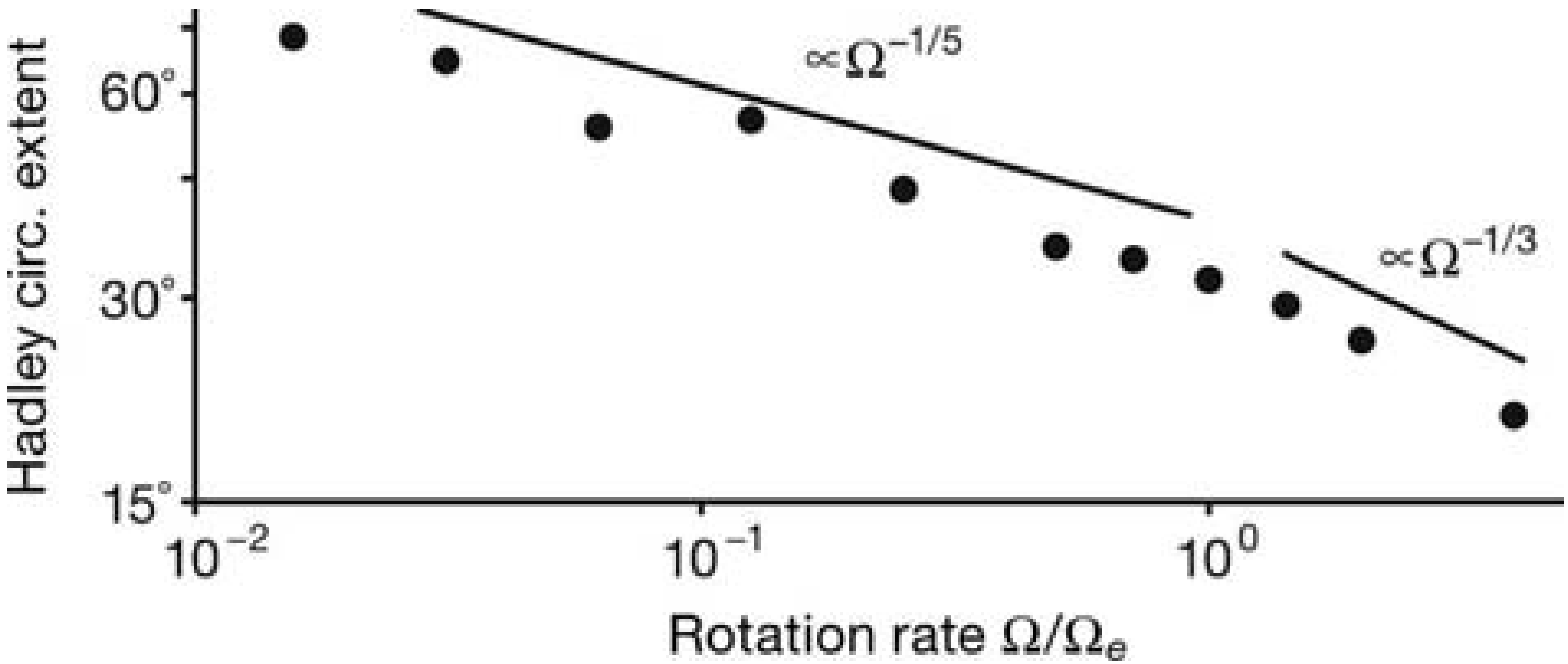
(Schneider and Walker 2006)

Wider circulations with slower rotation rates



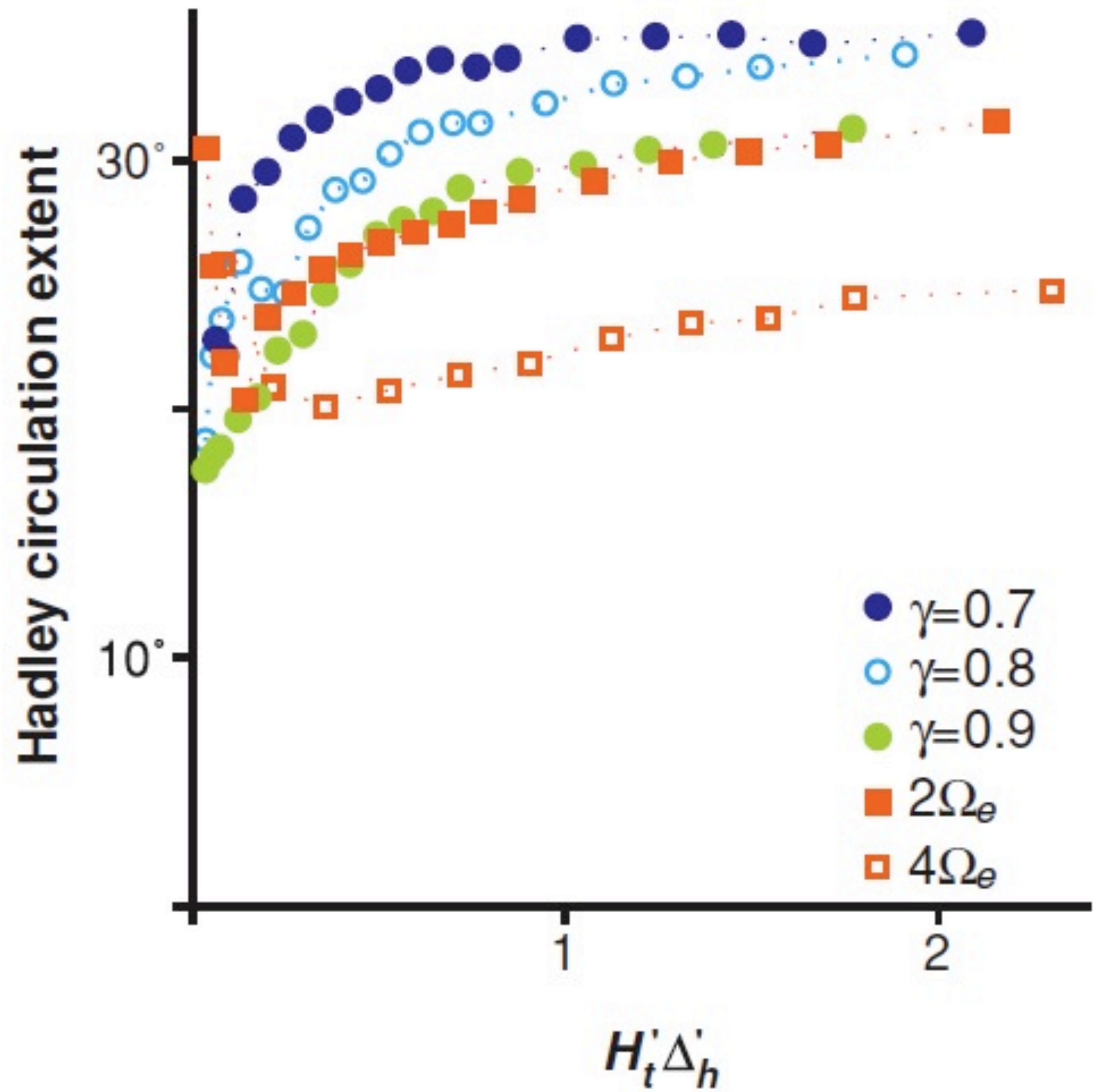
(Walker and Schneider 2006)

