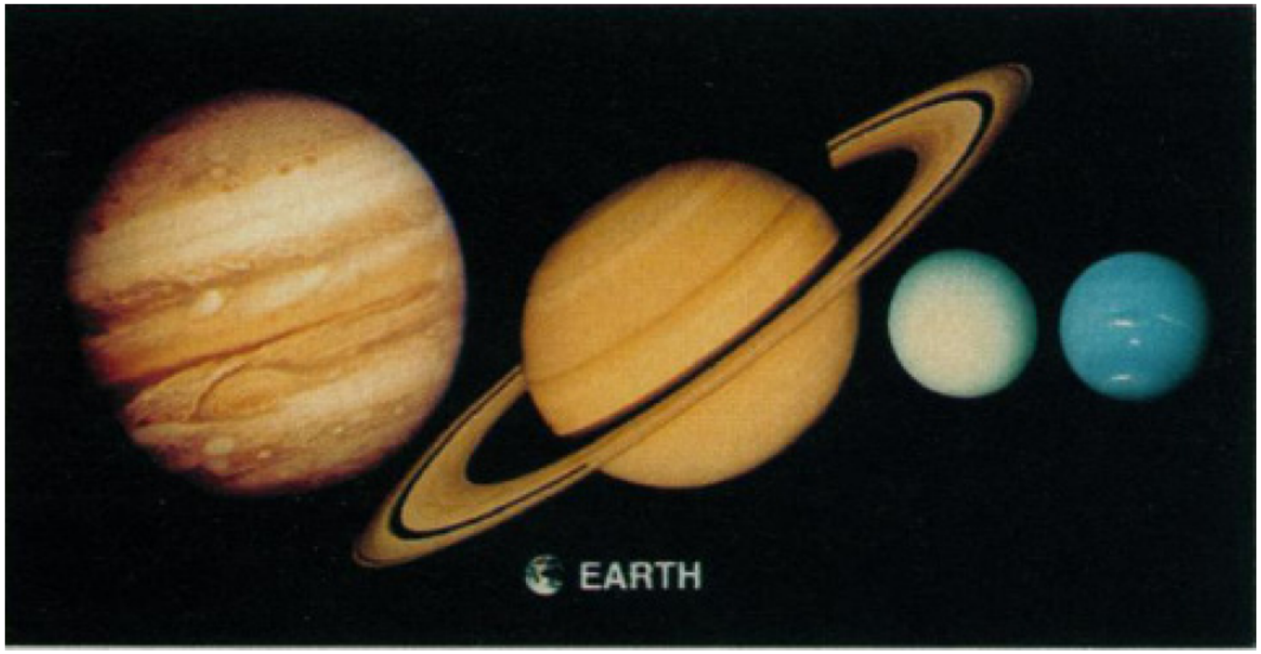
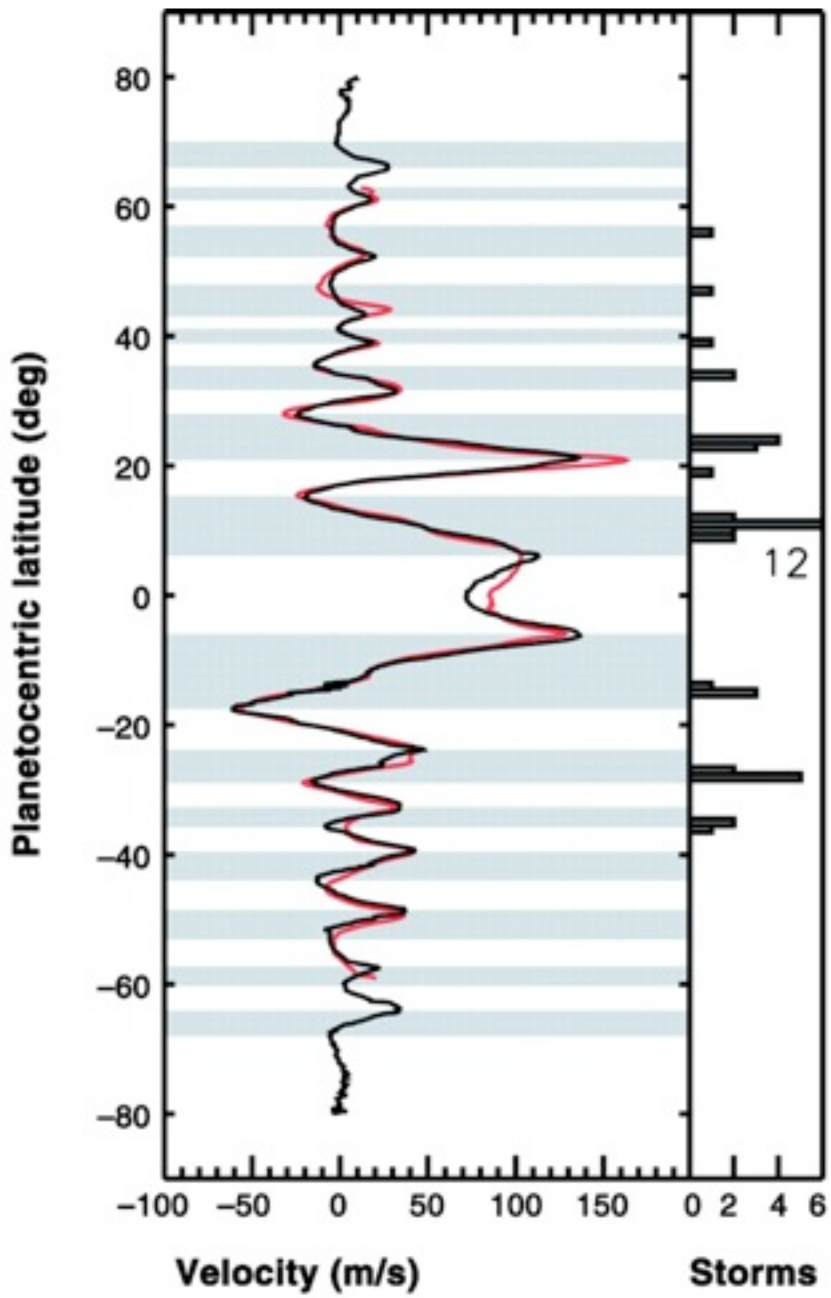
Mechanisms of Jet Formation on the Giant Planets



Tapio Schneider and Junjun Liu

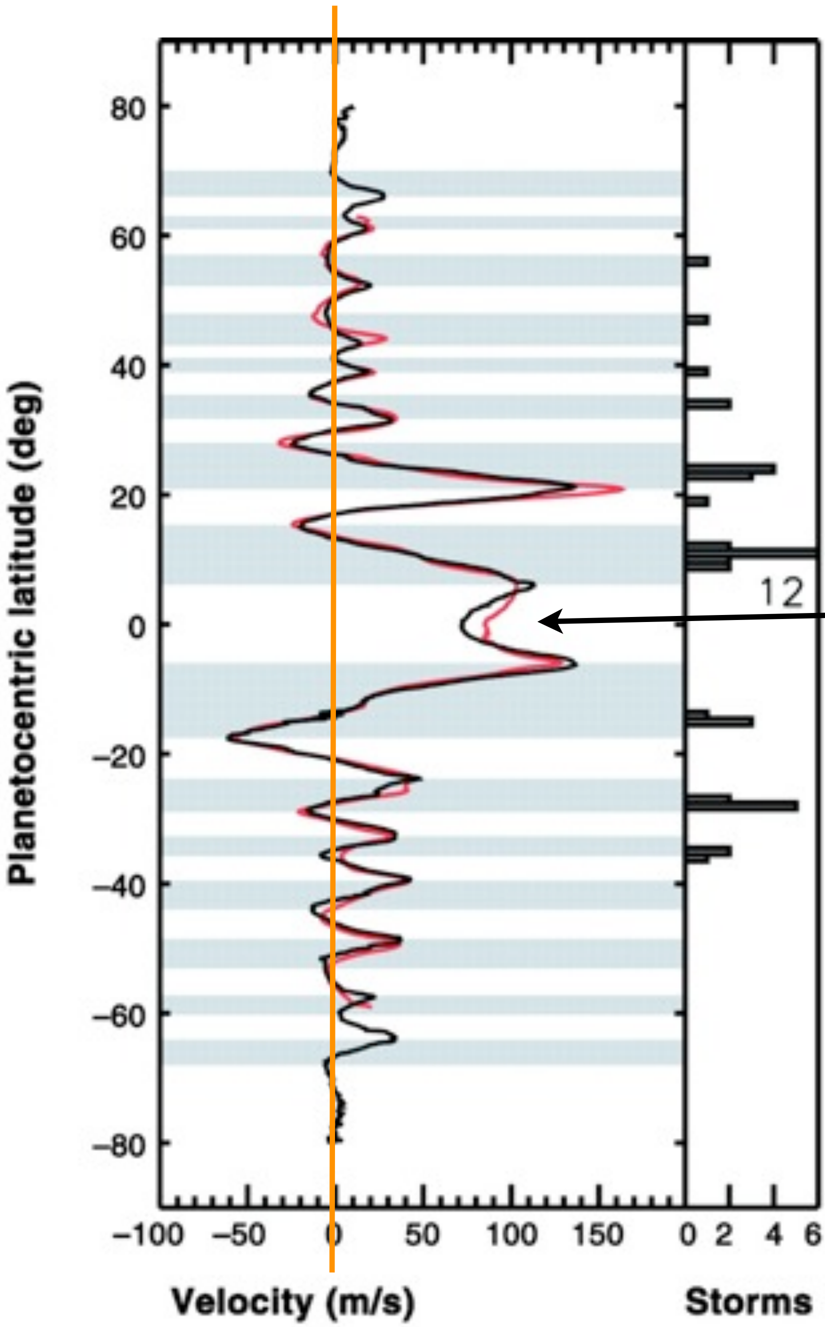
California Institute of Technology

Jupiter zonal wind



(Porco et al. 2003)

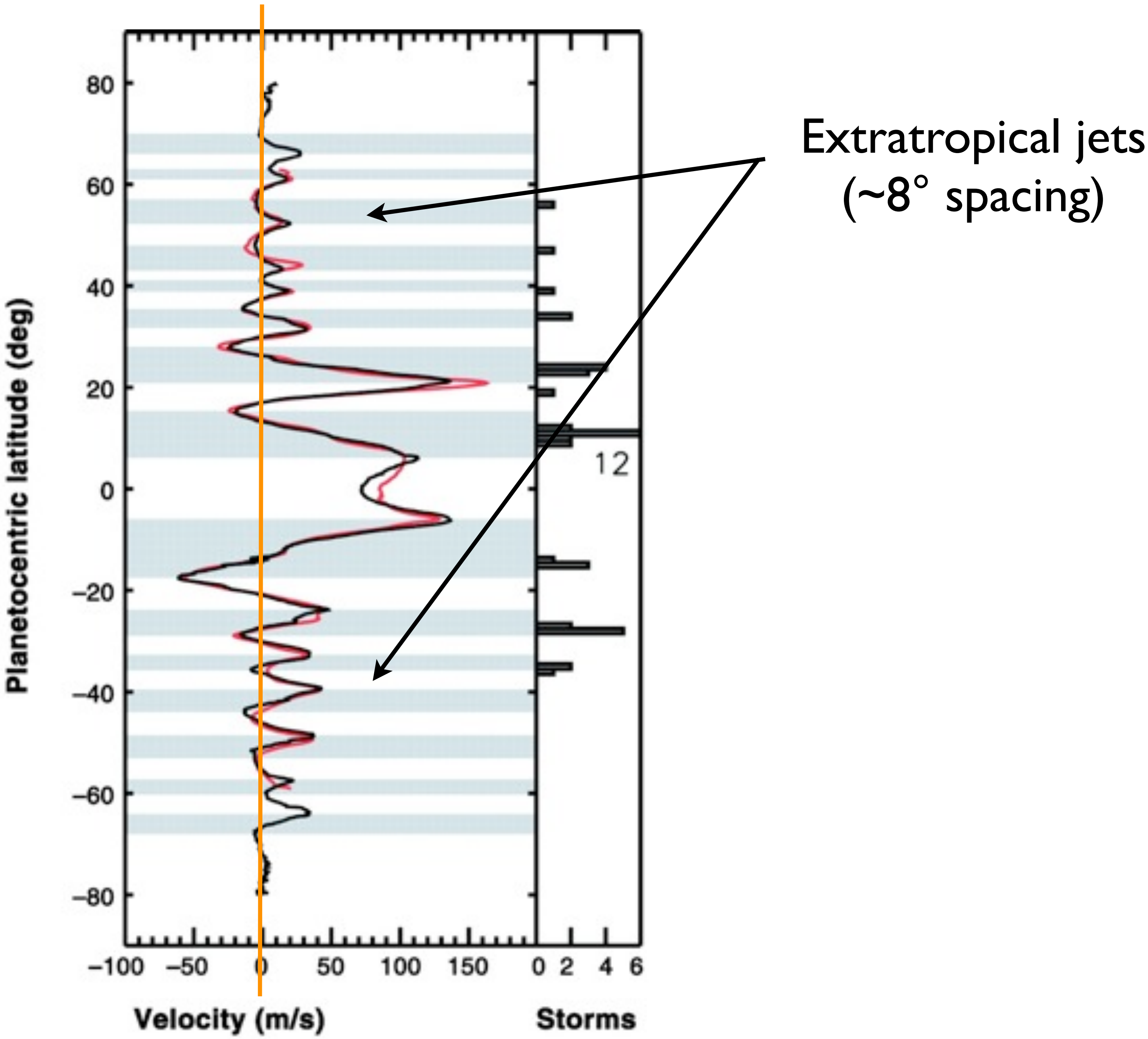
Jupiter zonal wind



Equatorial superrotation (~12°N/S)

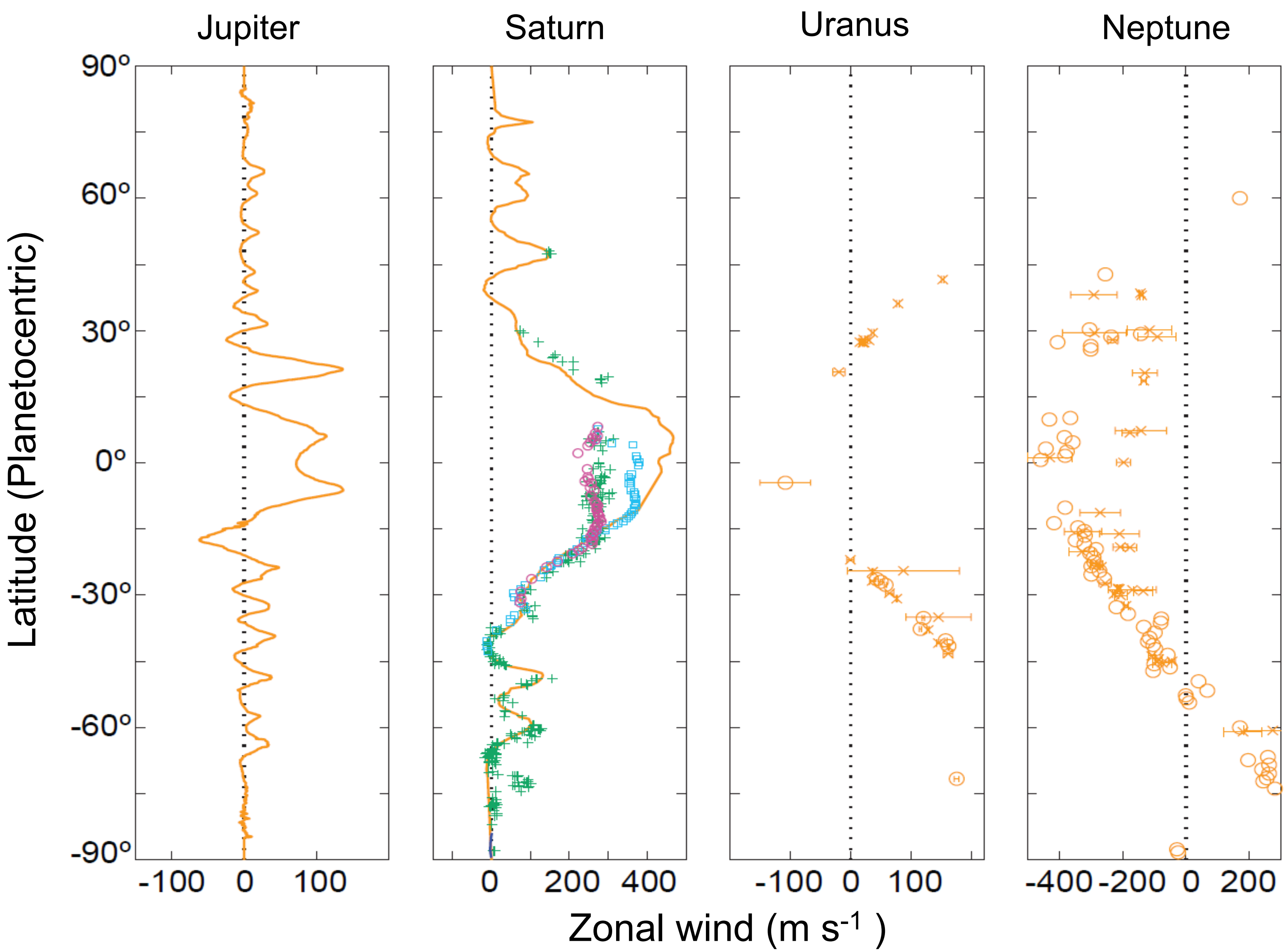
(Porco et al. 2003)

Jupiter zonal wind



(Porco et al. 2003)

