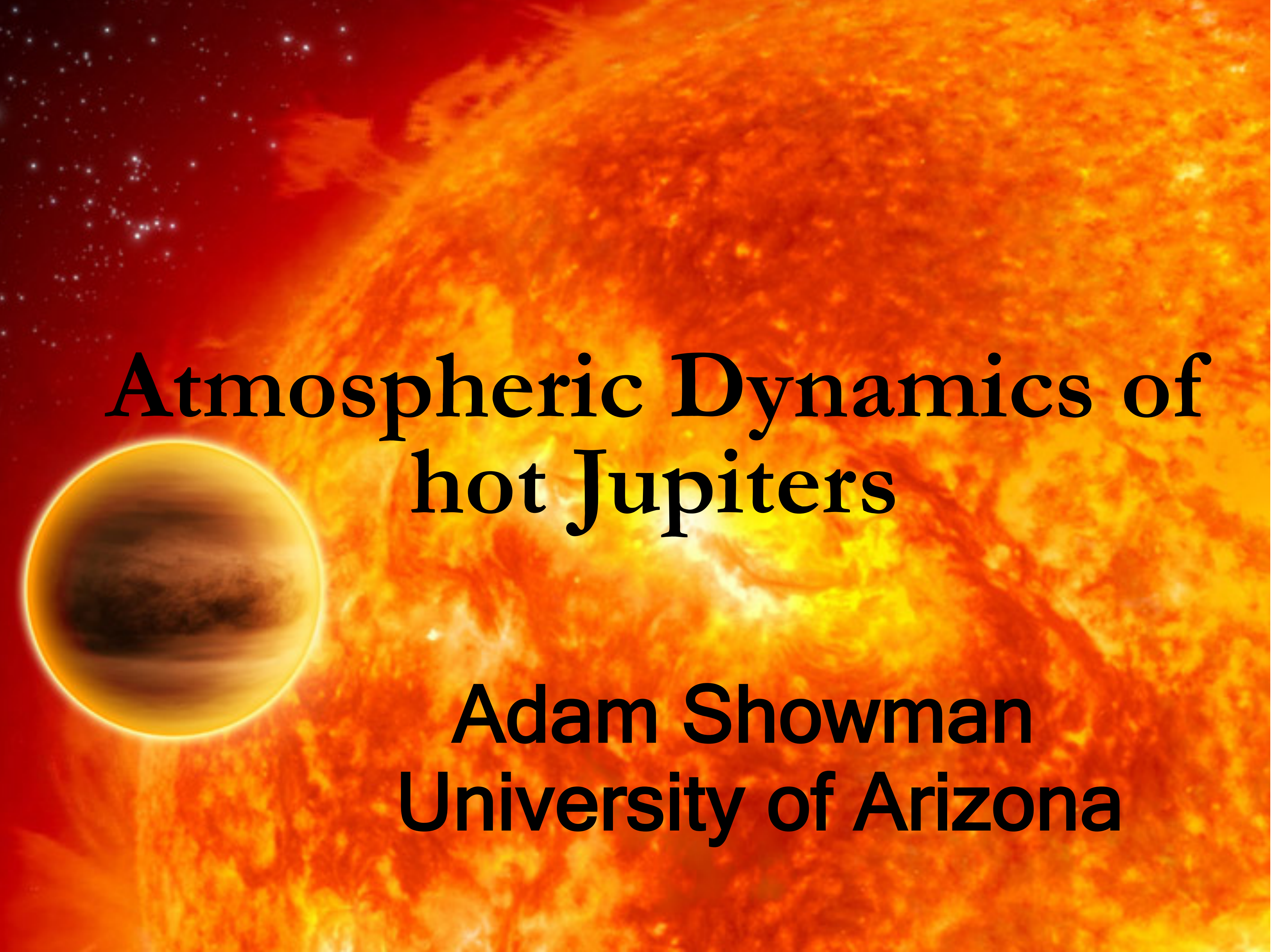
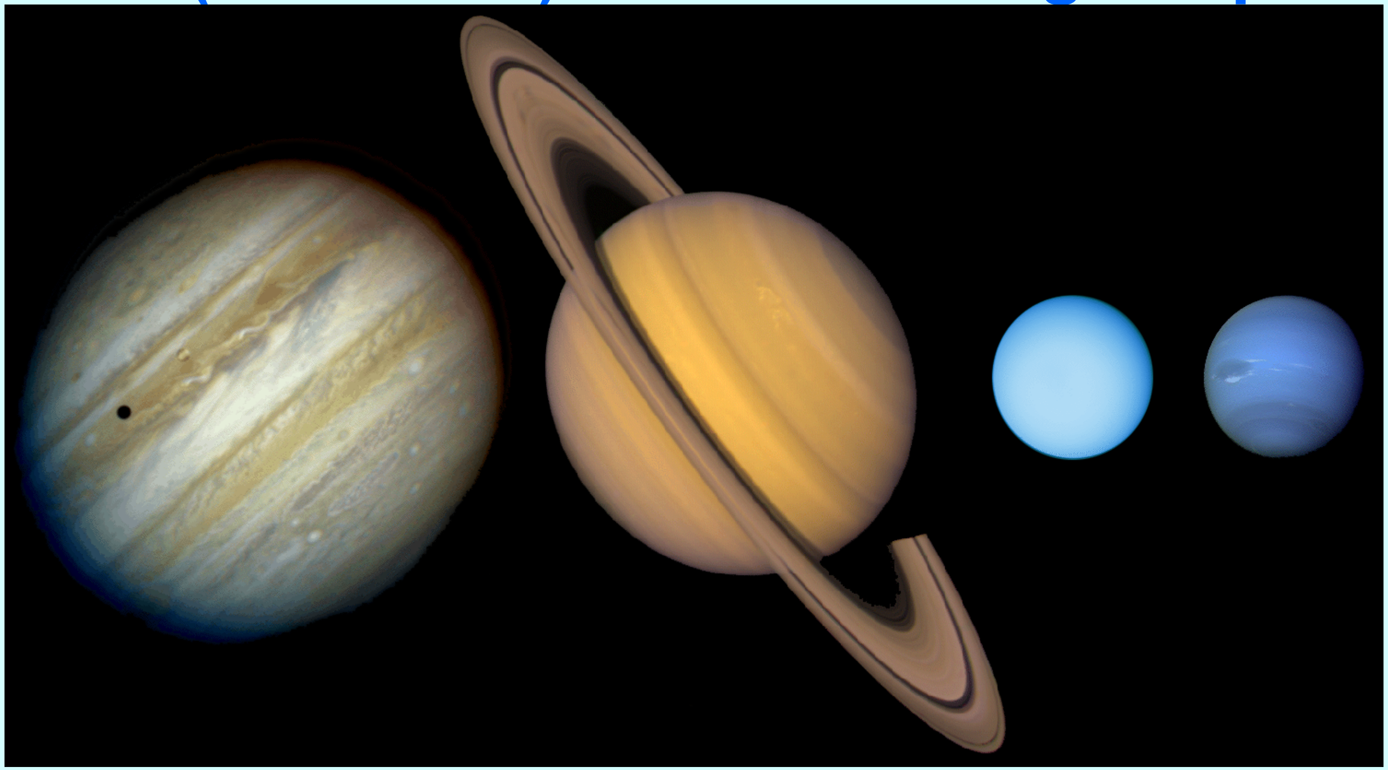