Hadley circulation width as a function of rotation rate



(Walker and Schneider 2006)

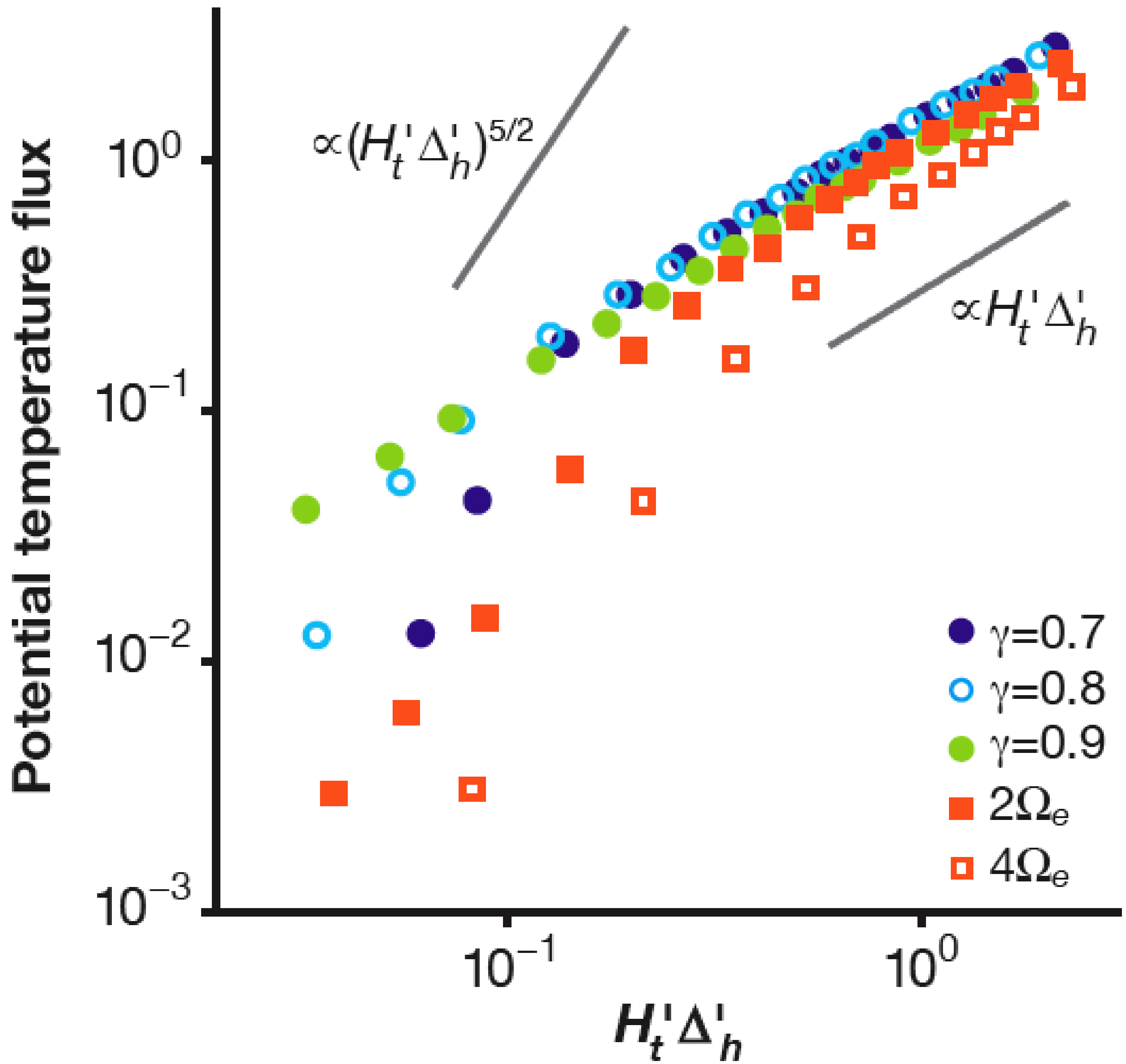
Hadley circulation width as a function of other parameters



Wider for more stable stratification

(Walker & Schneider 2006; Schneider 2006; Korty & Schneider 2008)

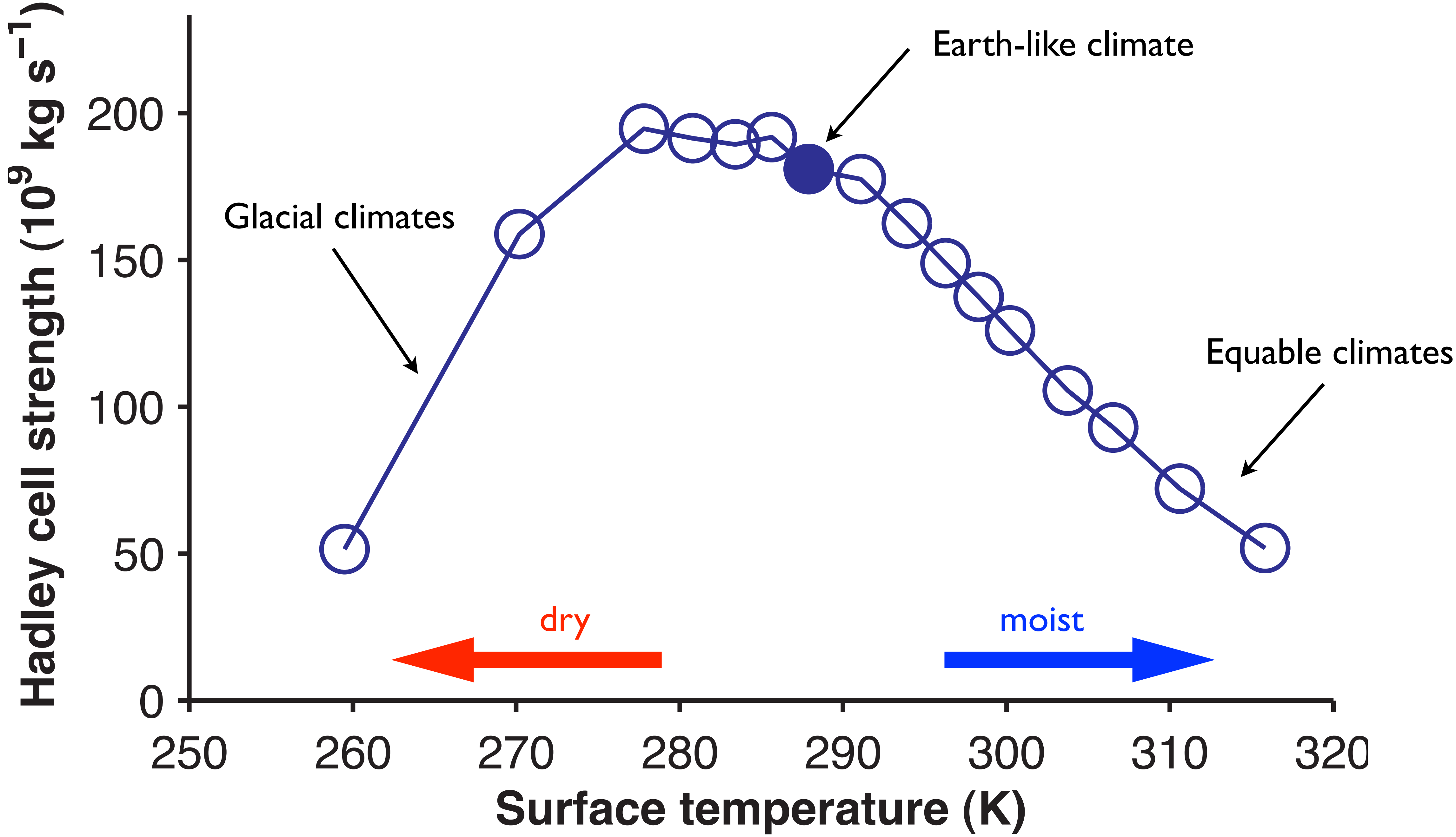
Hadley circulation strength in idealized GCM