Zonal wind on all giant planets



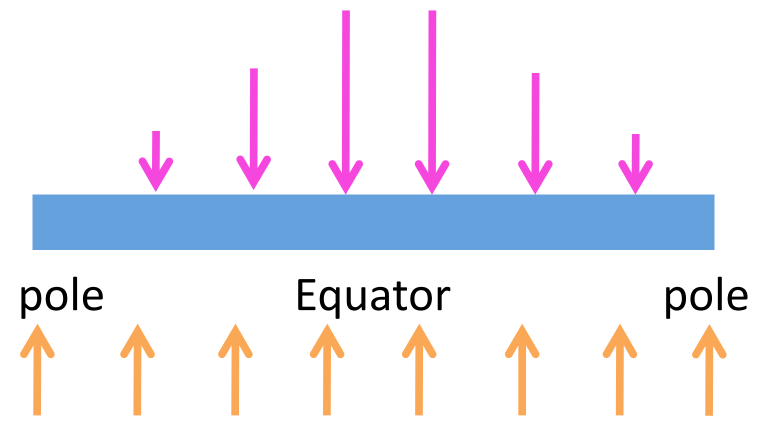
(Porco et al. 2003; Sanchez-Lavega et al. 2001; Hammel et al. 2001; Sromovsky et al. 2001)

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)

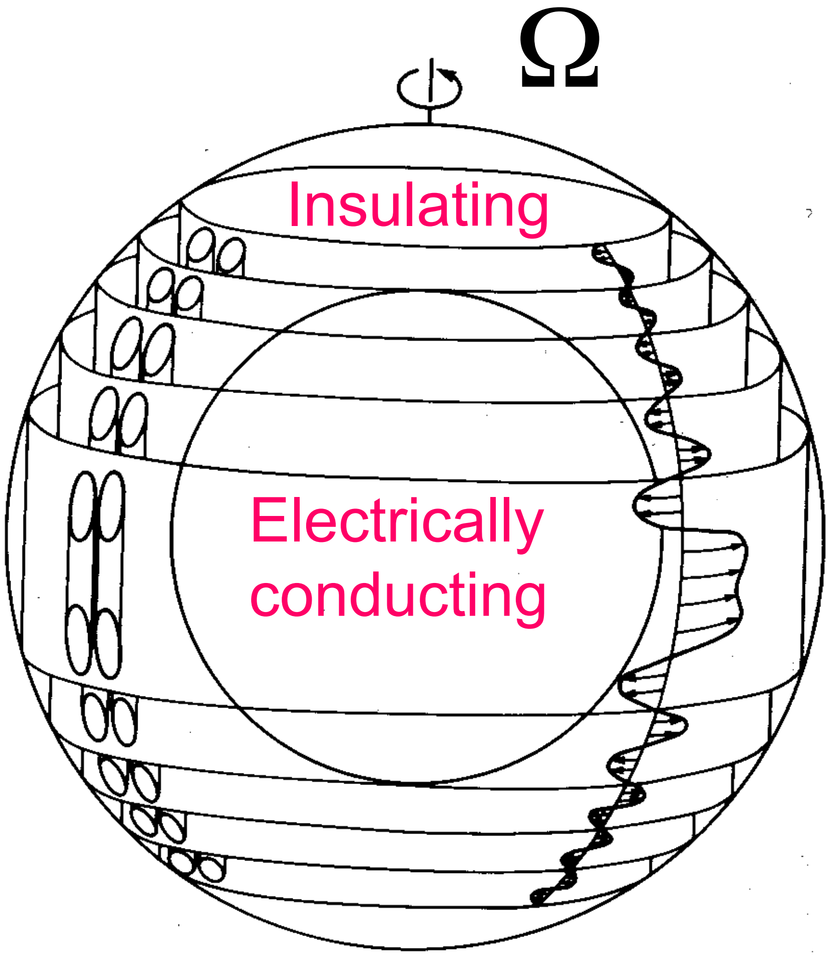


Giant planet properties

- 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

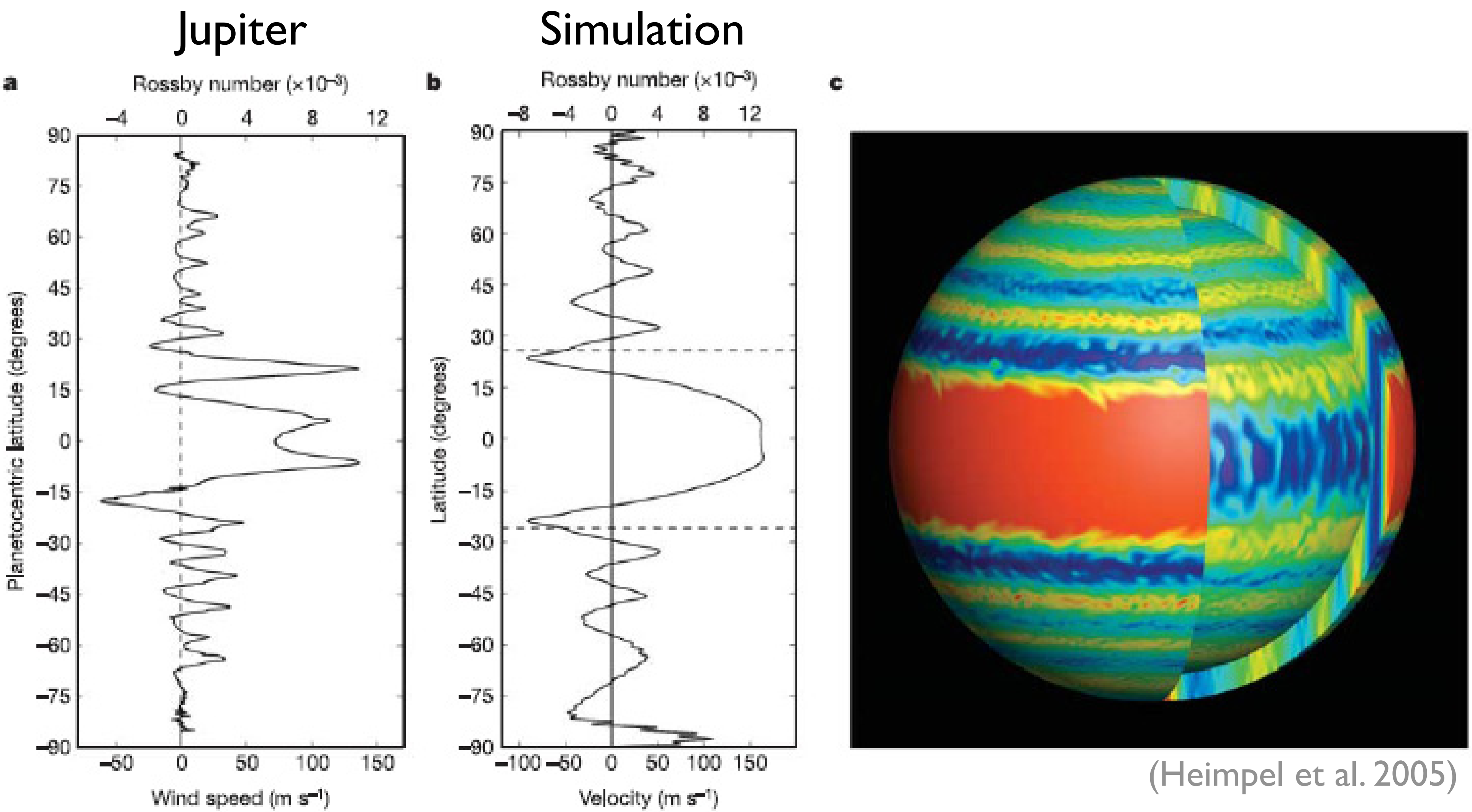
Deep-flow models



(Busse, 1983)

- Rotating Rayleigh-Benard convection
- Surface zonal winds extend along cylinders through insulating layer (Busse 1976)
- But strength of deep winds constrained by Ohmic dissipation (Liu et al. 2008)

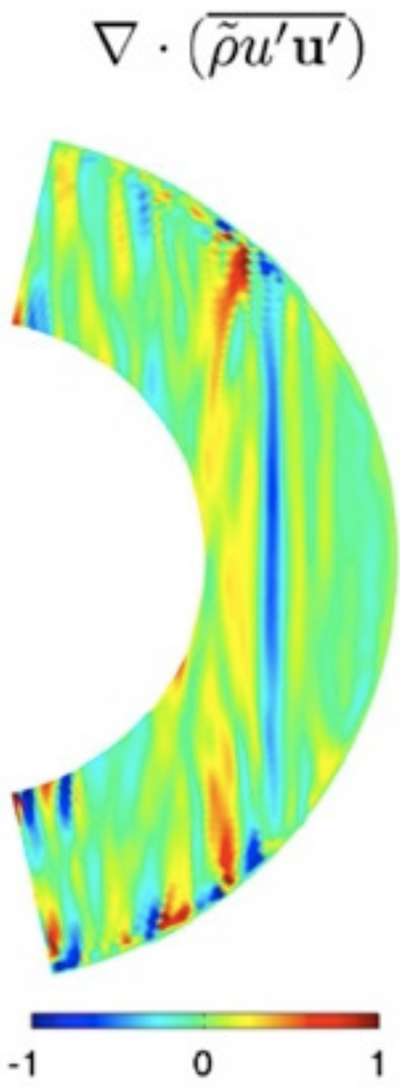
Zonal wind in deep-flow model



(Heimpel et al. 2005)

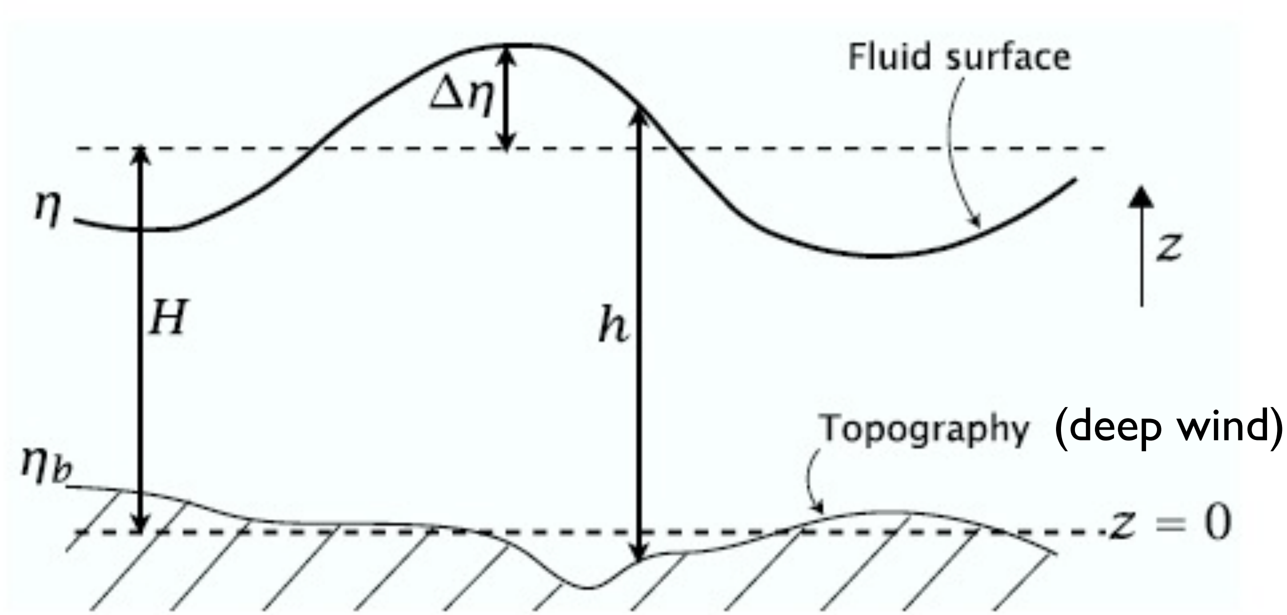
Implies excessive heat flux (viscous dissipation) and are ruled out by AM balance

AM flux (per unit volume) is barotropic in deep-flow models



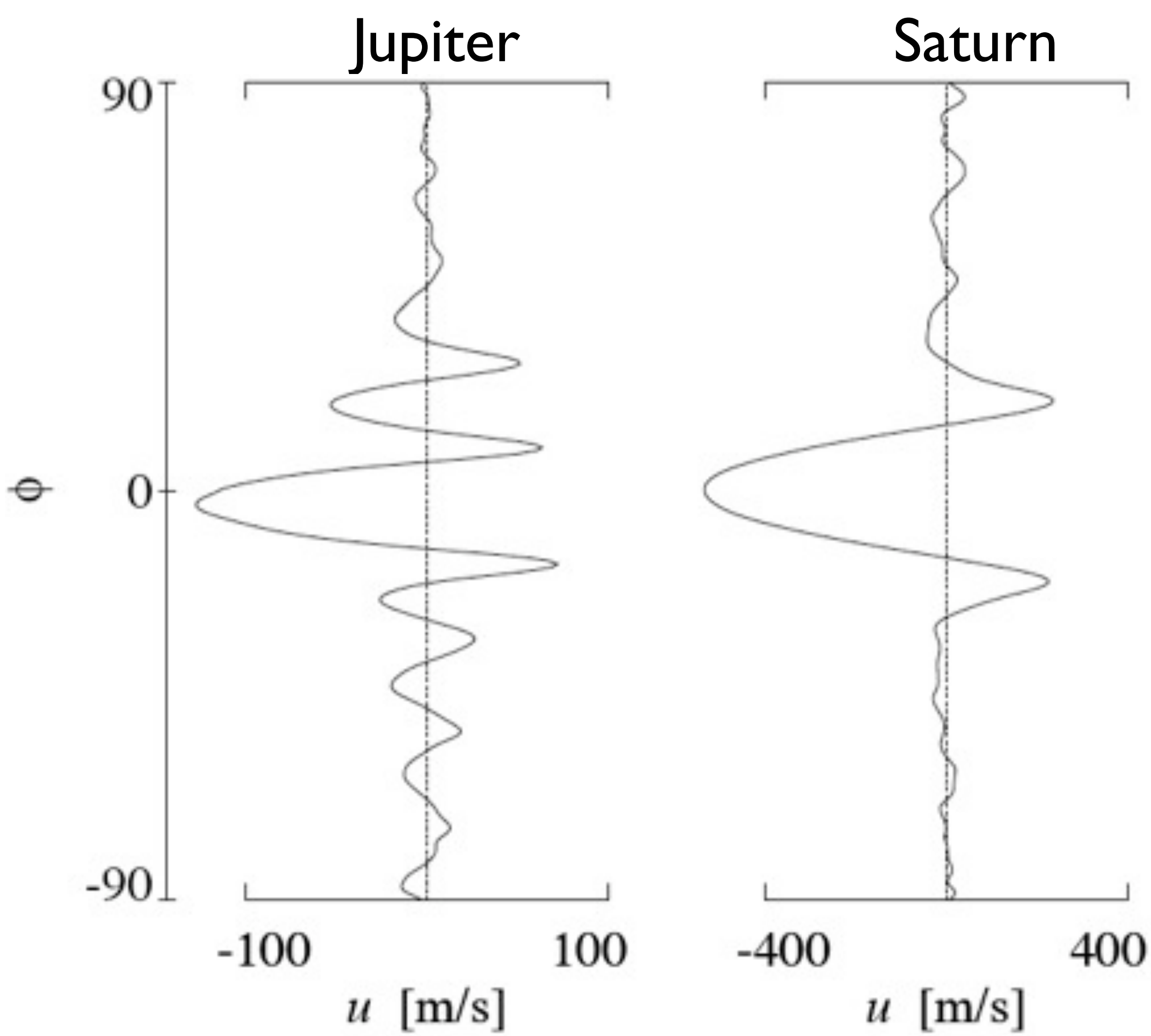
(Kaspi et al. 2009)

Shallow-flow models



- Shallow-water layer on rotating sphere
- Driven by small-scale forcing (convection) or large-scale mass/volume source (insolation gradient)
- Generation of extratropical jets by inverse cascade

Zonal wind in shallow model



- Usually does not reproduce equatorial superrotation
- Ignores baroclinicity/stratification

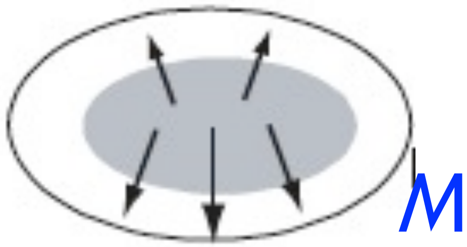
(Scott and Polvani 2007)

Hide's theorem and superrotation

If there is any (radial) viscous dissipation of angular momentum,

$$\frac{DM}{Dt} = \frac{\partial}{\partial r}\nu\frac{\partial M}{\partial r},$$

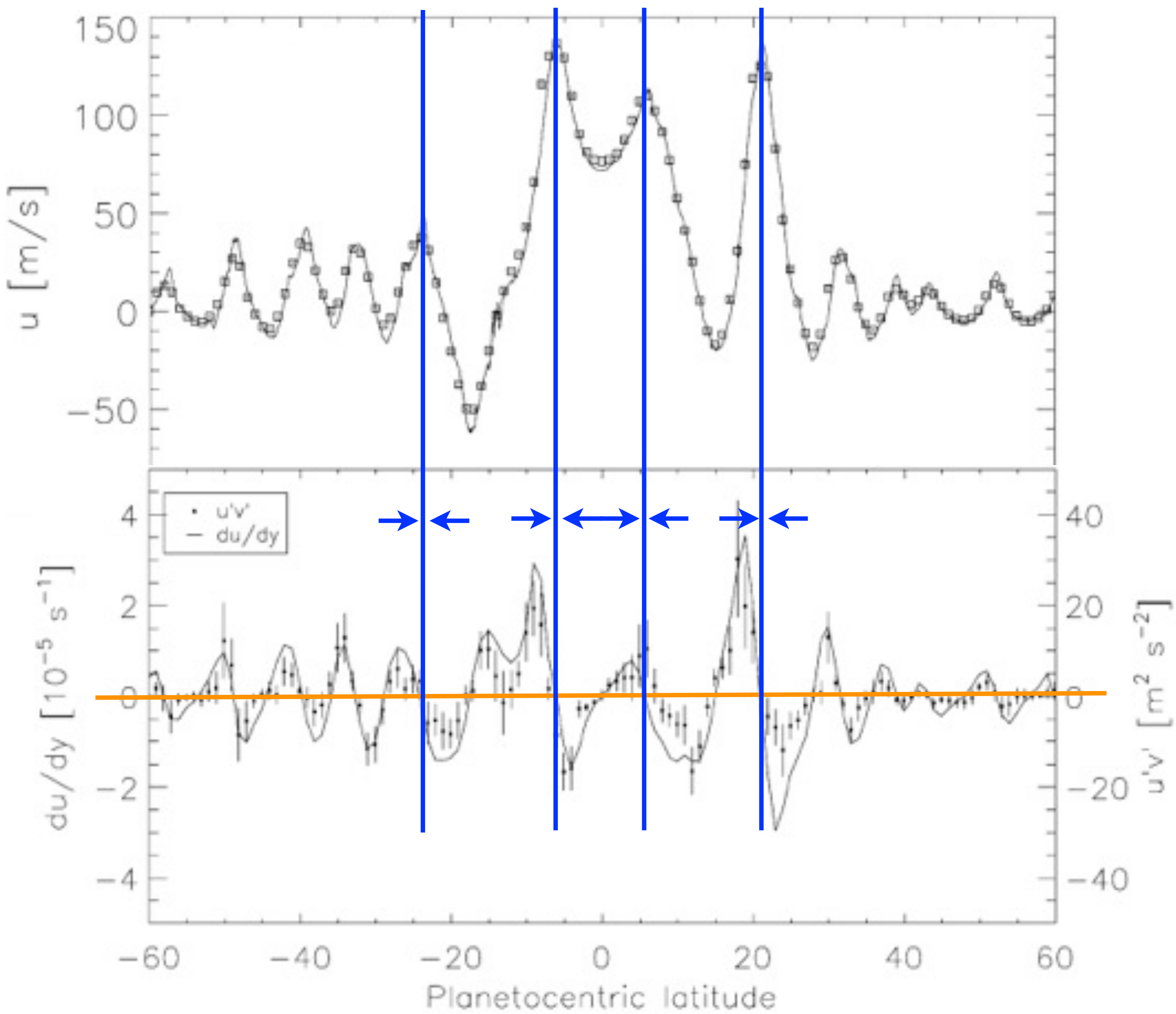
with $M = (a\Omega\cos\phi + u)a\cos\phi,$ interior extrema of angular momentum are impossible in steady flow.