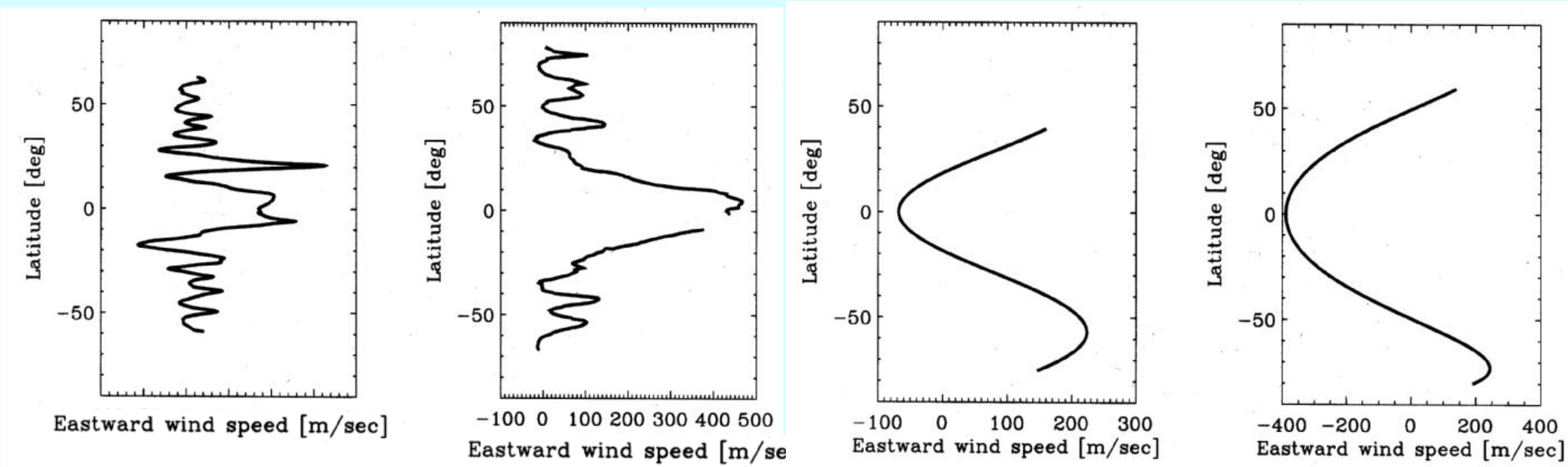