Convective lapse rate $\quad \gamma\Gamma_d = \gamma(g/c_p)$

(Walker & Schneider 2006; Schneider 2006)

Hadley circulation strength in moist GCM



Variations in optical thickness of longwave absorber

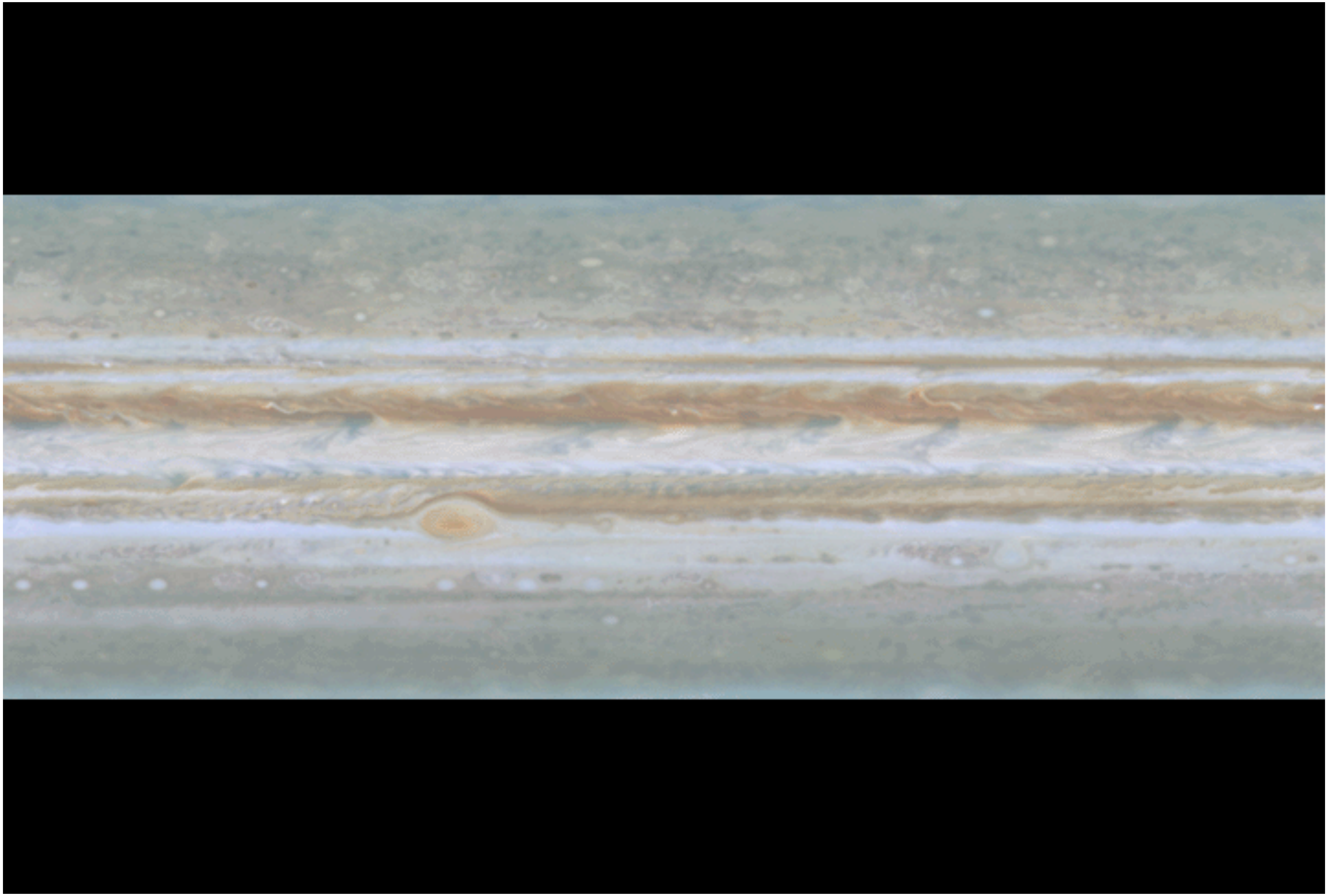
(O'Gorman & Schneider 2008; Schneider et al. 2010)

Terrestrial Hadley circulations

- During equinox, summer, and in annual mean controlled by eddy fluxes
- Eddy scaling imprinted on scalings
- Weaker in warmer *and* (much) colder climates
- Changes in width likewise eddy-controlled (but slowly rotating wider, and less influenced by eddies)