Therefore, $u \leq \Omega a \sin^2\phi/\cos\phi.$

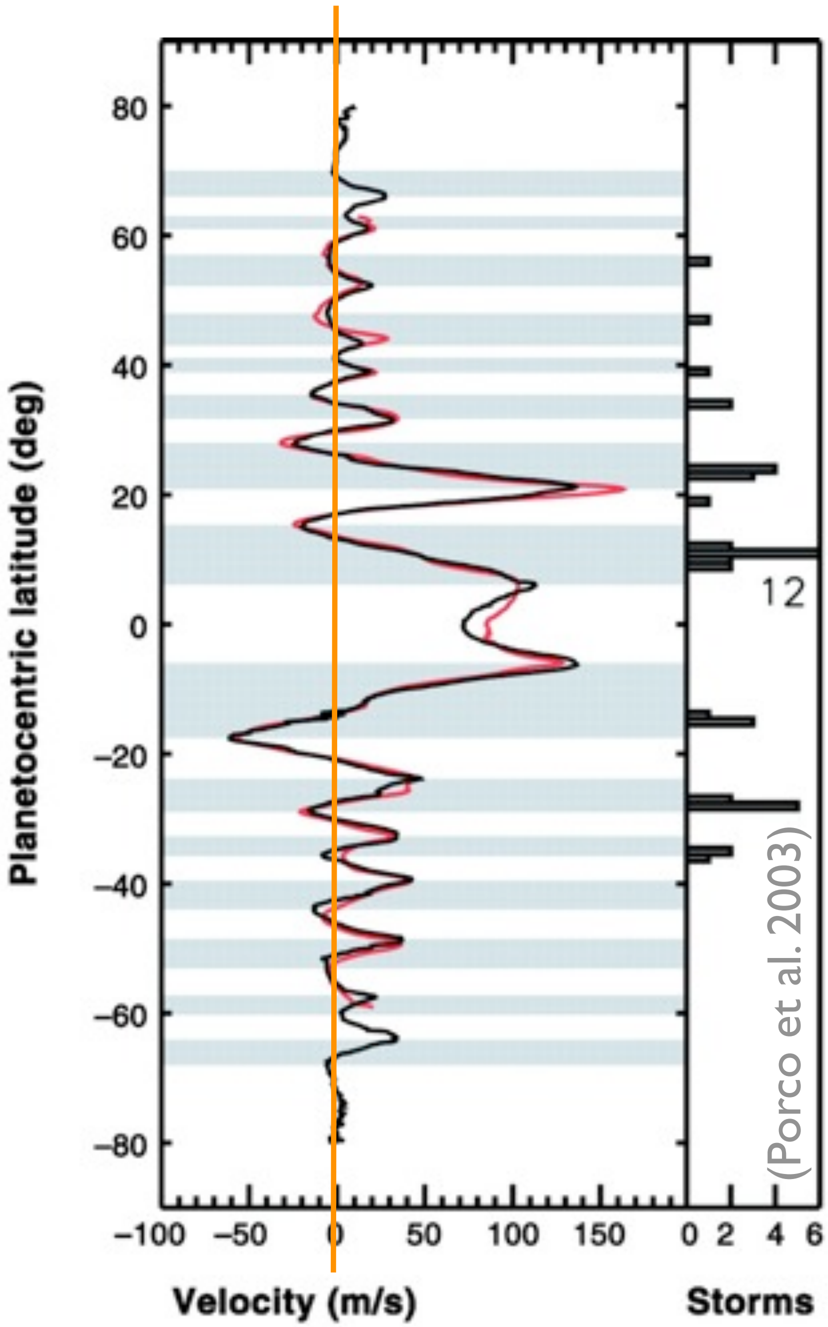
(Hide 1969; Schneider 1977)

Eddy angular momentum flux on Jupiter



(Salyk et al. 2006)

Scales of waves on Jupiter



- Gravity wave speed:

$$c \approx 450\,\mathrm{m\,s}^{-1}$$

(Ingersoll & Kanamori 1995)

- Midlatitude Rossby radius:

$$c/f \sim 2000\,\mathrm{km}$$

- Equatorial Rossby radius:

$$\sqrt{c/\beta} \sim 10{,}000\,\mathrm{km} \sim 8^\circ$$

Generation of equatorial waves by convection

Thermodynamic balance in equatorial region (Charney 1963):

$$\cancel{\partial_t b} + \cancel{\mathbf{v} \cdot \nabla_h b} + N^2 w = Q$$

Sufficiently strong convective heating leads to divergence:

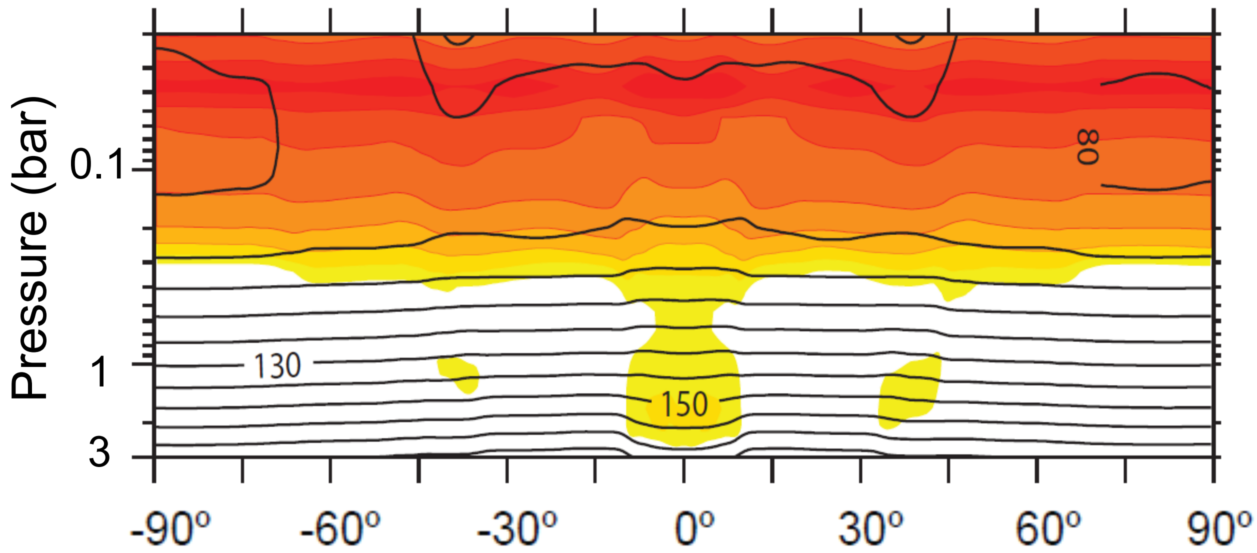
$$\nabla_h \cdot \mathbf{v}_\chi = -\partial_z w = -\partial_z (Q/N^2)$$

Divergence is source of rotational flow (Sardeshmukh & Hoskins 1988):

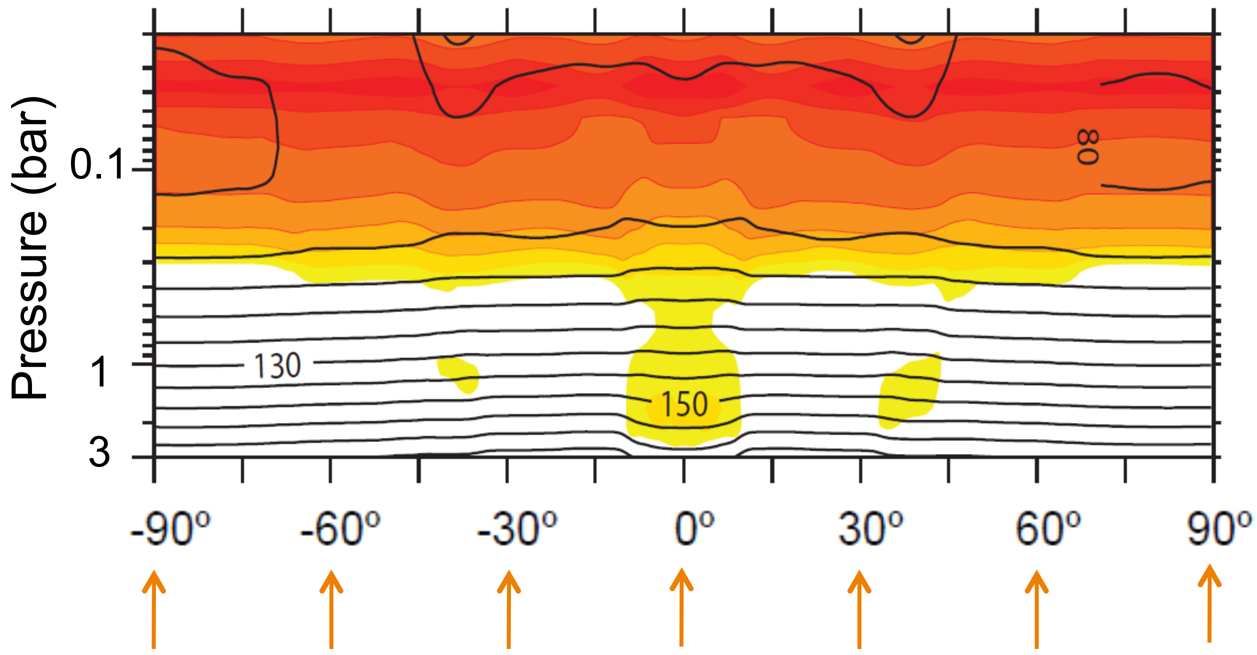
$$(\partial_t + \mathbf{v}_\Psi \cdot \nabla_h)\zeta_a = -\nabla_h \cdot (\zeta_a \mathbf{v}_\chi)$$

Convective heating at weak stratification generates Rossby waves that propagate out of equatorial waveguide

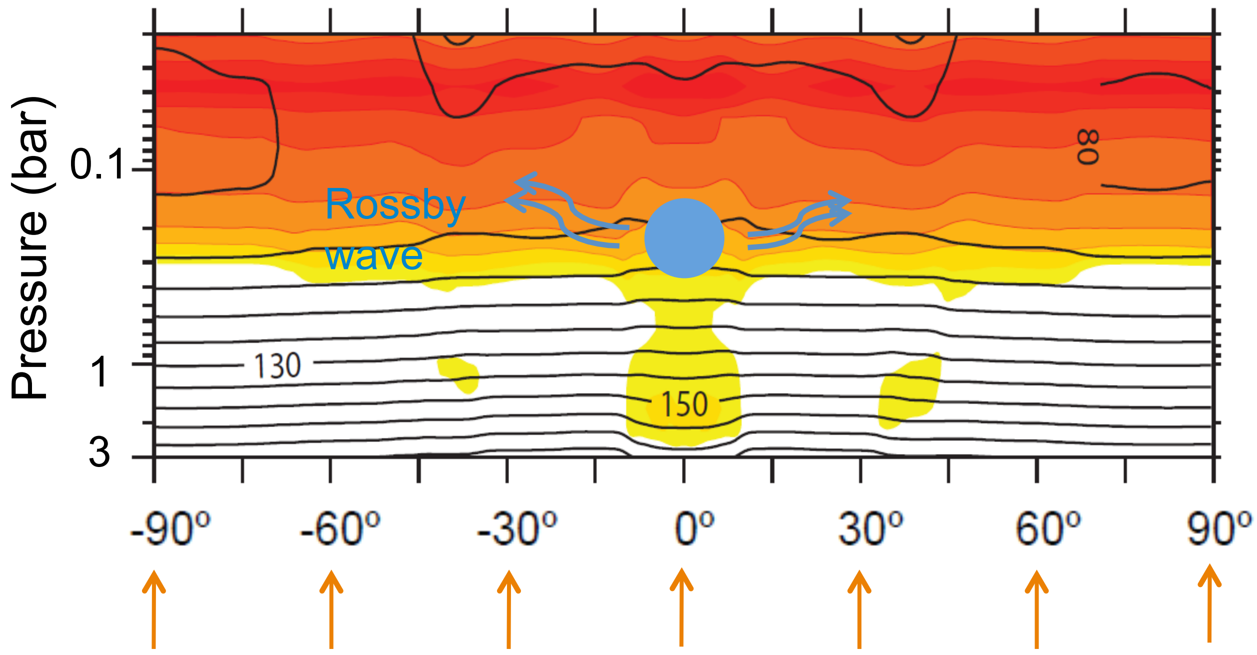
Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



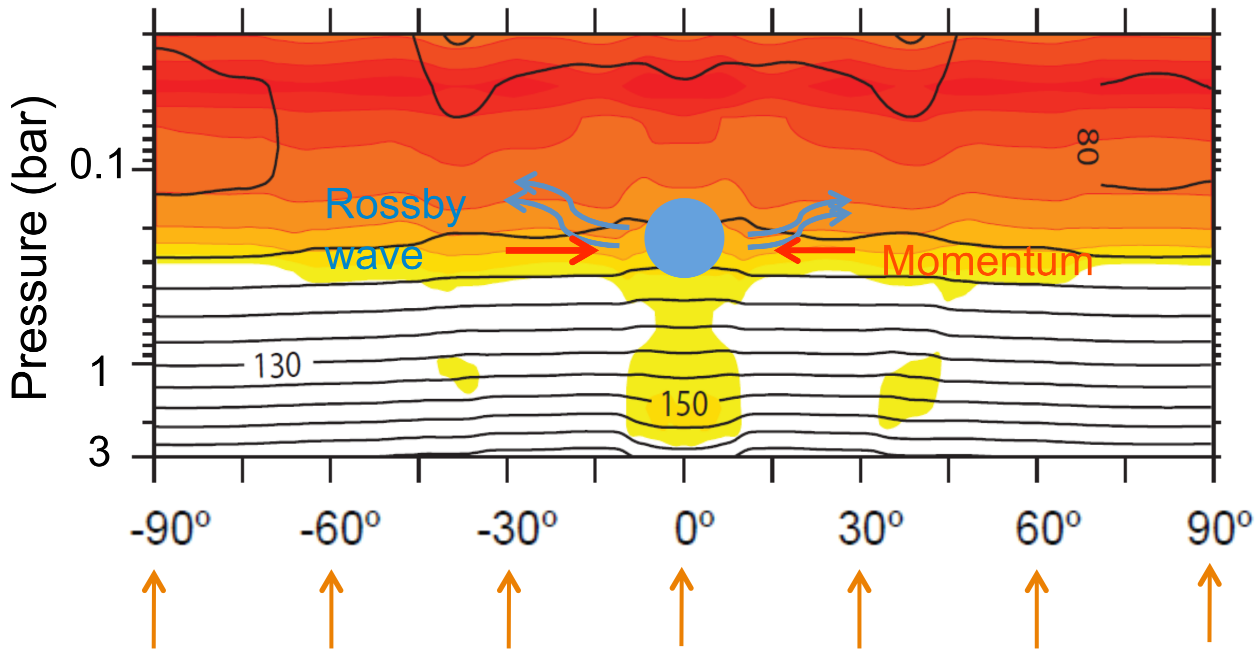
Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