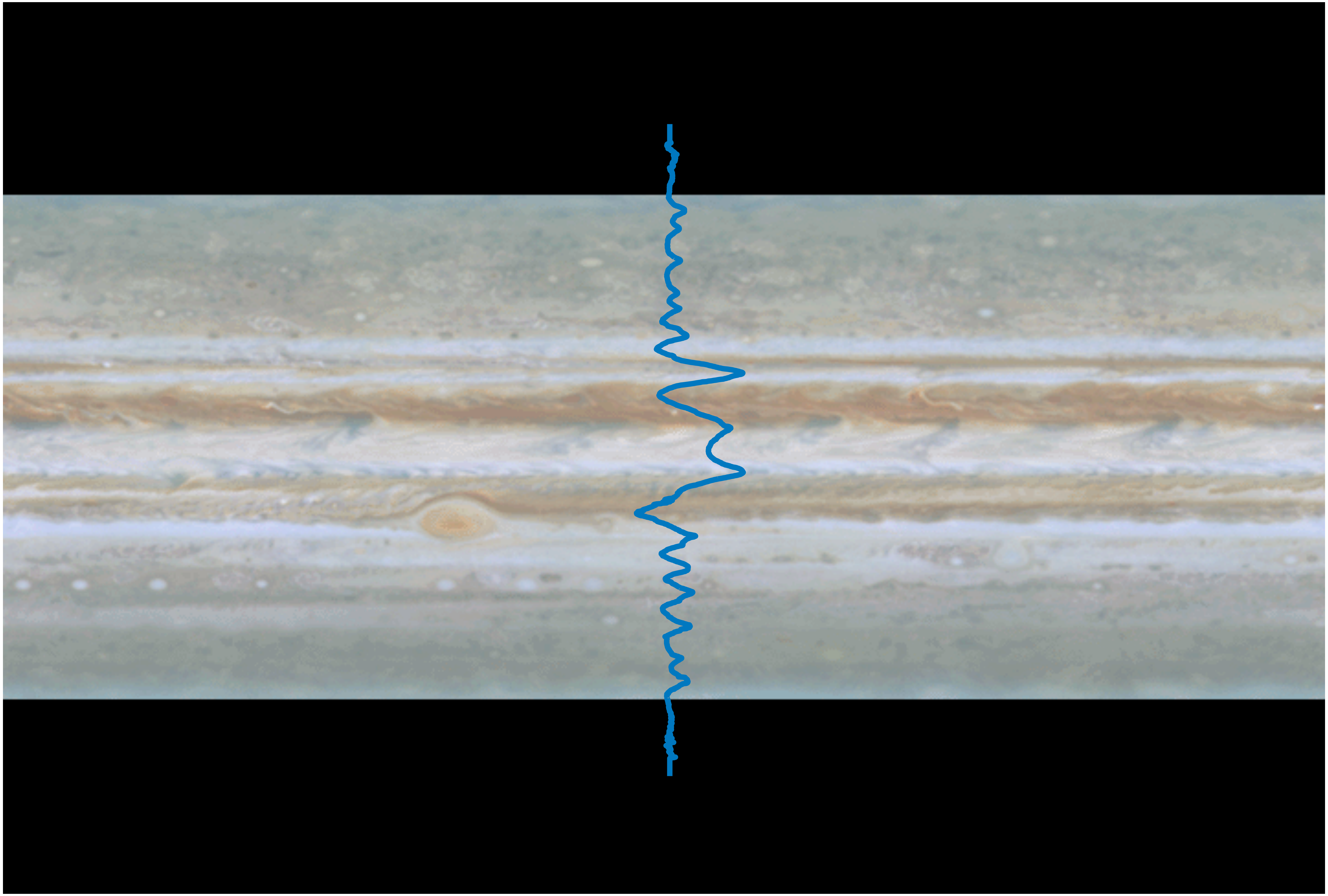
Need theory that takes eddy effects into account (intermediate Rossby number)

Jupiter from *Cassini*



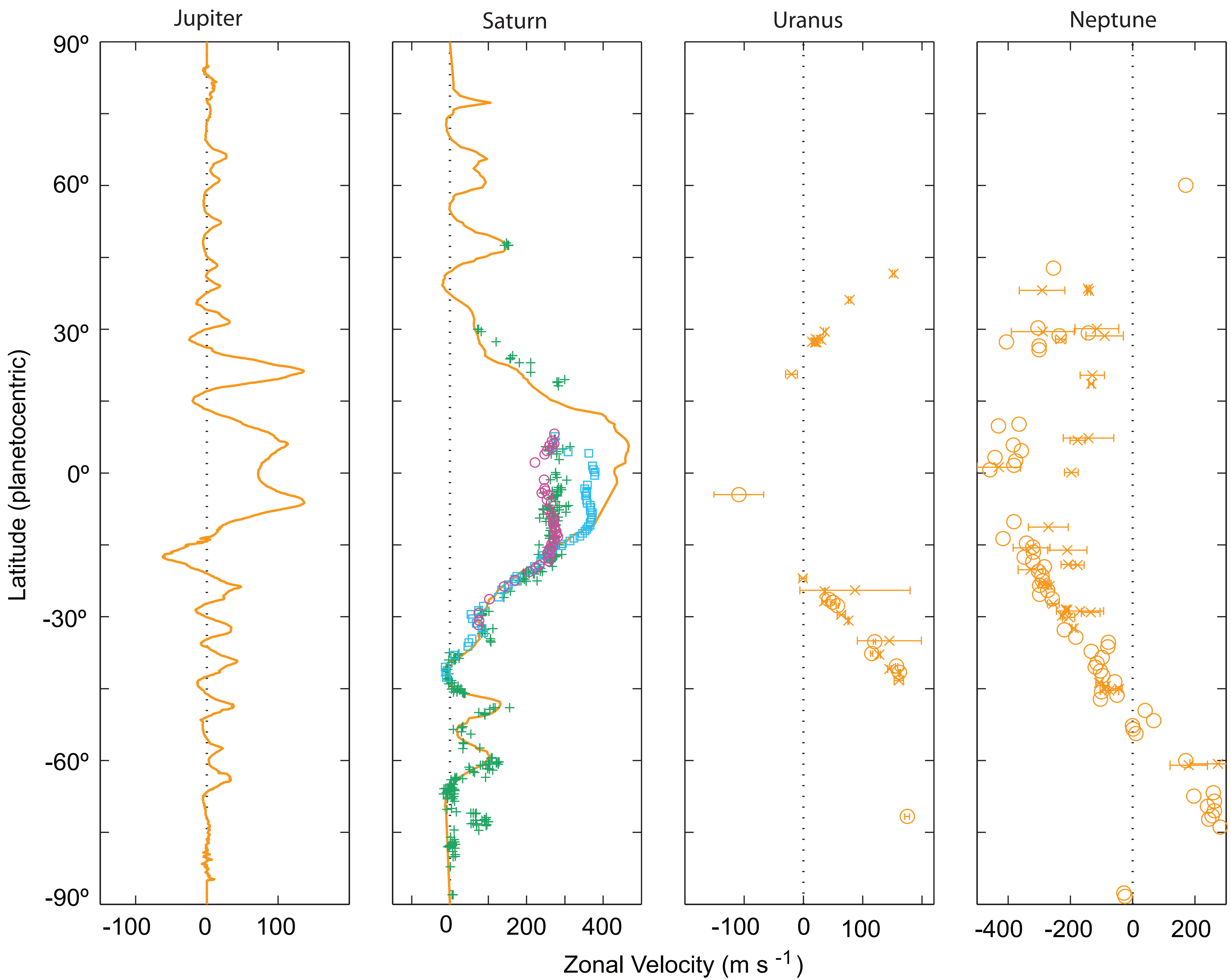
(Cassini Imaging Team 2000)

Jupiter from *Cassini*



(Cassini Imaging Team 2000)

Winds on giant planets



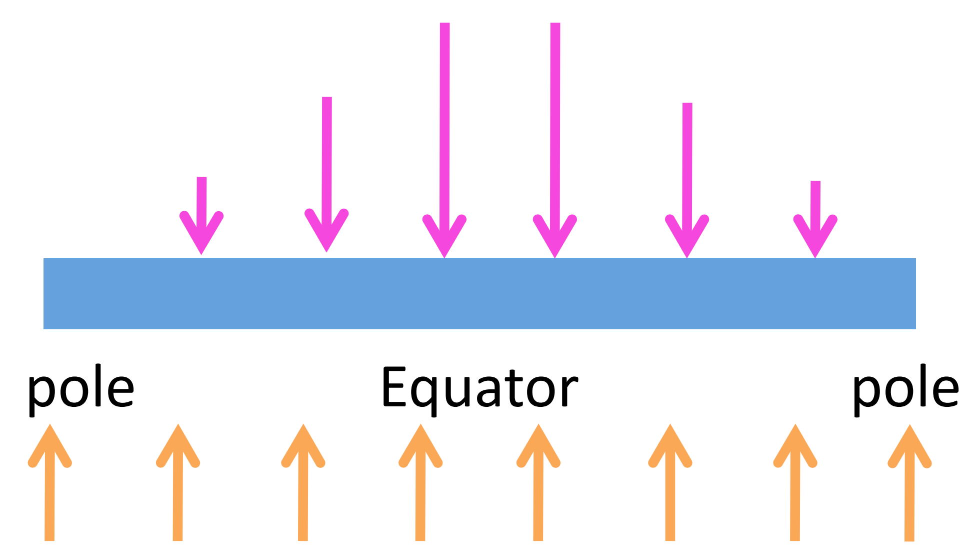
(Based on data from *Voyager, Cassini, HST;* Liu & Schneider 2010)

Energy budget of giant planets

- Emit more energy than they receive from the sun
- Internal heat flux can generate convection
- Differential solar radiative heating from above

	Absorbed insolation	Internal heat flux
Jupiter	8.1 Wm^{-2}	5.7 Wm^{-2}
Saturn	2.7 Wm^{-2}	2.0 Wm^{-2}
Uranus	0.7 Wm^{-2}	0.04 Wm^{-2}
Neptune	0.3 Wm^{-2}	0.4 Wm^{-2}

(Guillot 2005)

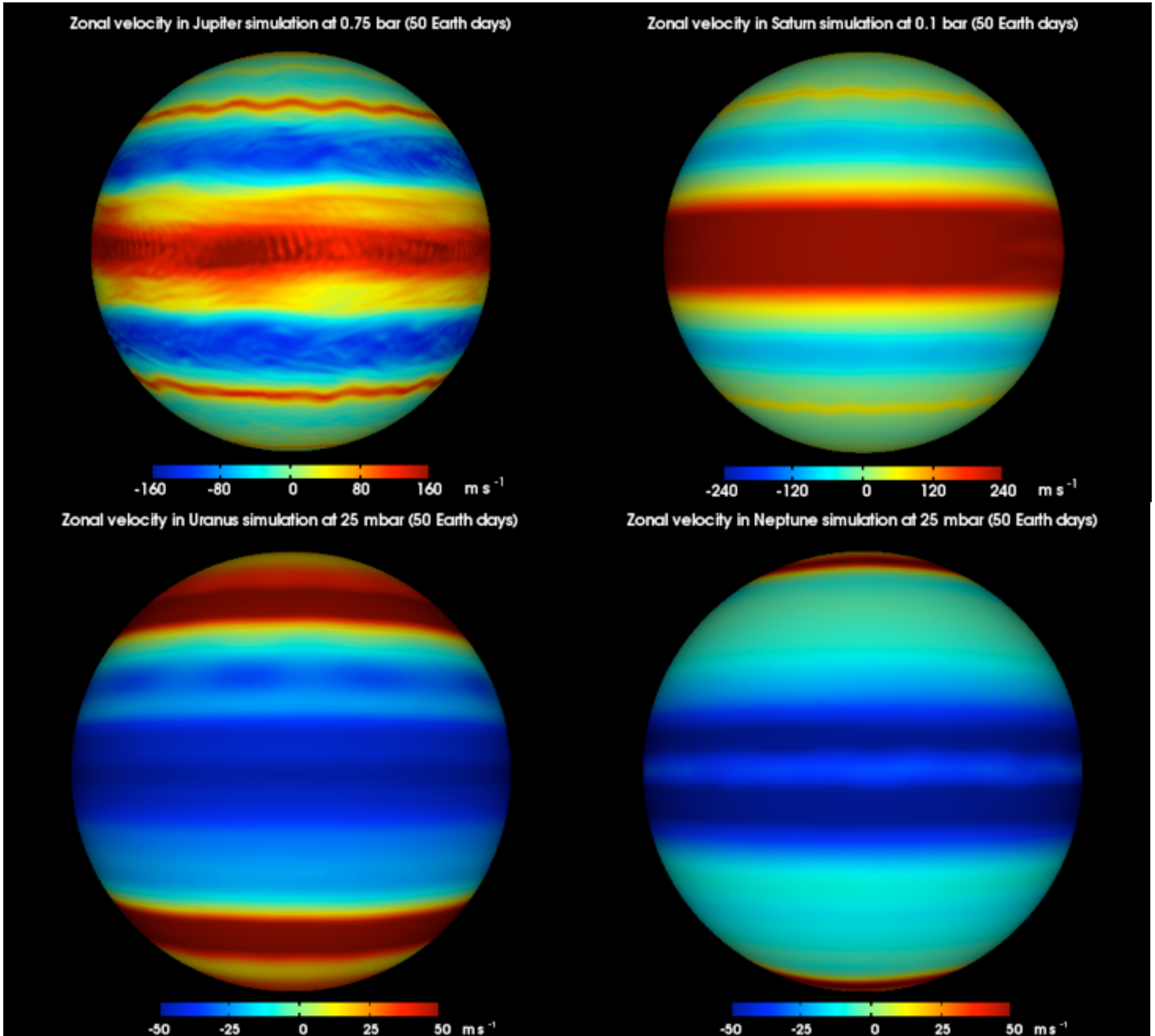


Giant planet properties

- Have similar radii and rotation rates
- Differ in energy budgets
- Very different flows:
  - Jupiter, Saturn superrotating
  - Uranus, Neptune subrotating

Differences in flows likely caused by differences in energy budgets and dissipation. How?