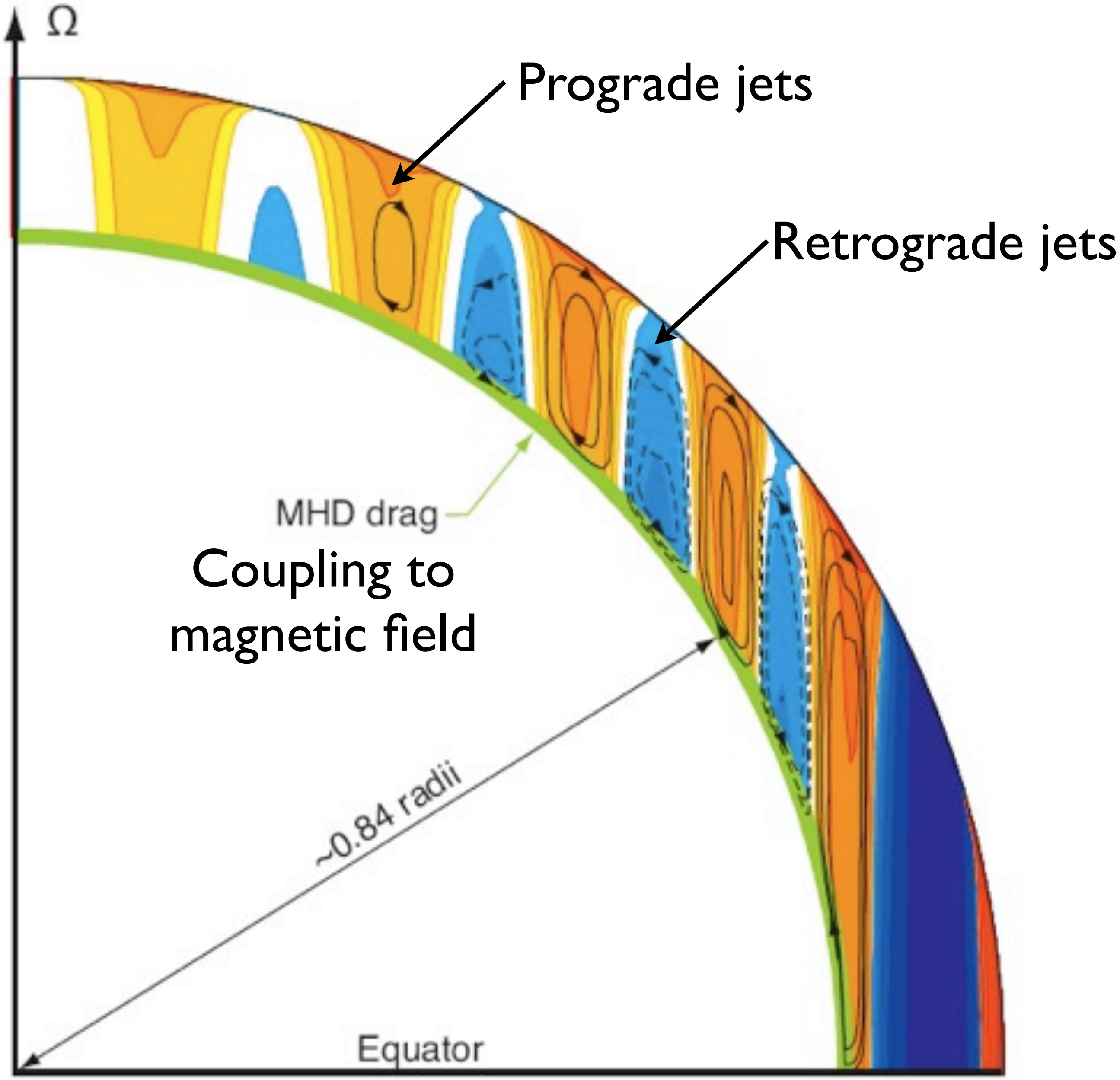
Uniform convection generates *equatorial* Rossby waves, which transport angular momentum toward equator



Giant planet GCM

- Ideal-gas atmosphere in thin shell with Jovian rotation rate, gravitational acceleration, gas constant, etc.
- Scattering gray radiative transfer with diffuse insolation
- Quasi-equilibrium dry convection scheme
- Exponential SGS filter in horizontal
- Up to T213 horizontal resolution, 30 vertical levels
- Imposed *uniform* heat flux at lower boundary
- Rayleigh drag at artificial lower boundary at 3 bar

Mean meridional circulations on Jupiter

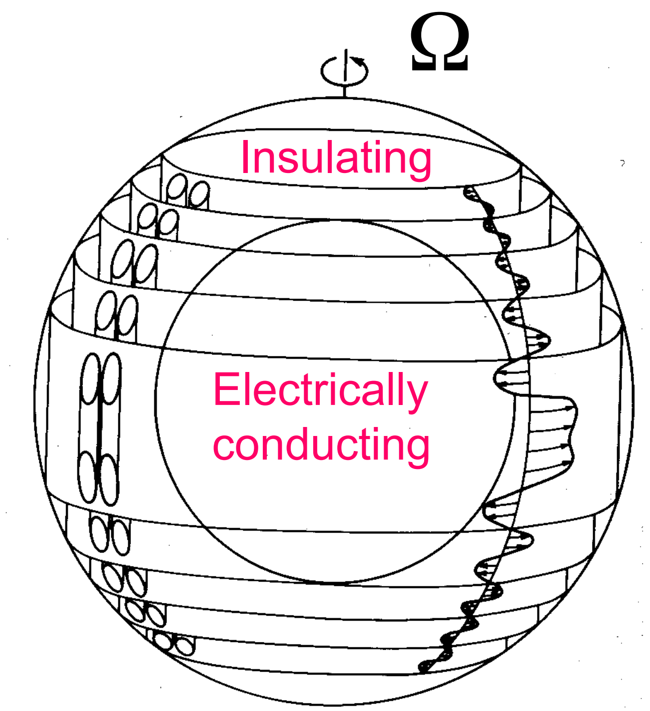


(Schneider & Liu 2009)

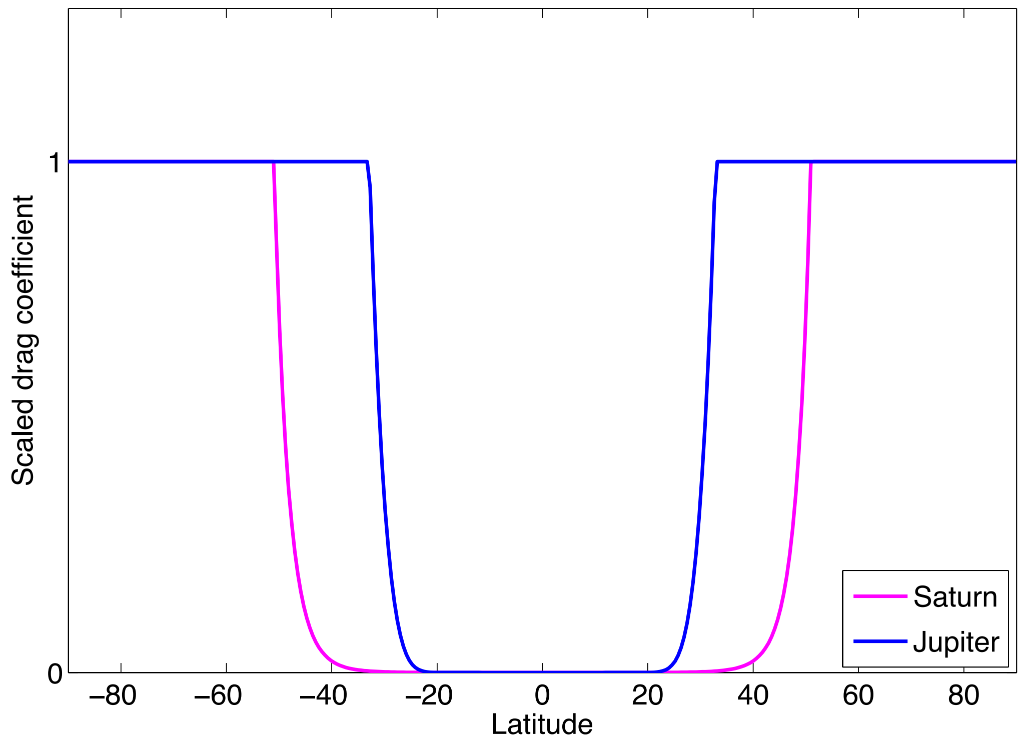
Modeling of deep MHD drag in thin shell

Model momentum dissipation as Rayleigh drag

$$\partial_t \mathbf{v} \cdots = -r\mathbf{v}$$

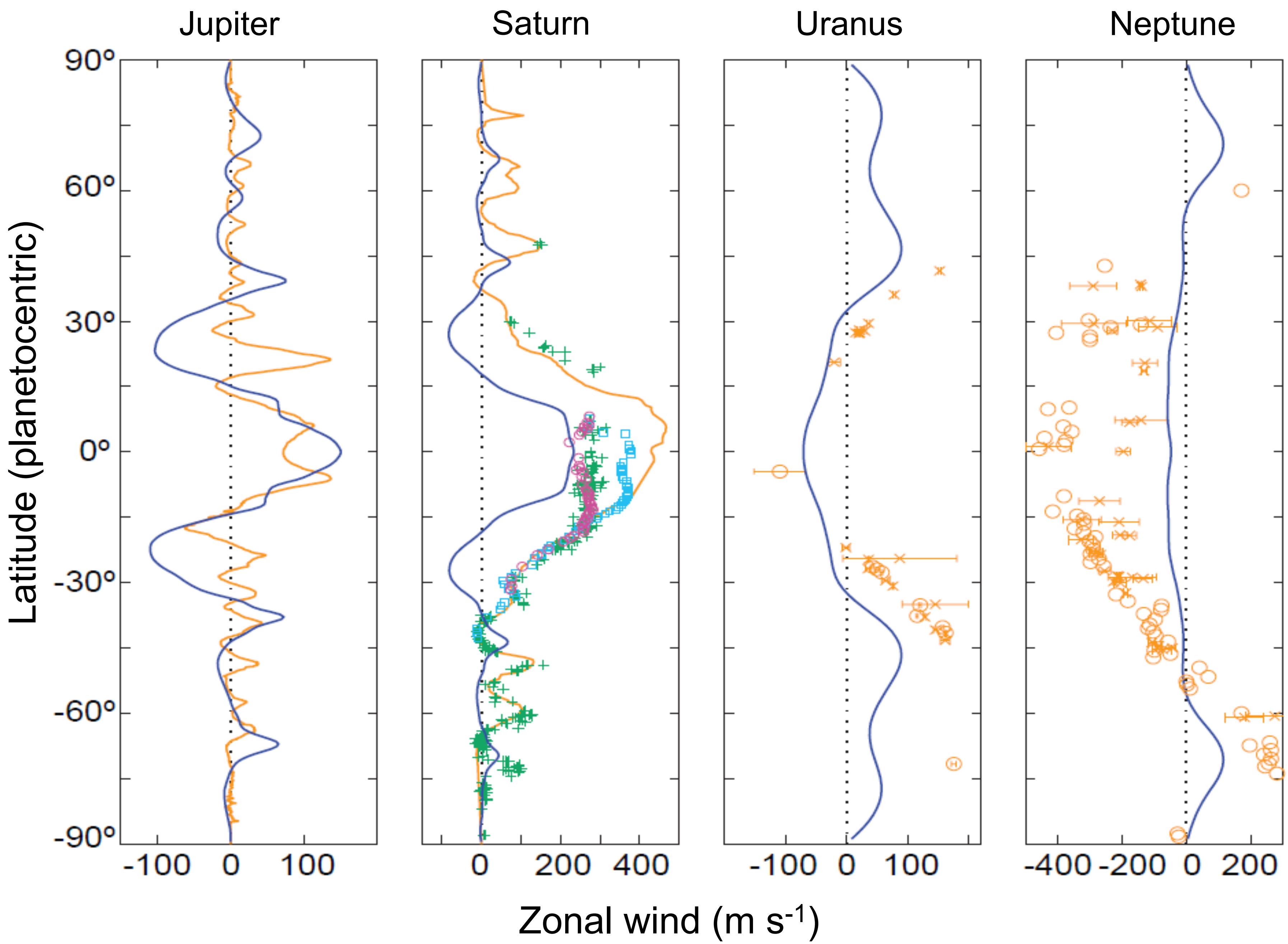


(Busse, 1983)



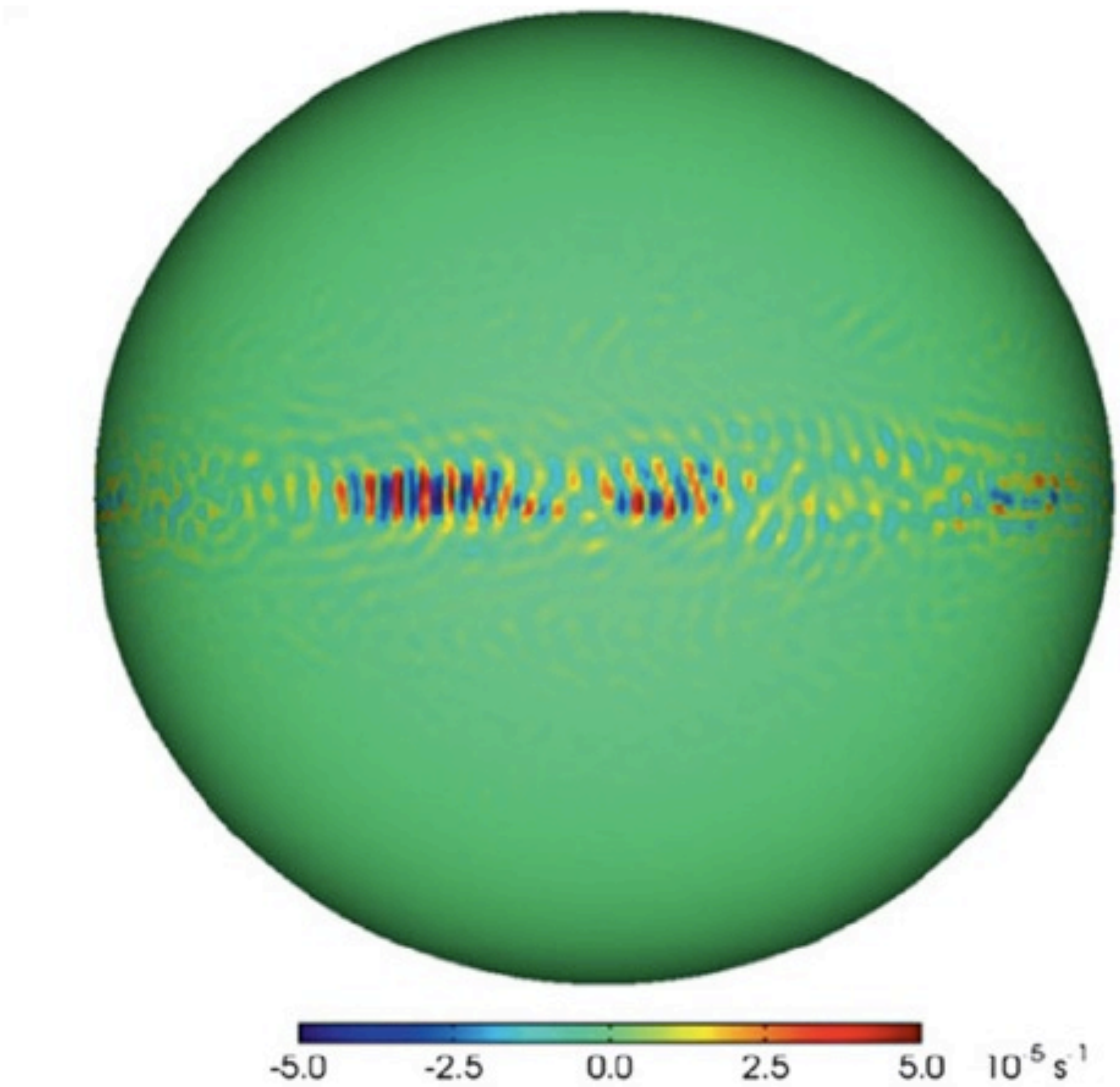
(Liu et al. 2008)

Simulated zonal wind in upper troposphere



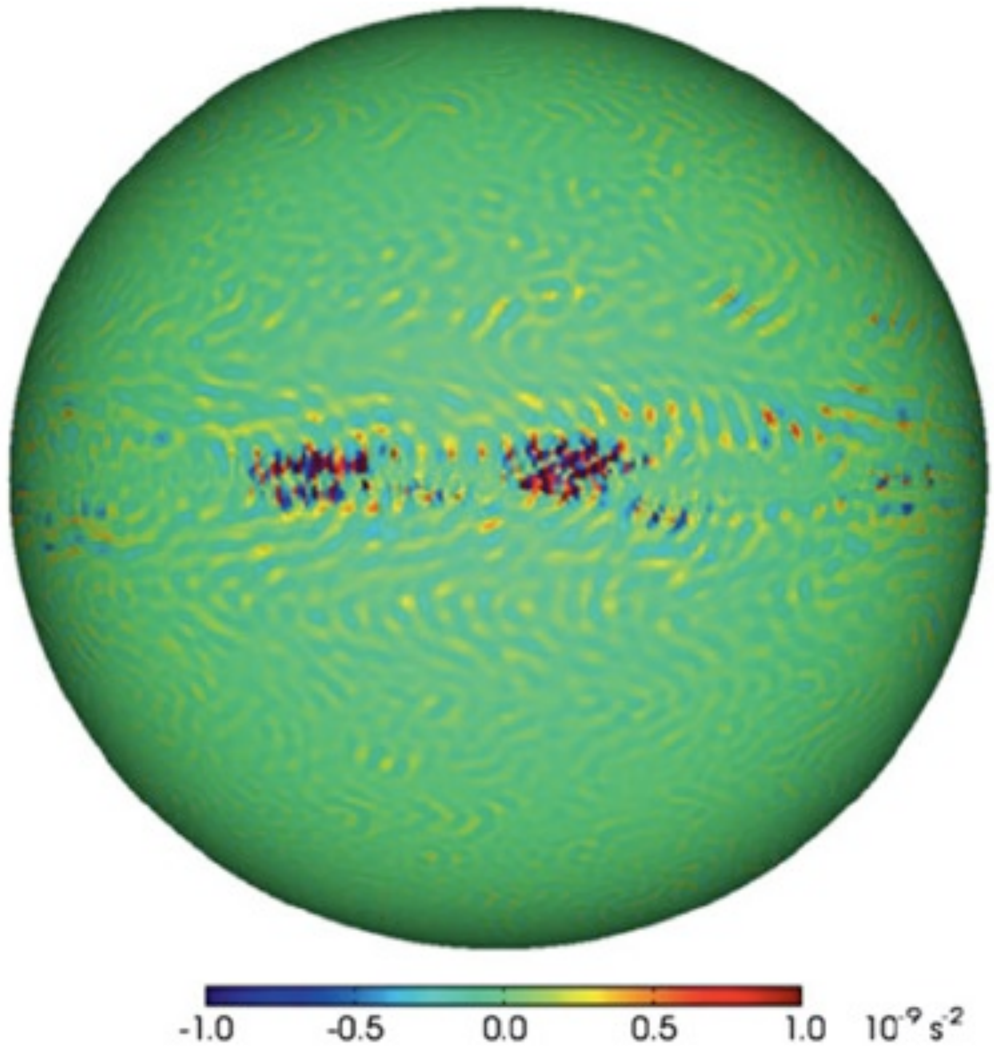
(Liu & Schneider 2009)

Divergence (Jupiter upper troposphere)



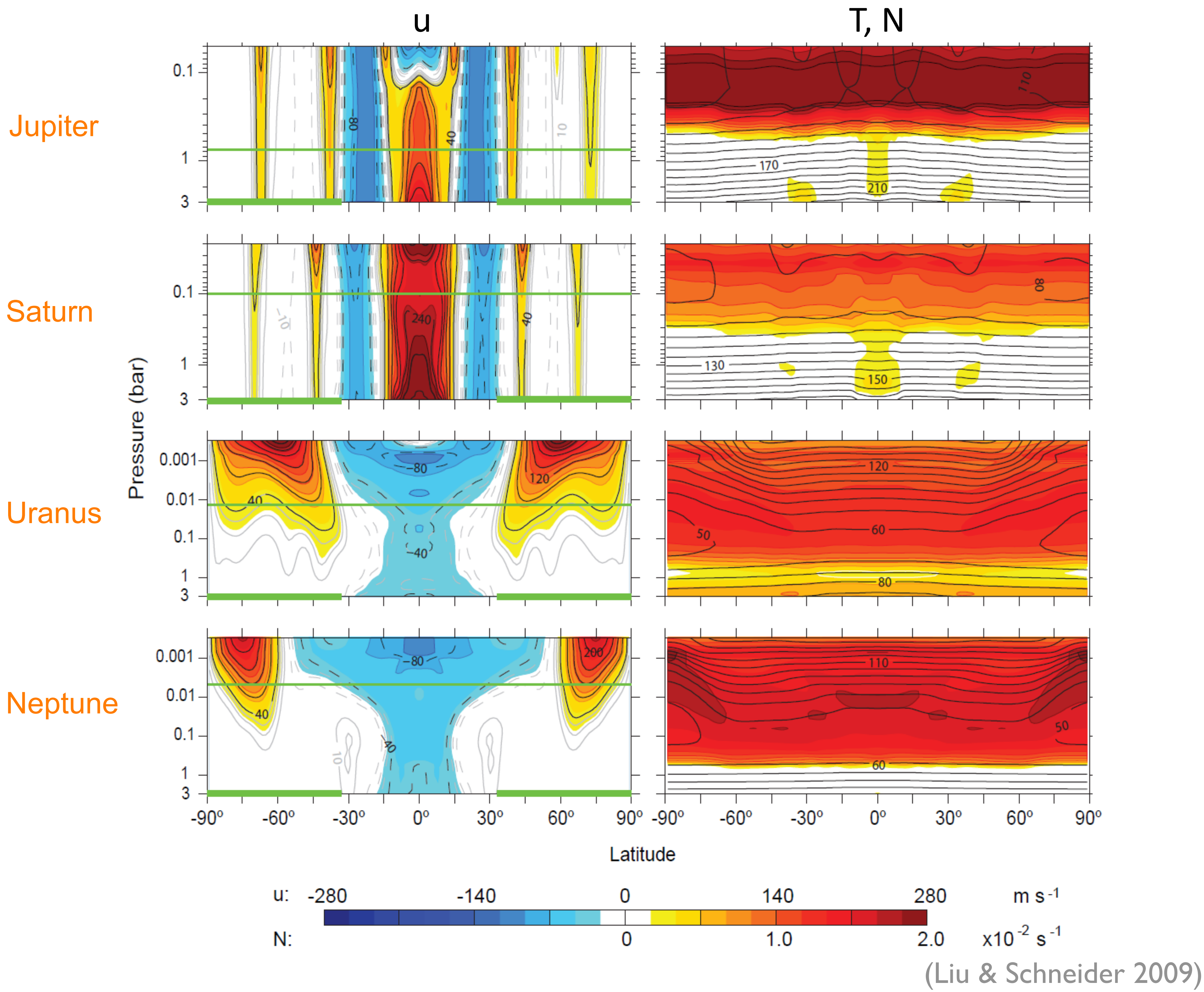
(Schneider & Liu 2009)

Rossby wave source (Jupiter troposphere)



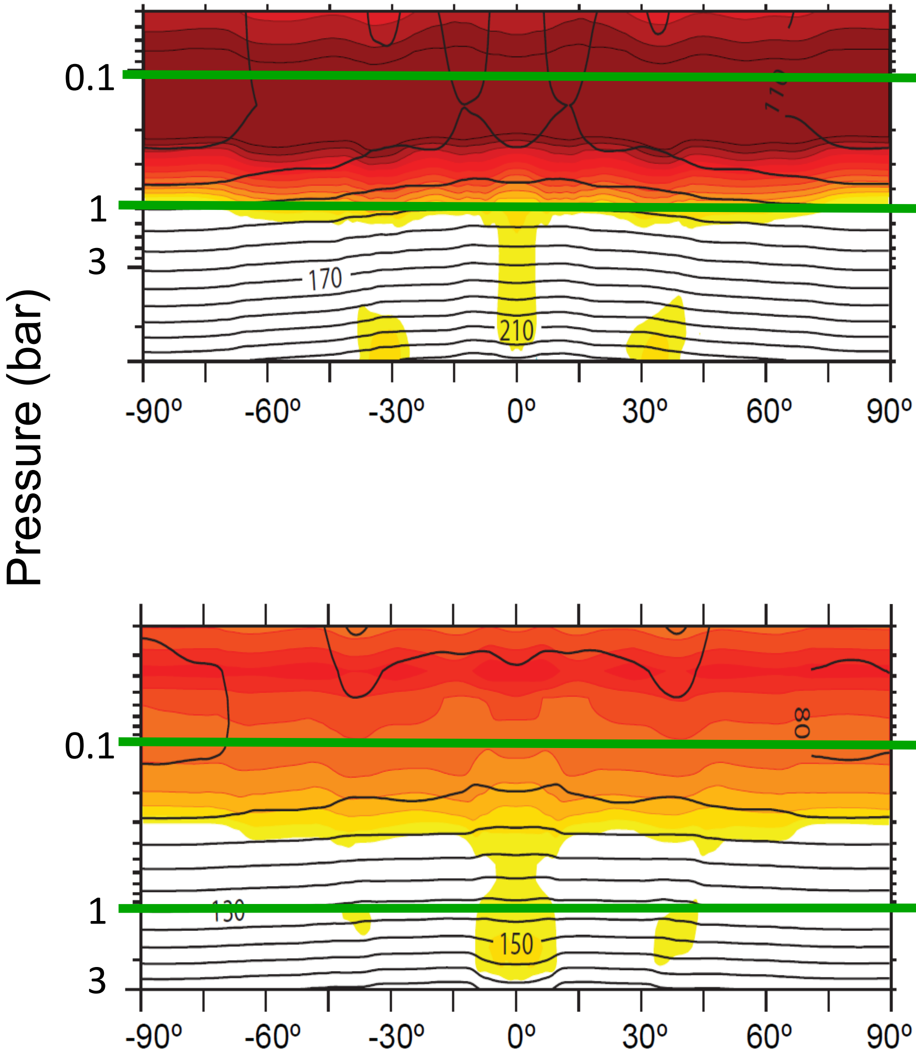
$$R = -\nabla_h \cdot (\zeta_a \mathbf{v}_\chi - \overline{\zeta_a \mathbf{v}_\chi})$$

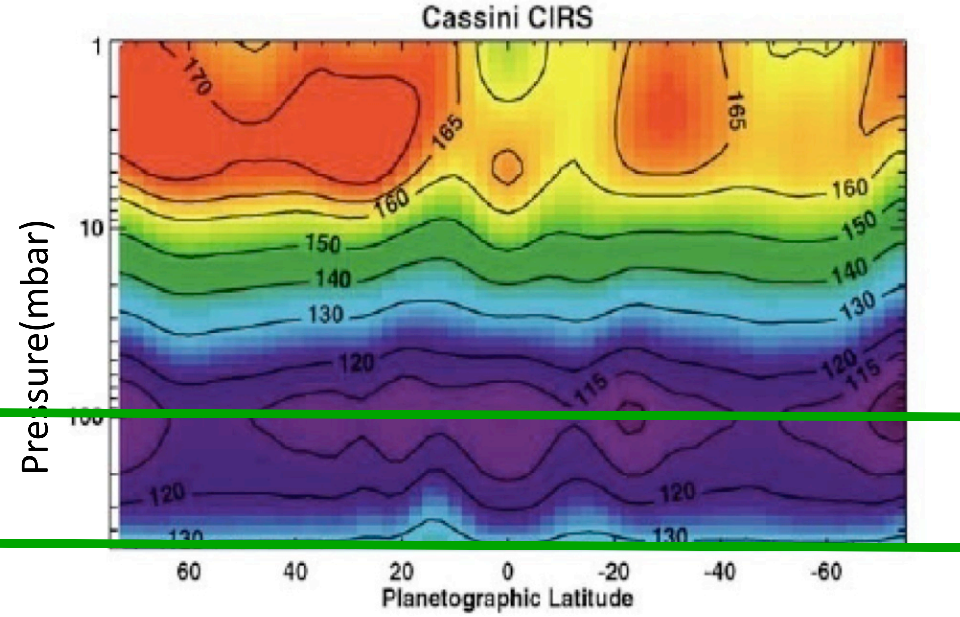
(Schneider & Liu 2009)


u
T, N
Jupiter
Saturn
Uranus
Neptune
Pressure (bar)
Latitude
u: -280 -140 0 140 280 m s -1
N: 0 1.0 2.0 x10 -2 s -1
(Liu & Schneider 2009)

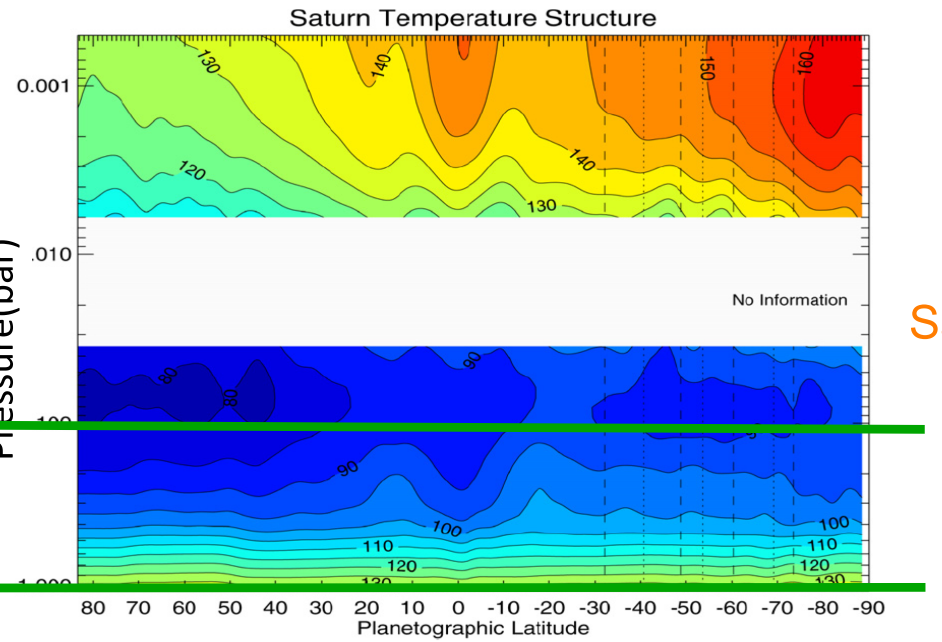
Temperature: Comparison with observations

Simulations





Jupiter

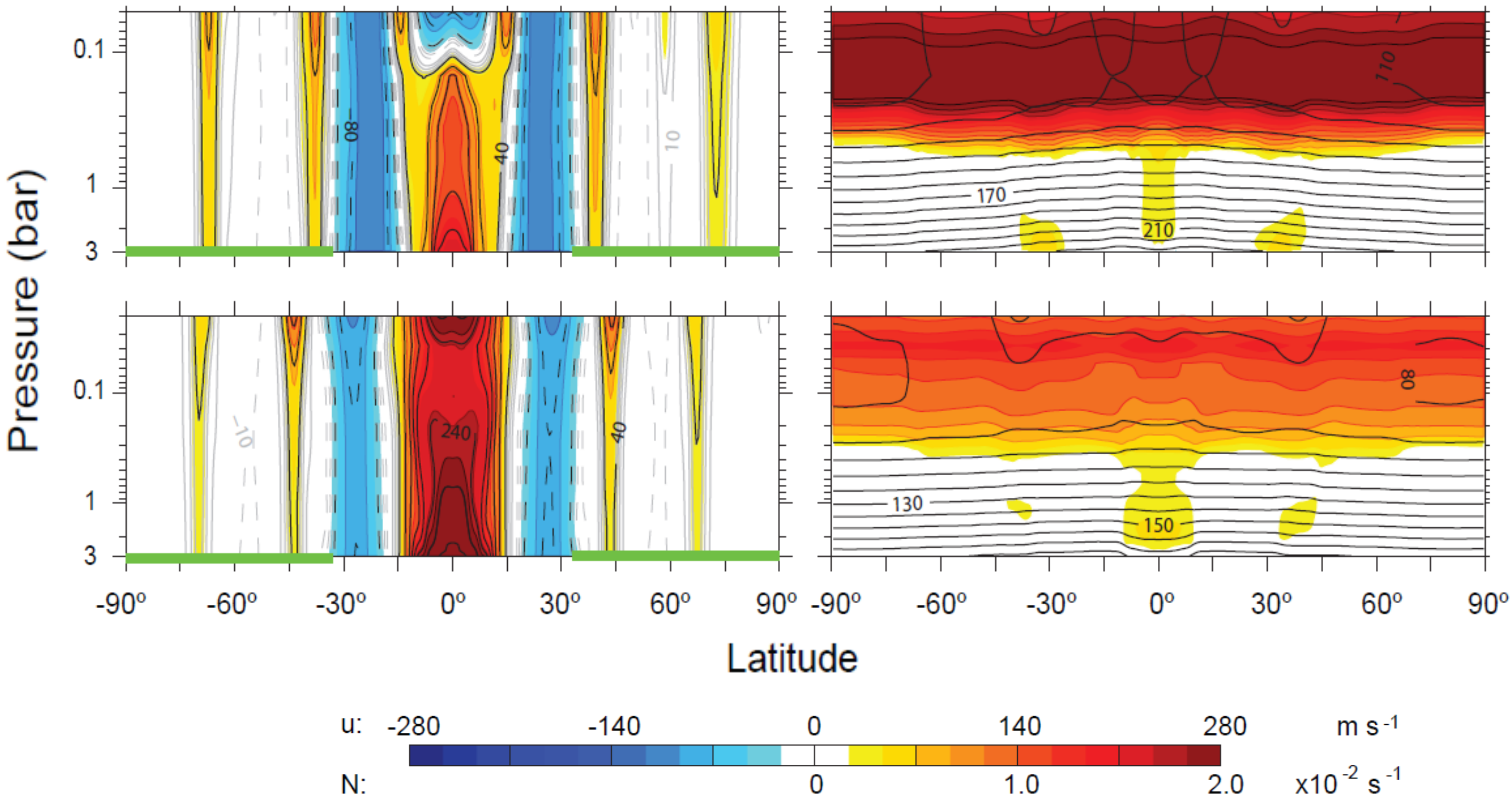


Saturn

(Simon-Miller et al. 2006; Fletcher et al. 2007)

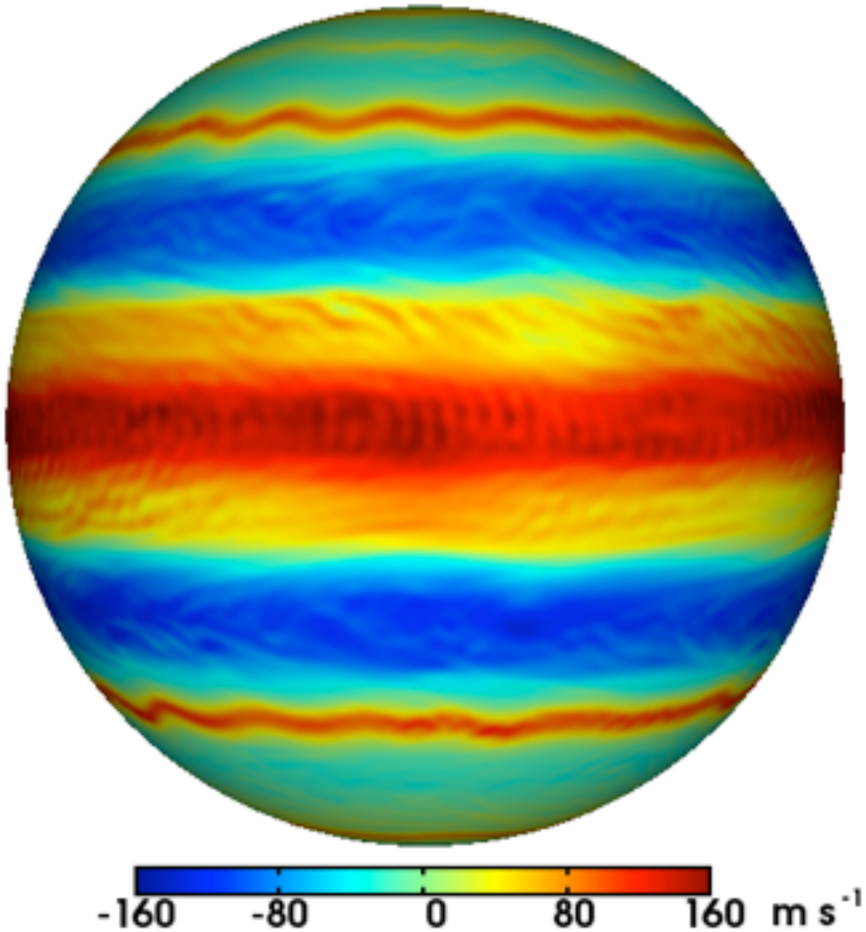
Why are Jupiter and Saturn superrotating?