3D simulation of all giant planets



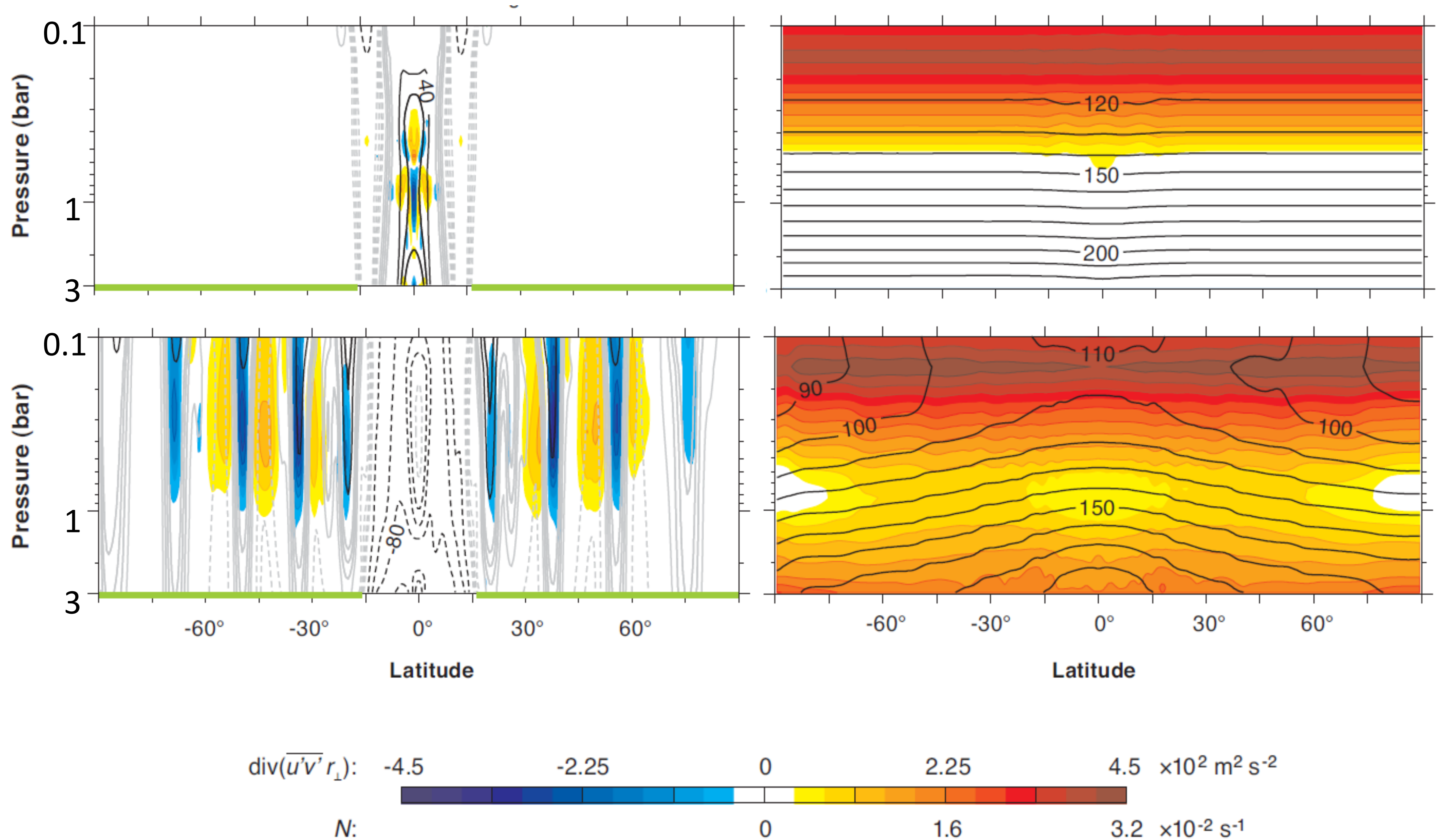
(Liu & Schneider 2010)

Jupiter control simulations

u, Eddy momentum divergence | T, N

Uniform solar radiation

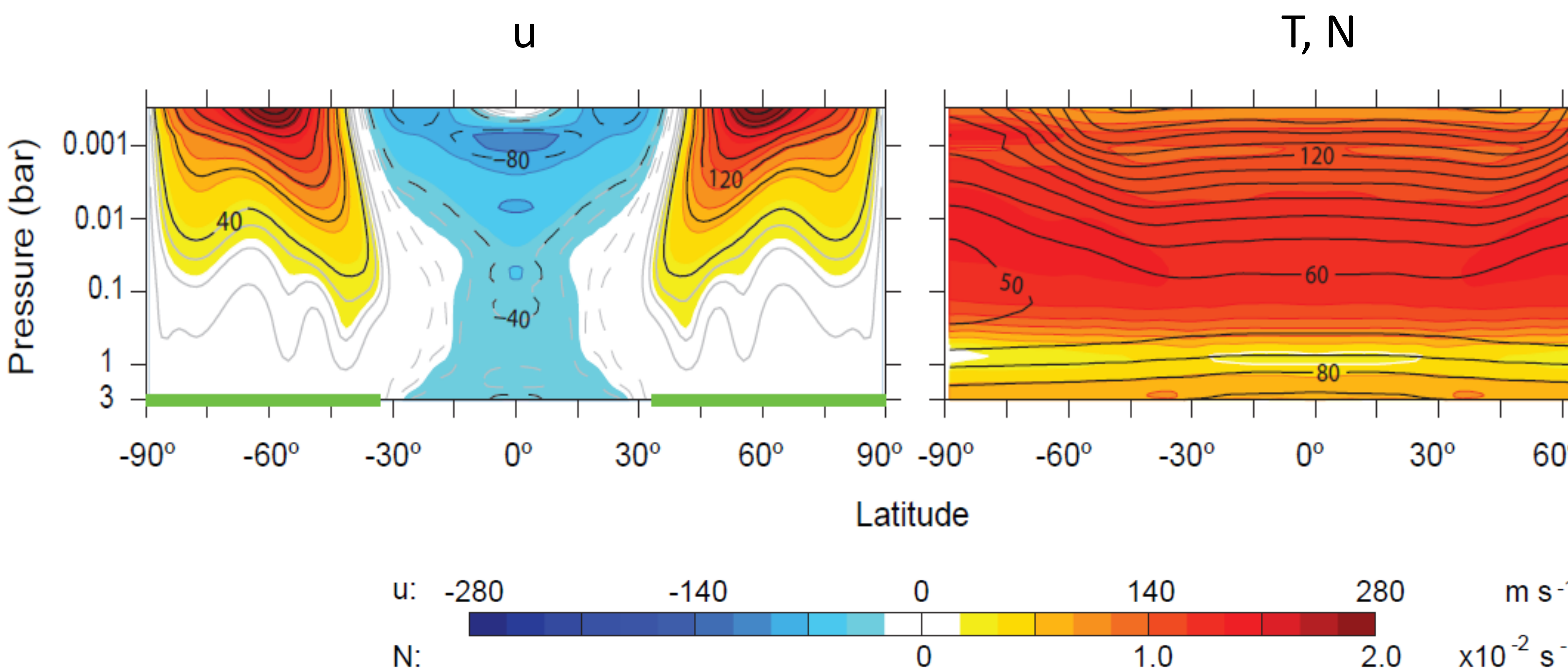
No internal heatflux



(Schneider & Liu 2009)

Why is Uranus subrotating?