--- strong internal heat flux (5.7 W m^{-2} on Jupiter and 2.01 W m^{-2} on Saturn) generates convection.



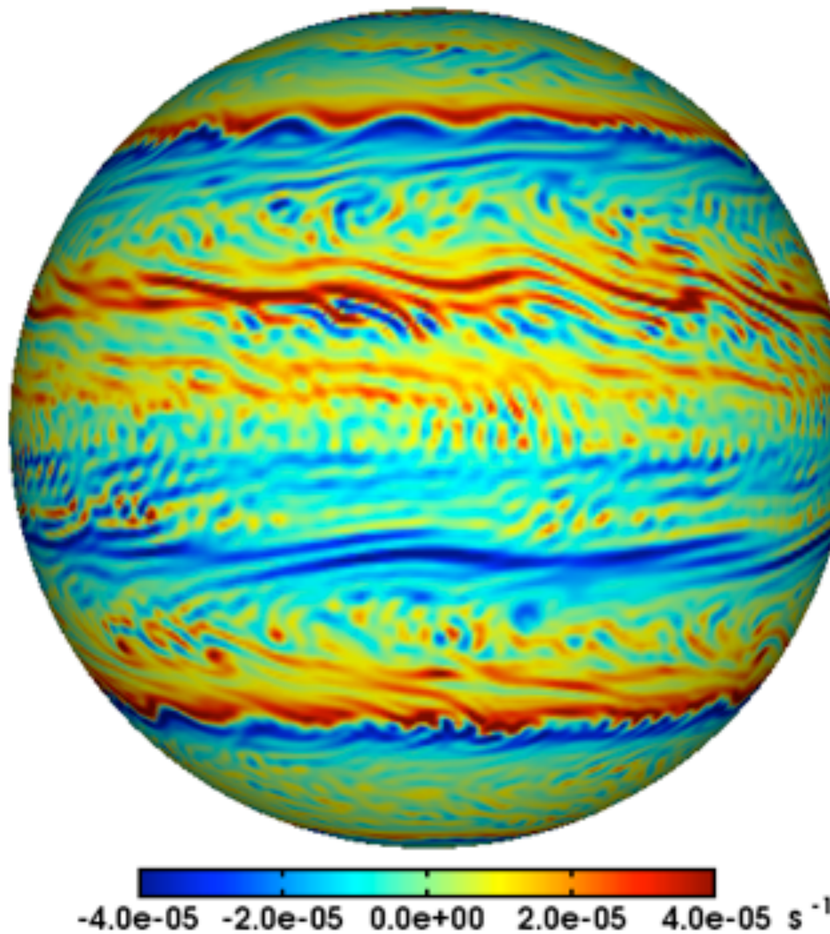
(Liu & Schneider 2009)

Zonal velocity in Jupiter simulation (100 Earth days)



retrograde prograde

Vorticity in Jupiter simulation (100 Earth days)



(Schneider & Liu 2009)

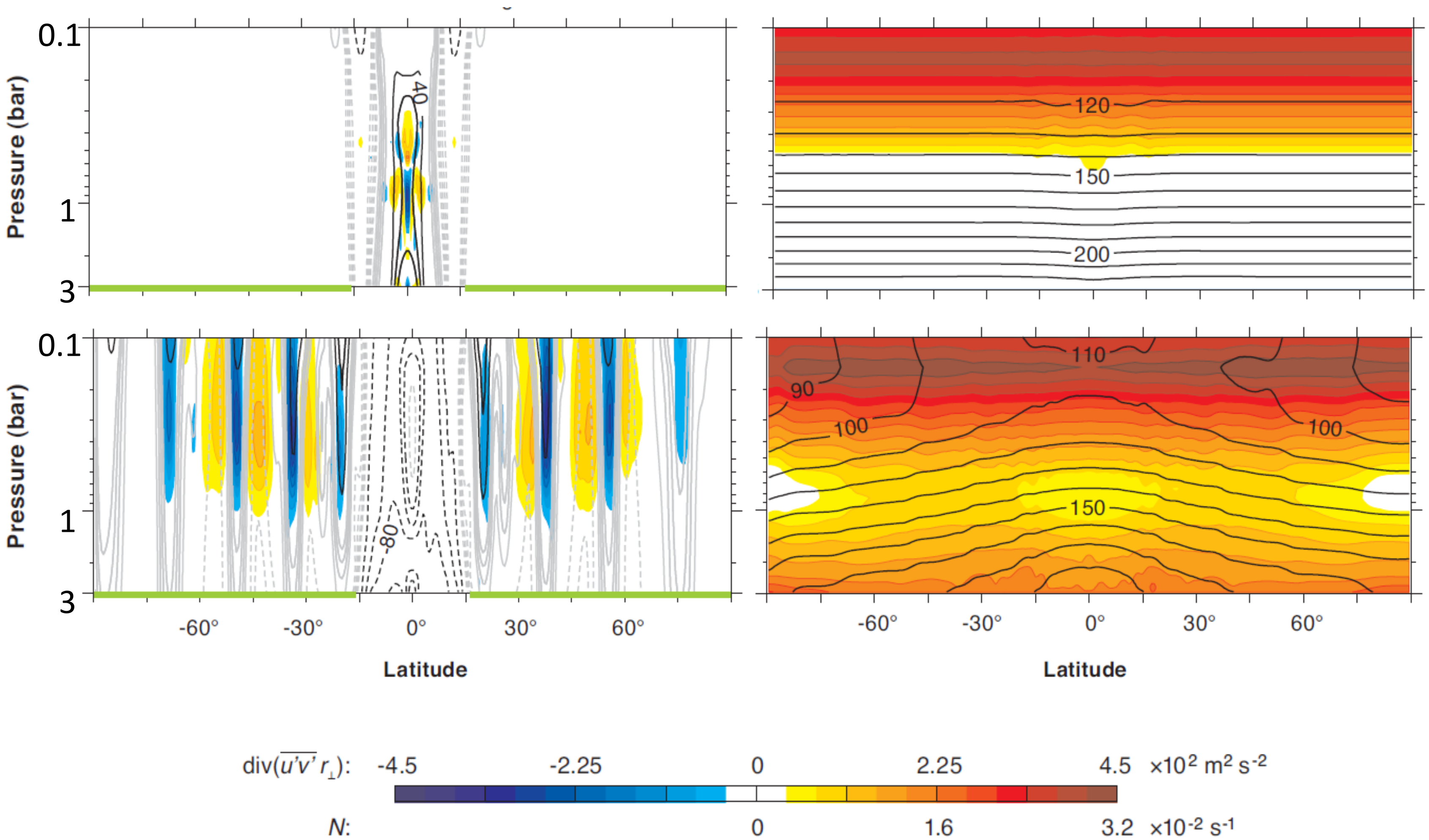
Jupiter control simulations

u, Eddy momentum divergence

T, N

Uniform solar radiation

No internal heatflux



(Schneider & Liu 2009)

Why is Saturn's equatorial jet stronger and wider than Jupiter's?

• Width of the equatorial jet is set by the equatorial Rossby radius:

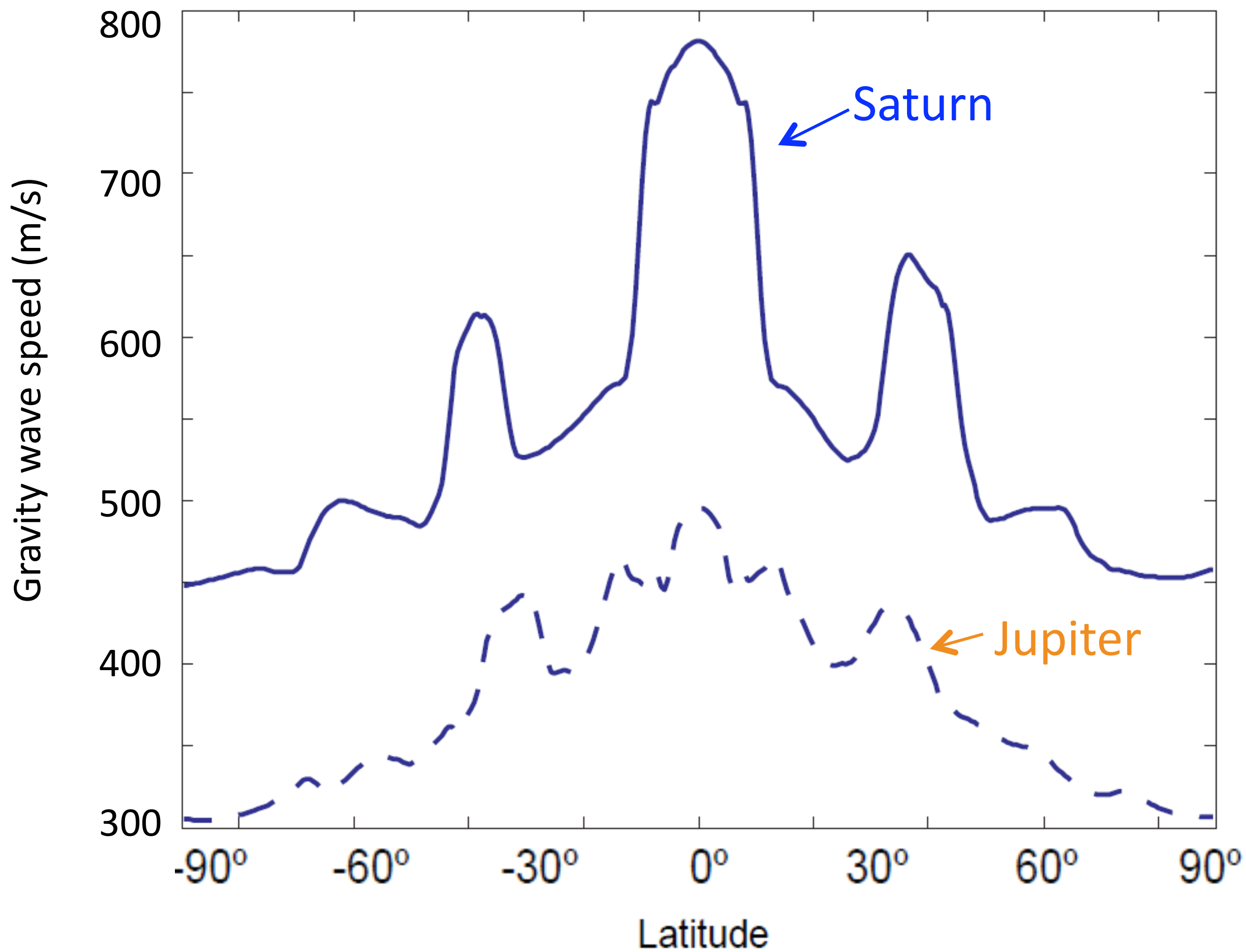
$$L = \sqrt{c/\beta}$$

$$c = \int_{p_t}^{p_s} N_p \, dp$$

$$N_p^2 = -(\bar{\rho}\bar{\theta})^{-1} \overline{\partial_p \theta}$$

• By vorticity mixing argument, strength of the equatorial jet increases with width:

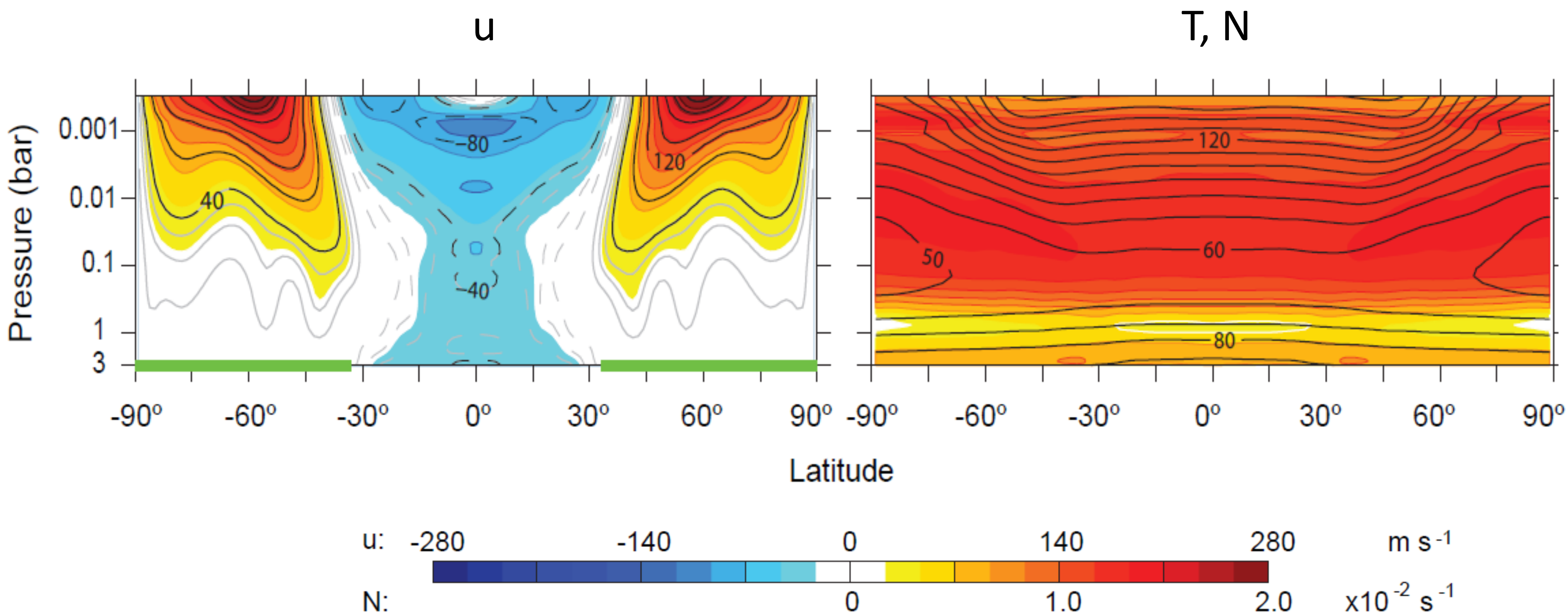
$$U \sim L^2 \beta/2 \sim c/2$$



(Schneider & Liu 2009)

Why is Uranus subrotating?

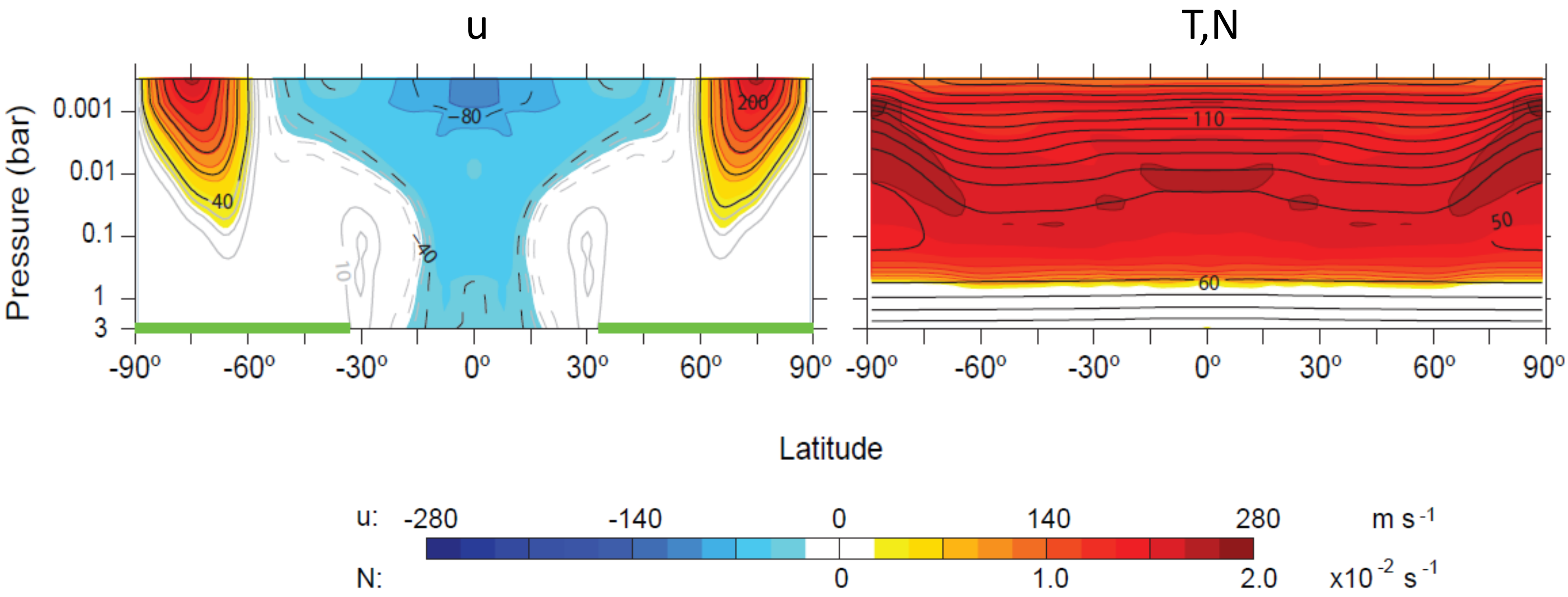
--- Almost no internal heat flux (0.042 W m^{-2}), the atmosphere is stably stratified.



(Liu & Schneider 2009)

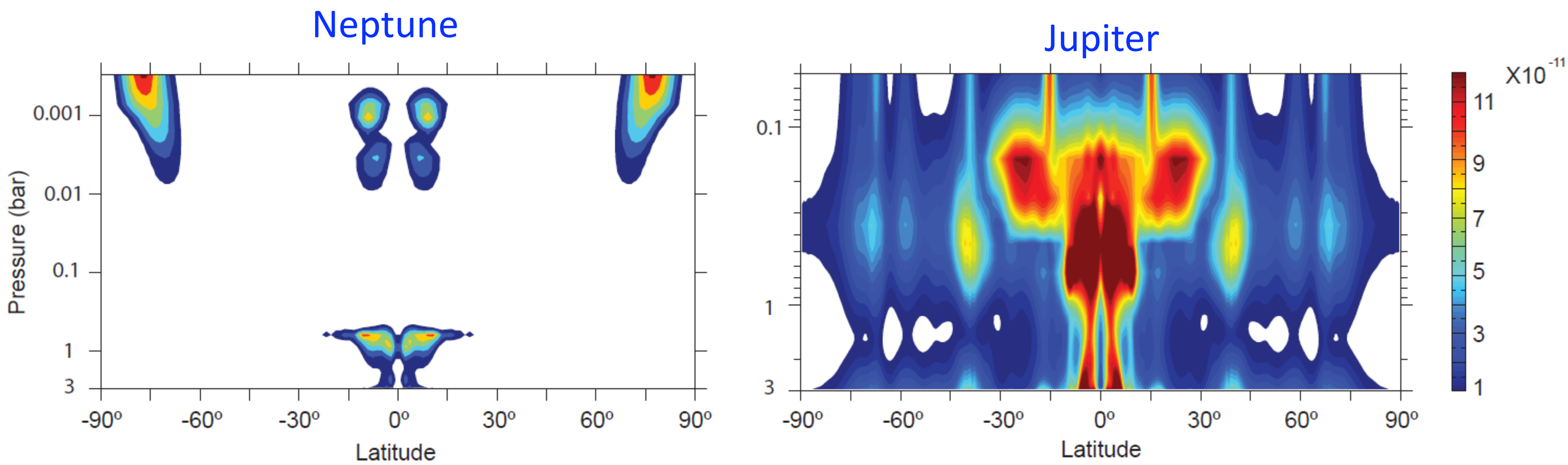
How about Neptune?

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

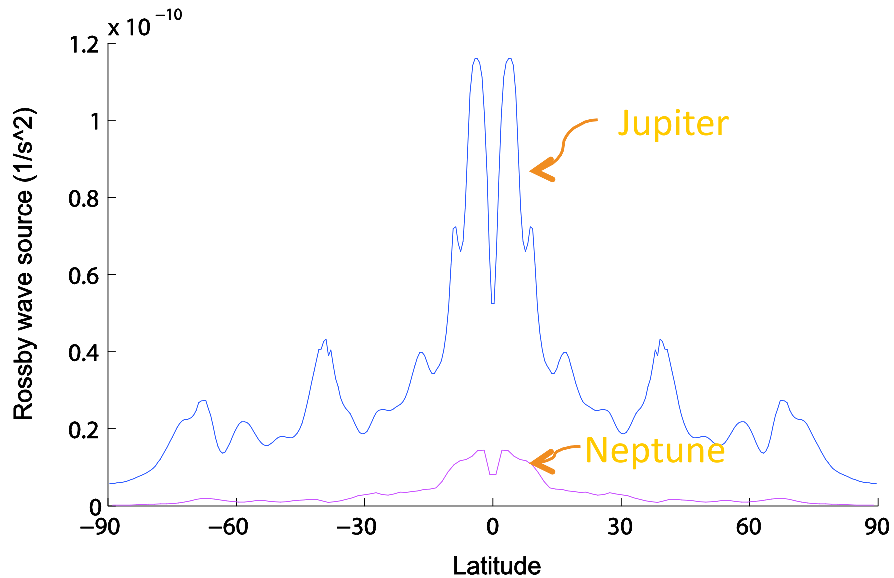


(Liu & Schneider 2009)

RMS Rossby wave source in Jupiter and Neptune simulations



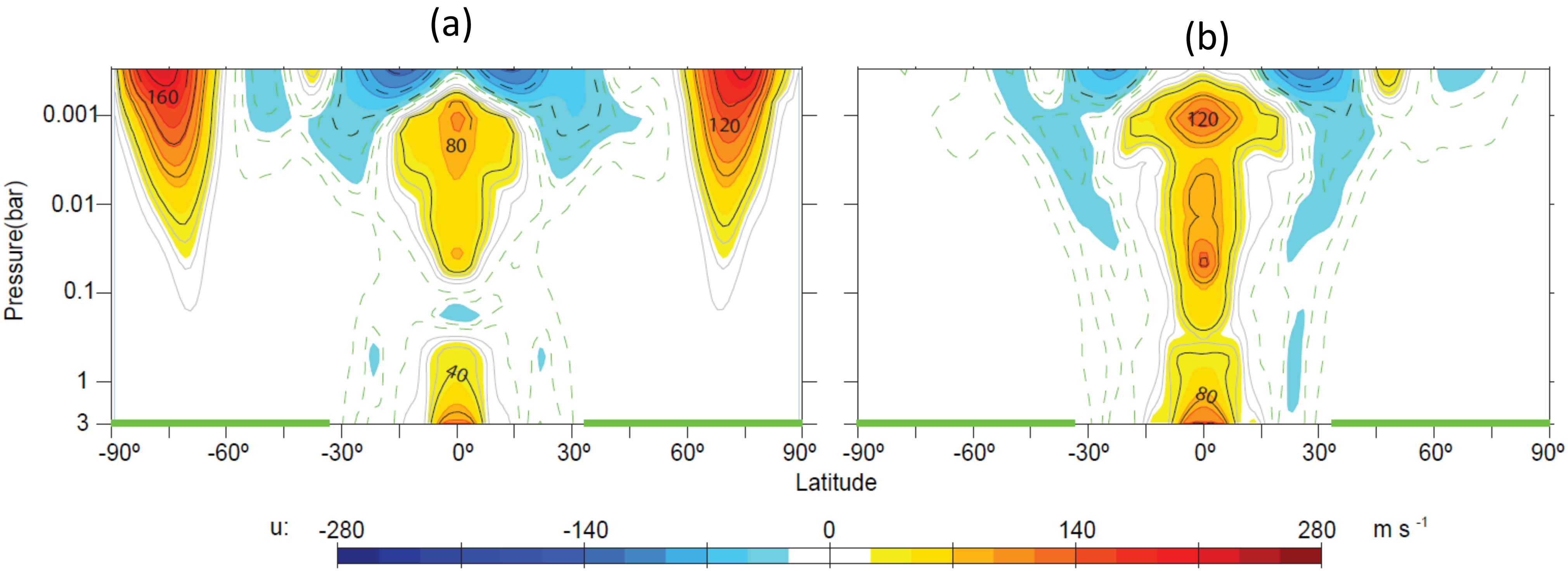
Vertically integrated Rossby wave source



- Jupiter’s vertically integrated Rossby wave source is an order of magnitude larger than Neptune’s.

(Liu & Schneider 2009)

Neptune control simulation

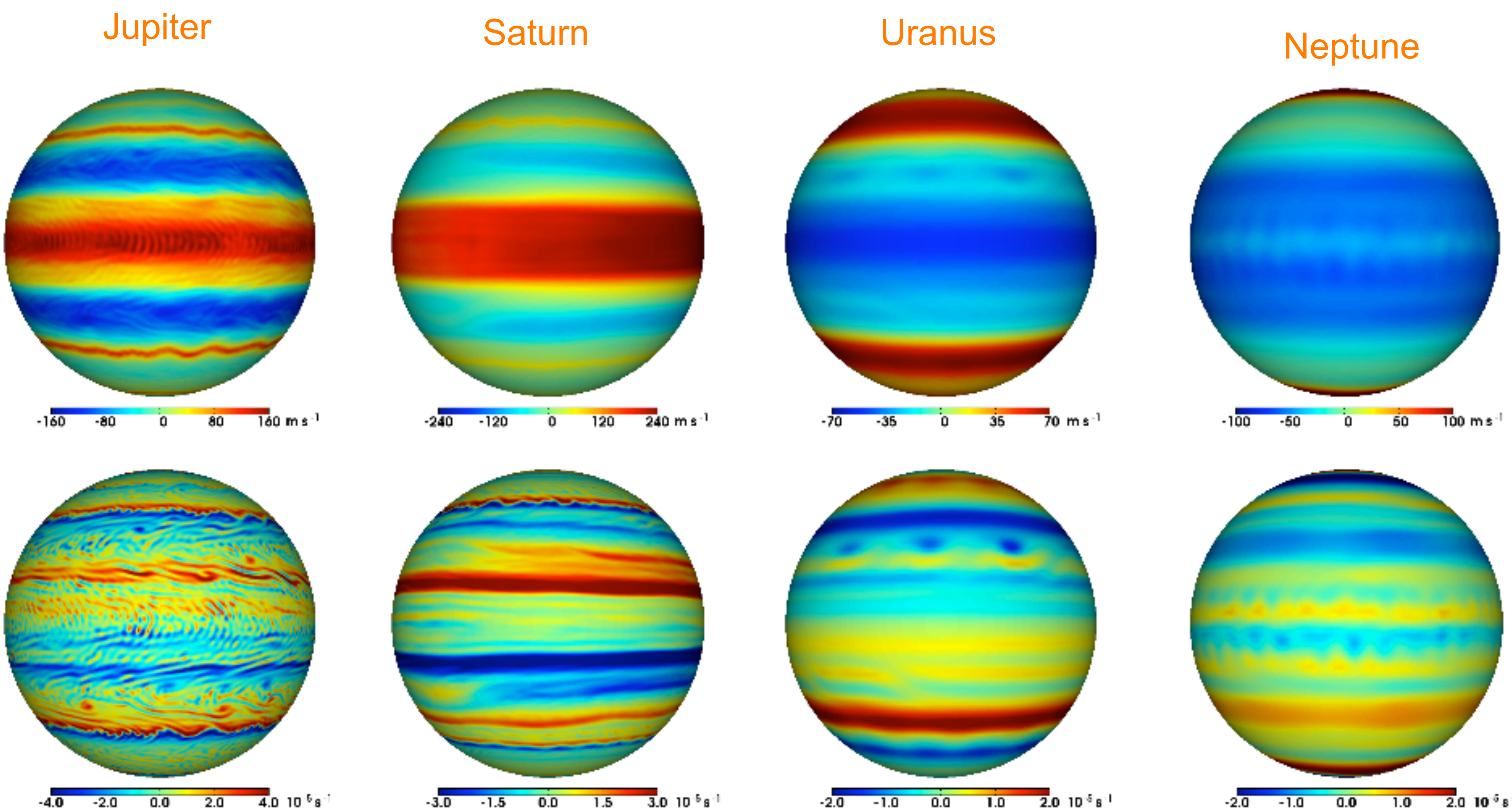


(a) Neptune's insolation and Saturn's internal heat flux 2.01 W m^{-2}

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

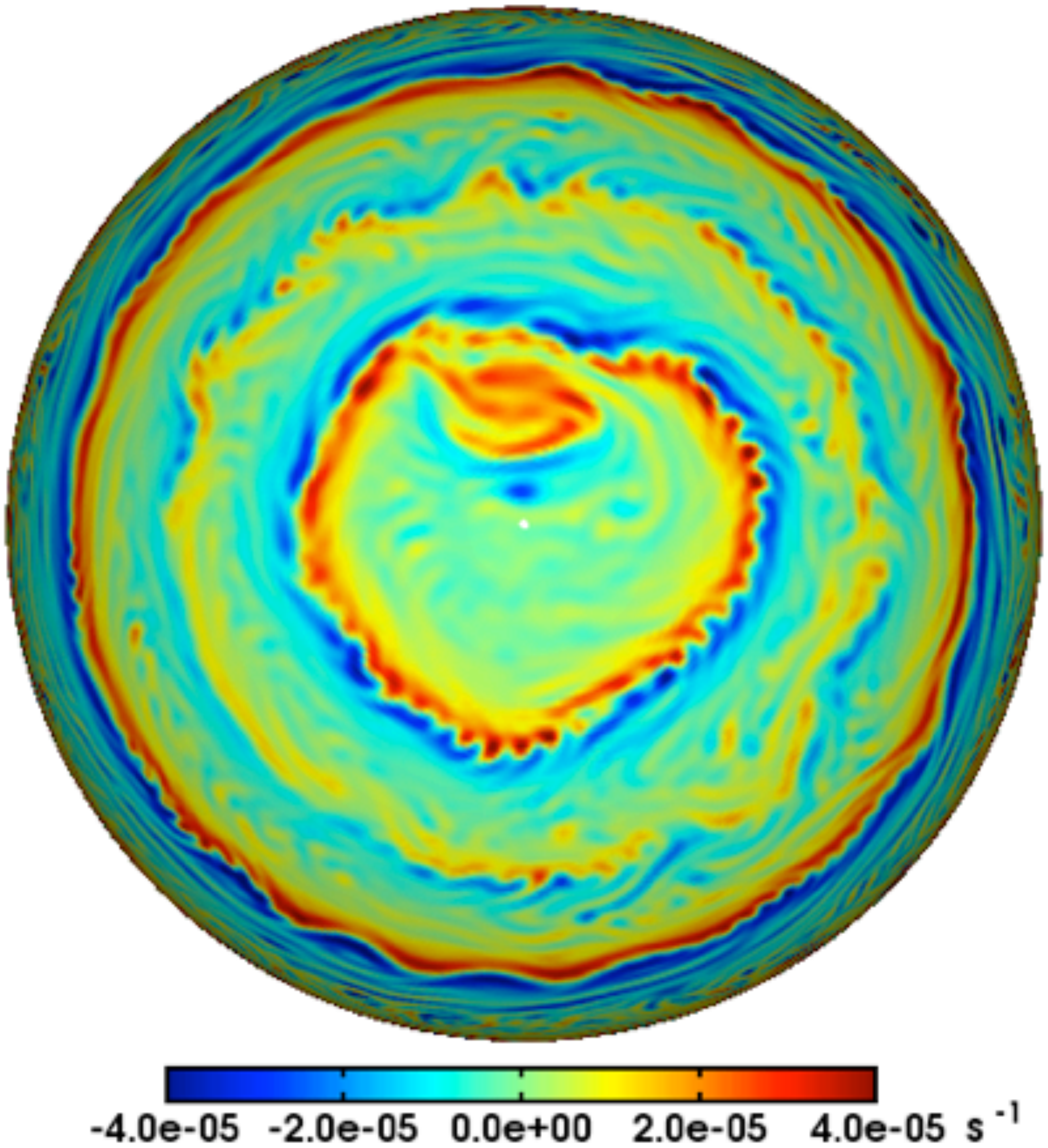
(Liu & Schneider 2009)

Instantaneous zonal wind and relative vorticity

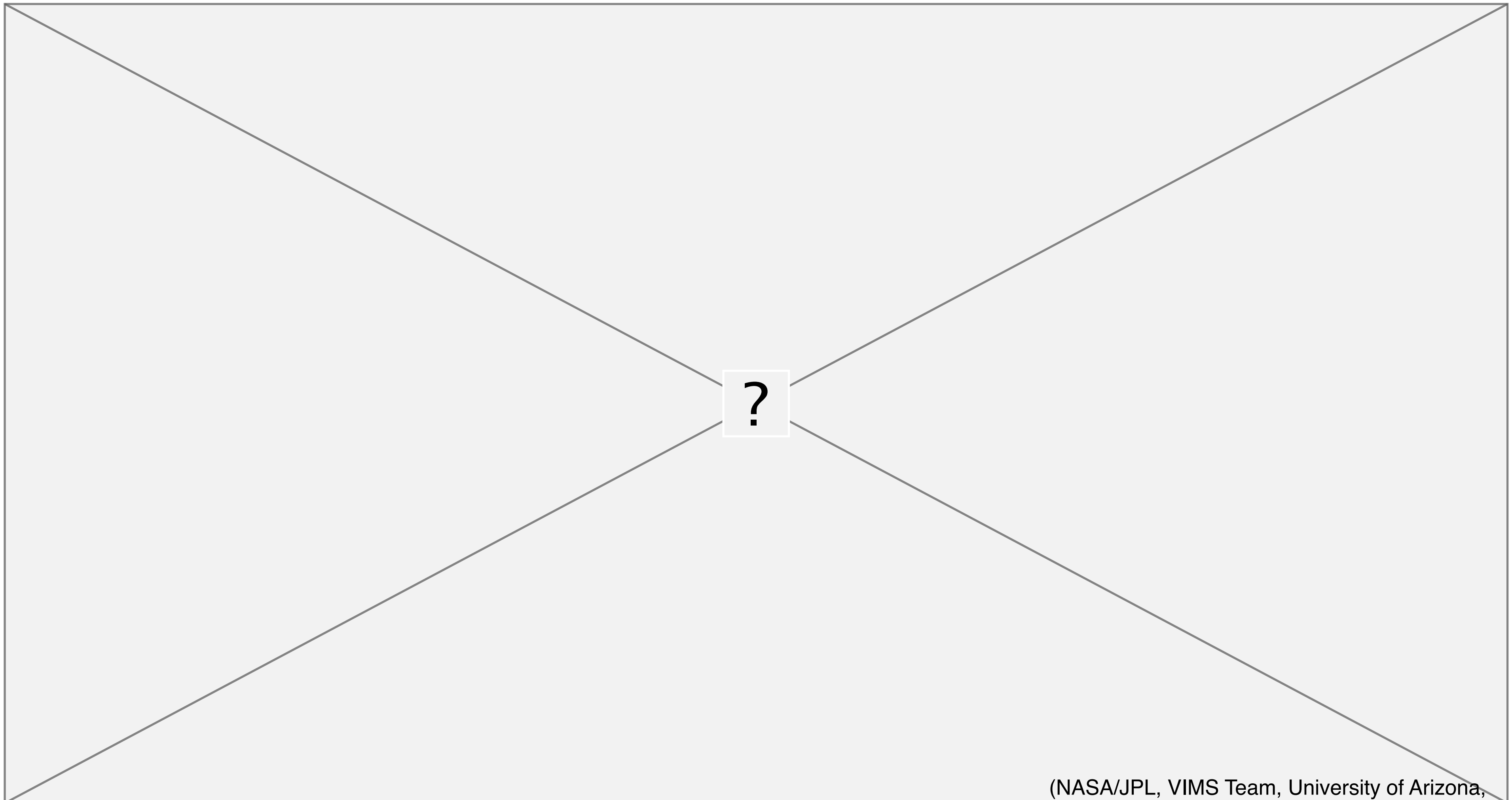


(Liu & Schneider 2009)