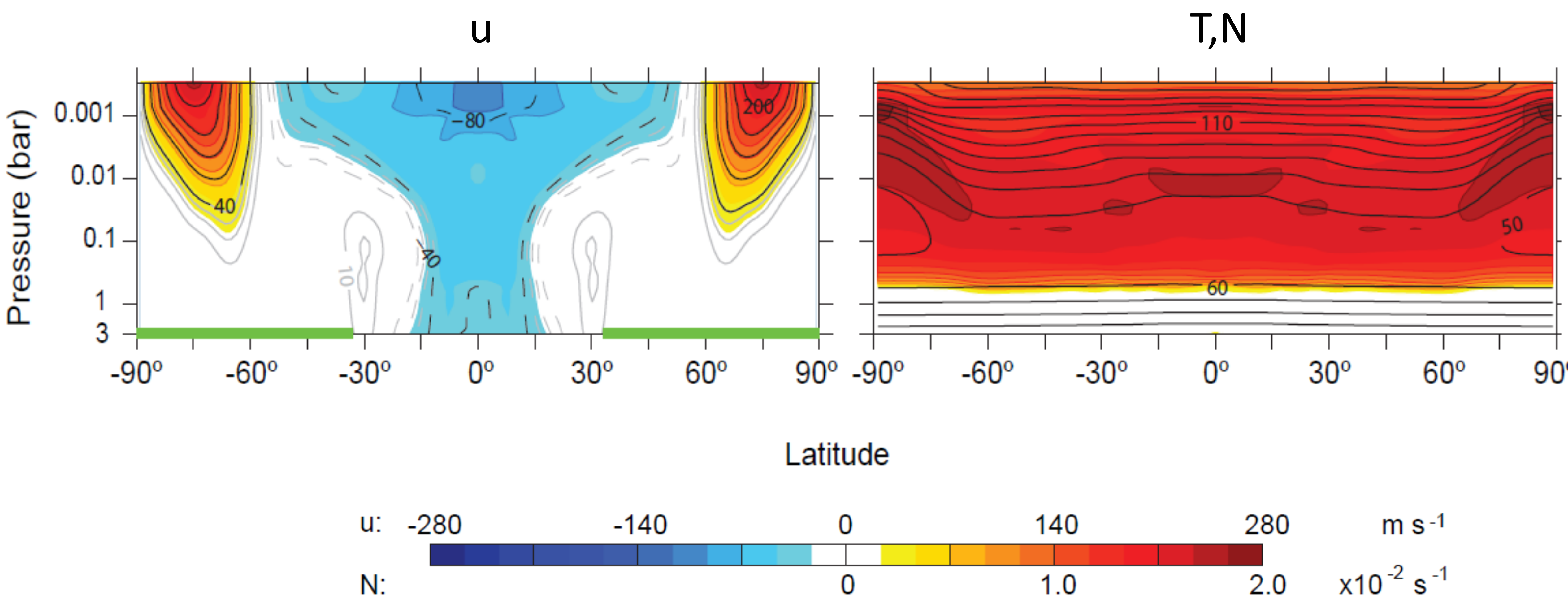
--- Almost no internal heat flux (0.042 W m^{-2}), the atmosphere is stably stratified.



(Liu & Schneider 2010)

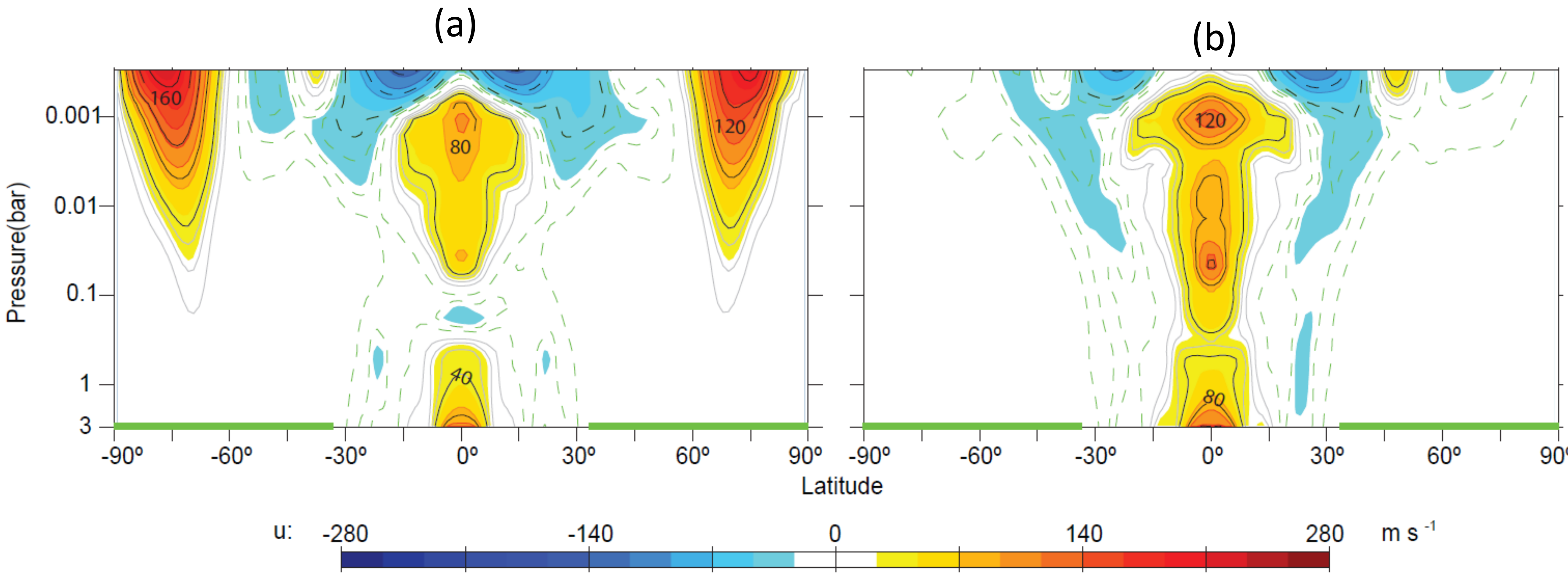
How about Neptune?

--- Has significant internal heat flux (0.43 W m^{-2}), the atmosphere is neutrally stratified below tropopause.



(Liu & Schneider 2010)

Neptune control simulation



(a) Neptune's insolation and Saturn's internal heat flux 2.01 W m^{-2}

(b) Uniform insolation and Neptune's internal heat flux 0.43 W m^{-2}

(Liu & Schneider 2010)