Vorticity in Jupiter simulation (north pole)

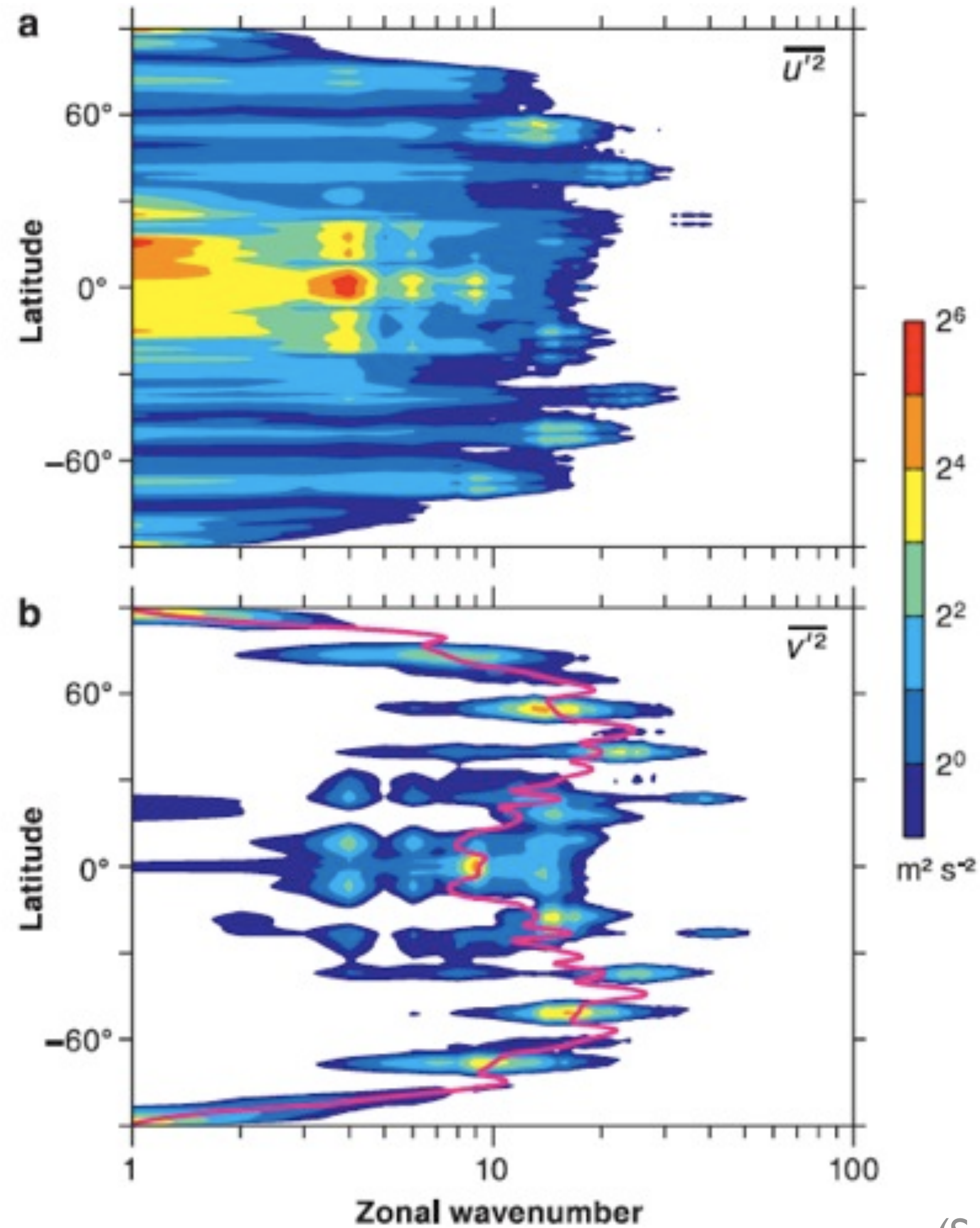


Polar jets and waves



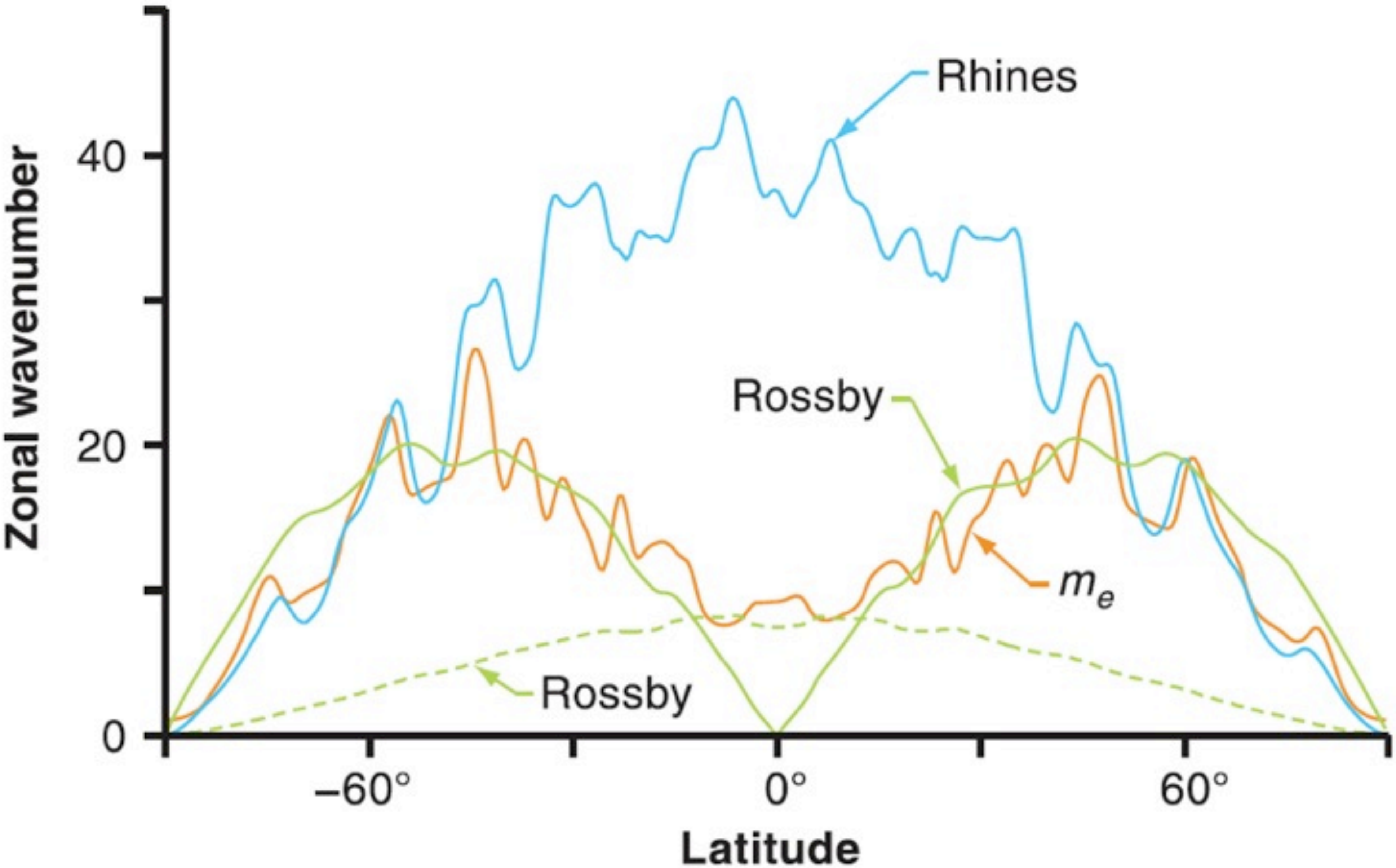
(NASA/JPL, VIMS Team, University of Arizona, http://apod.nasa.gov/apod/ap070403.html)

Velocity variance spectra (Jupiter simulation)



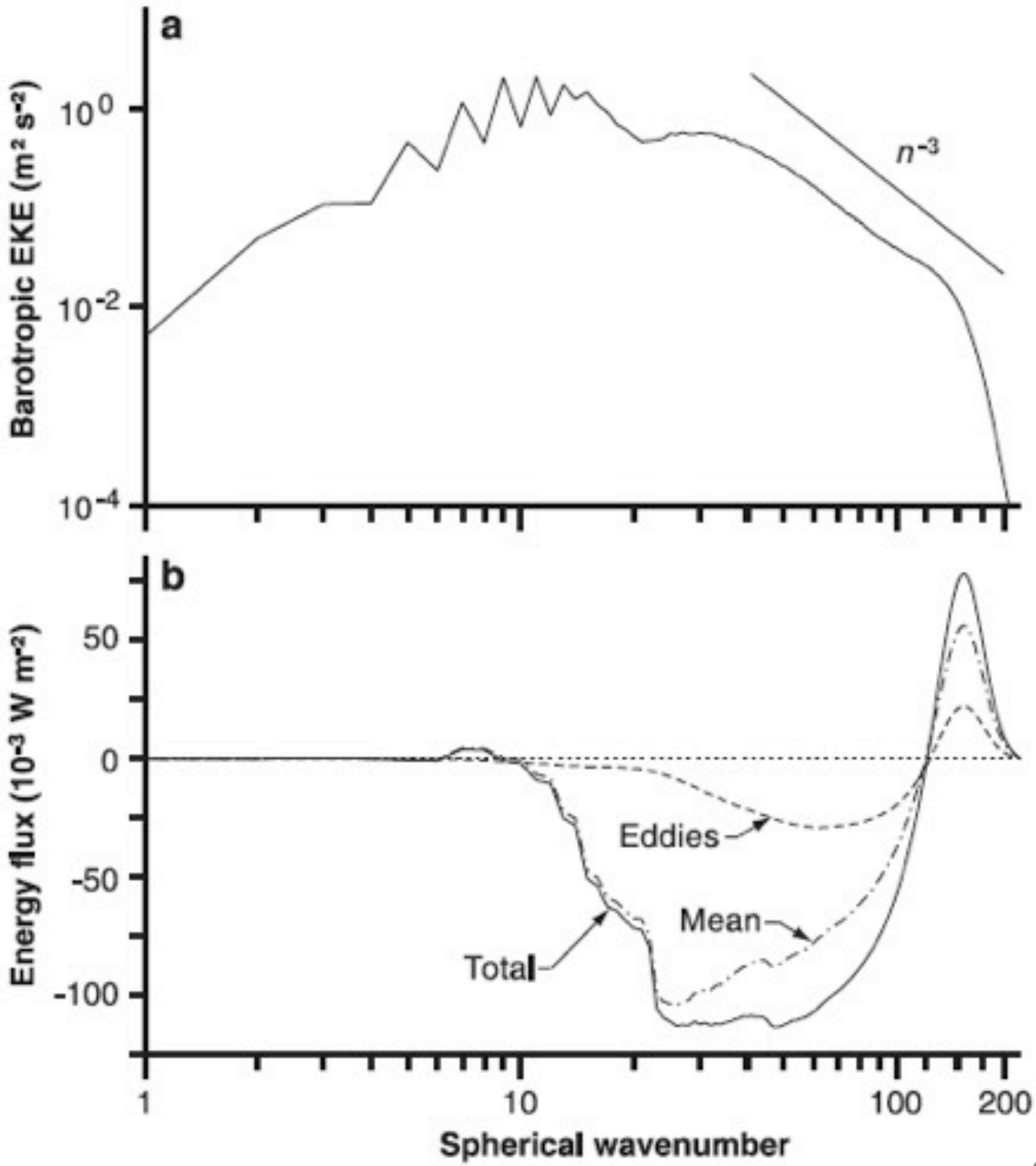
(Schneider & Liu 2009)

Eddy length scales (Jupiter simulation)



(Schneider & Liu 2009)

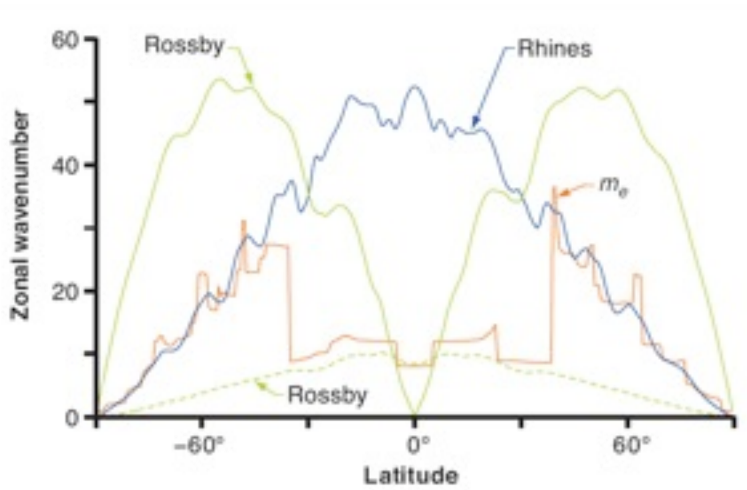
EKE spectrum and flux (Jupiter simulation)

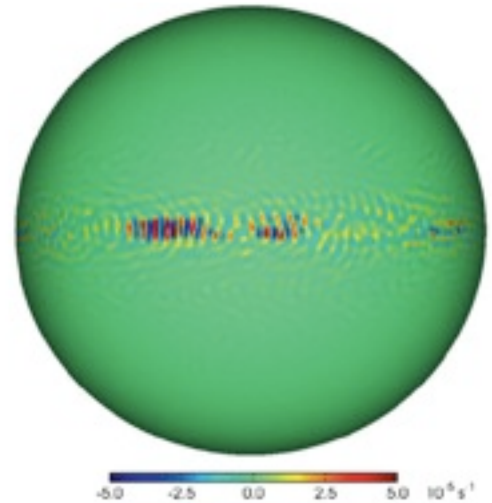


(Schneider & Liu 2009)

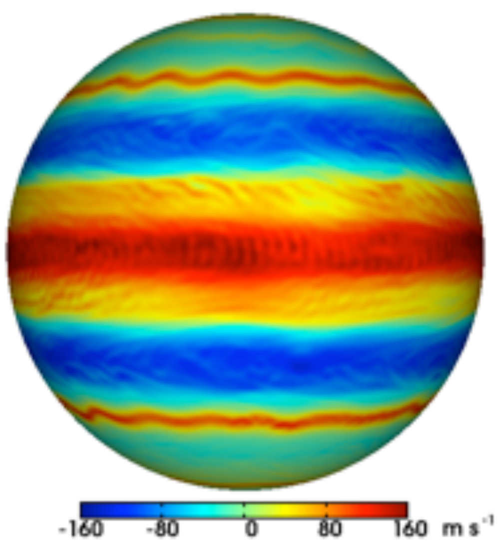
Conclusions

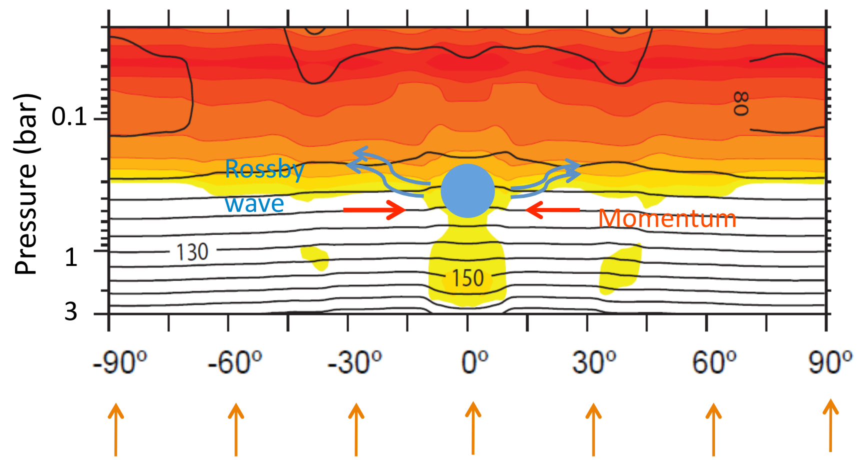
- Off-equatorial jets are baroclinically generated; equatorial superrotation generated by convection
- Internal heat flux destabilizes deep layer and increases baroclinicity
- Convection generates equatorial divergence and Rossby waves, leading to superrotation
- Momentum dissipation by coupling to magnetic field at depth
- Strength/scale of jets depends on strength of drag
- No inverse energy cascade necessary





Zonal velocity in Jupiter simulation (100 Earth days)





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