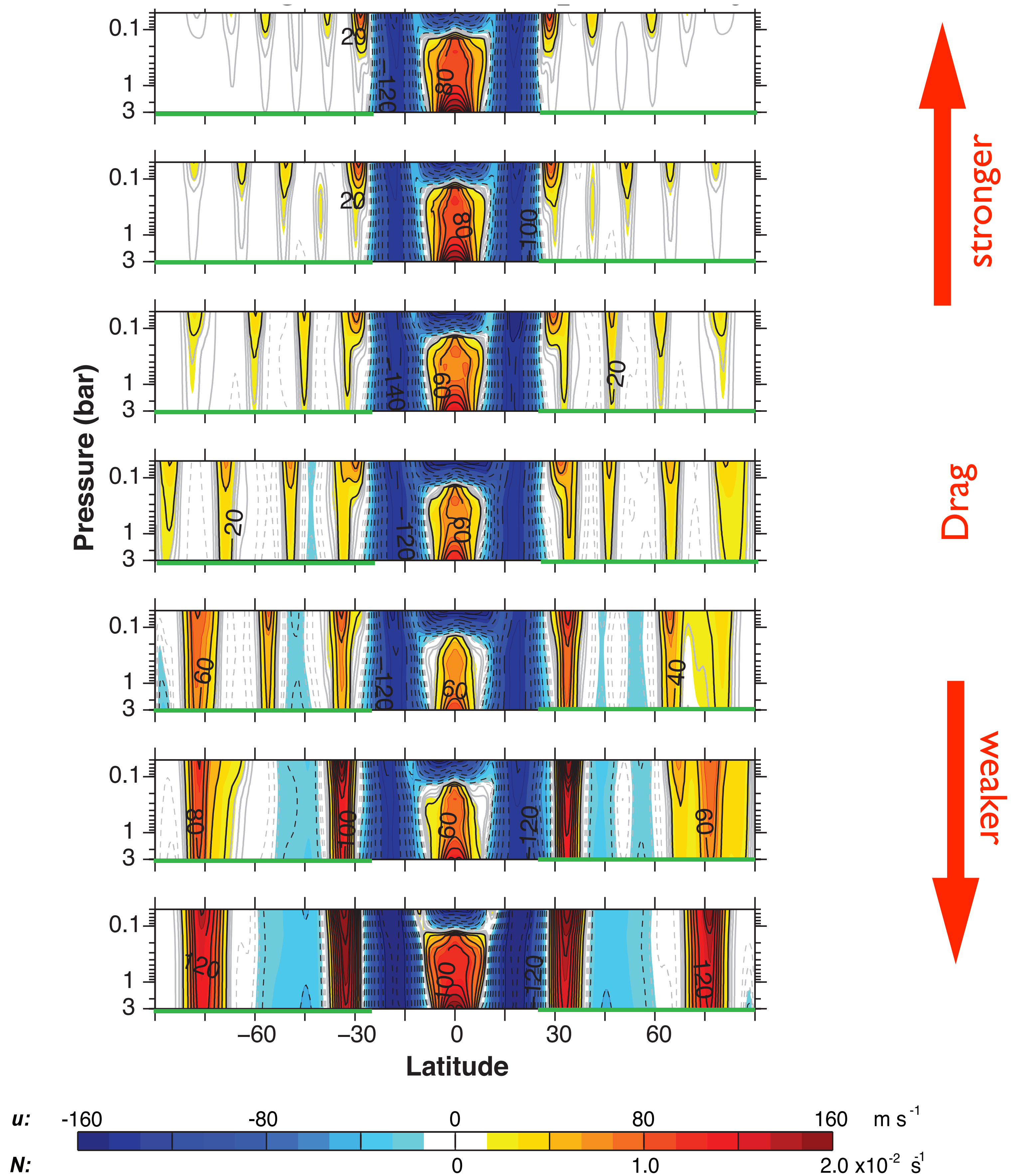
Equatorial superrotation favored when...

- *Planetary rotation rate low*
- *Convective (intrinsic) heating strong*
- *Baroclinicity low*

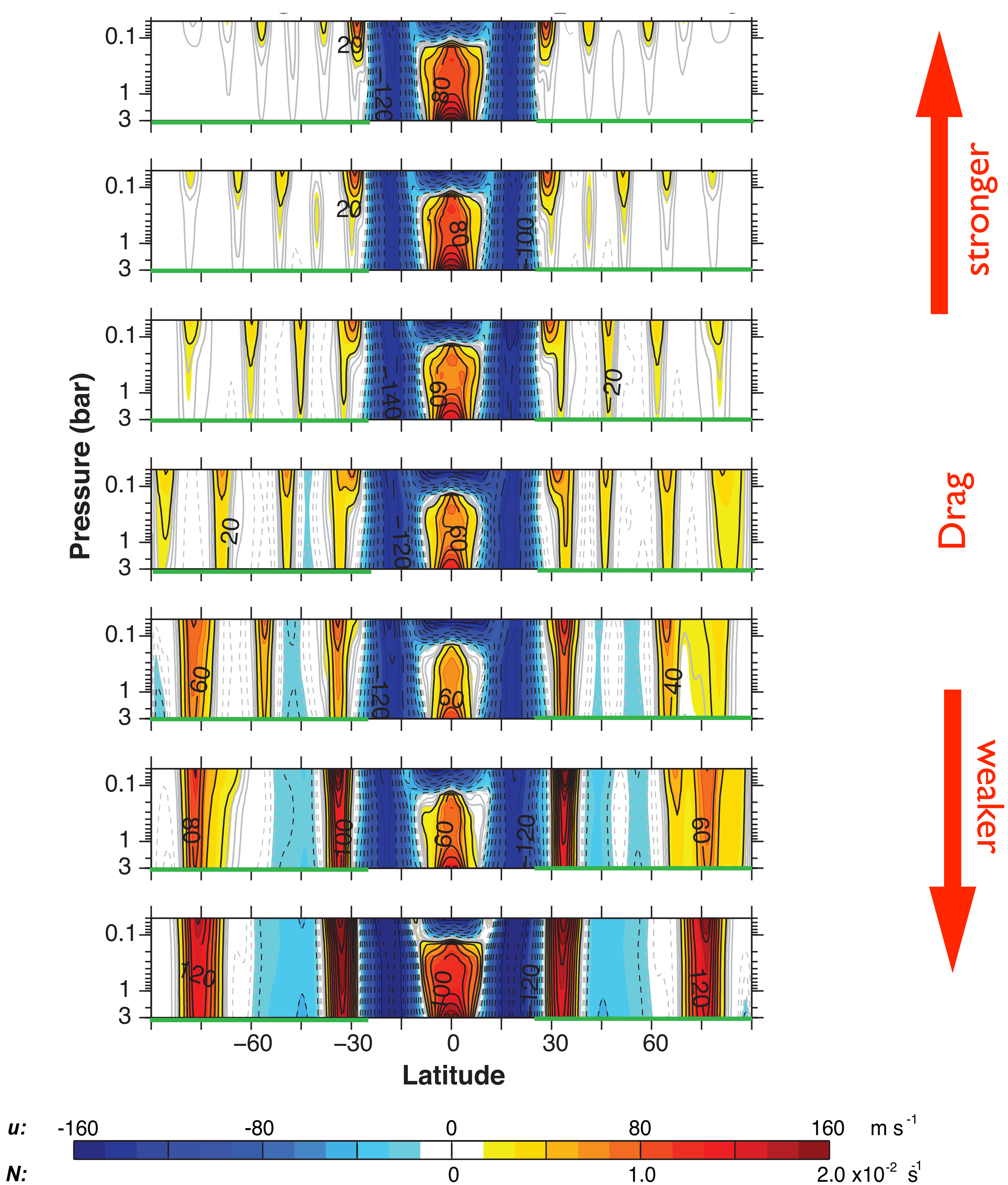
Width and strength of SR jets can be understood from vorticity homogenization arguments

(Schneider & Liu 2009, Liu & Schneider 2010, 2011)

Drag dependence of off-equatorial jets



Drag dependence of off-equatorial jets



Junjun Liu's poster!

Conclusions

- Terrestrial tropical circulations are influenced by eddies, but mean meridional AM fluxes also play a role, so they are in intermediate Rossby number regime (theoretical terra incognita)
- Still need general theory for Hadley circulation
- Equatorial superrotation arises when baroclinicity is weak enough, heating strong enough, and rotation rate low enough
- Off-equatorial jets can be baroclinically generated (difficult to generate them otherwise!)
- Scaling of off-equatorial jets not entirely clear. Rossby radius and Rhines scale play a role; inverse cascades not necessarily