Atmospheric Dynamics of hot Jupiters

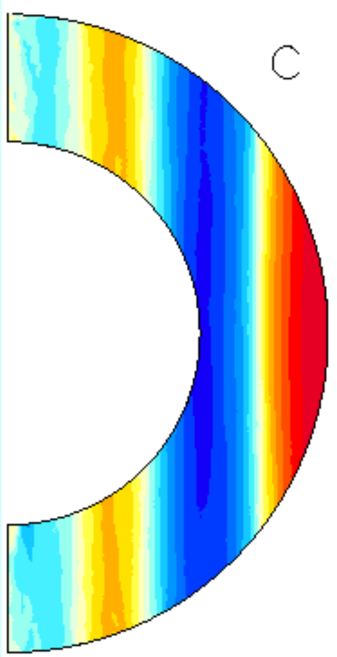
Adam Showman
University of Arizona

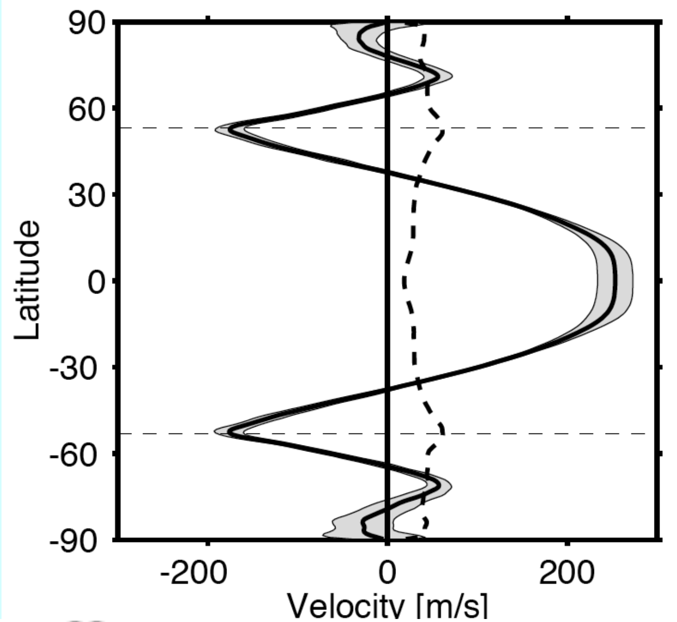
Zonal (east-west) winds on the giant planets



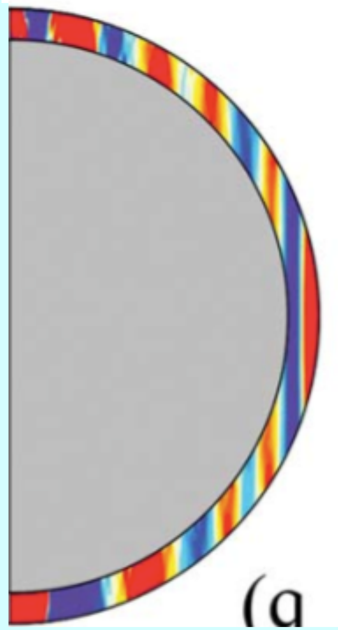


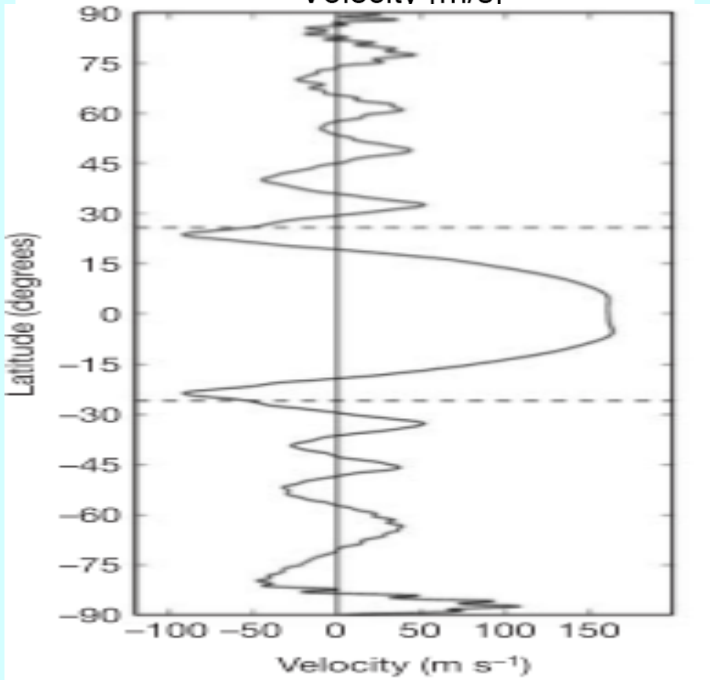
Deep convection models





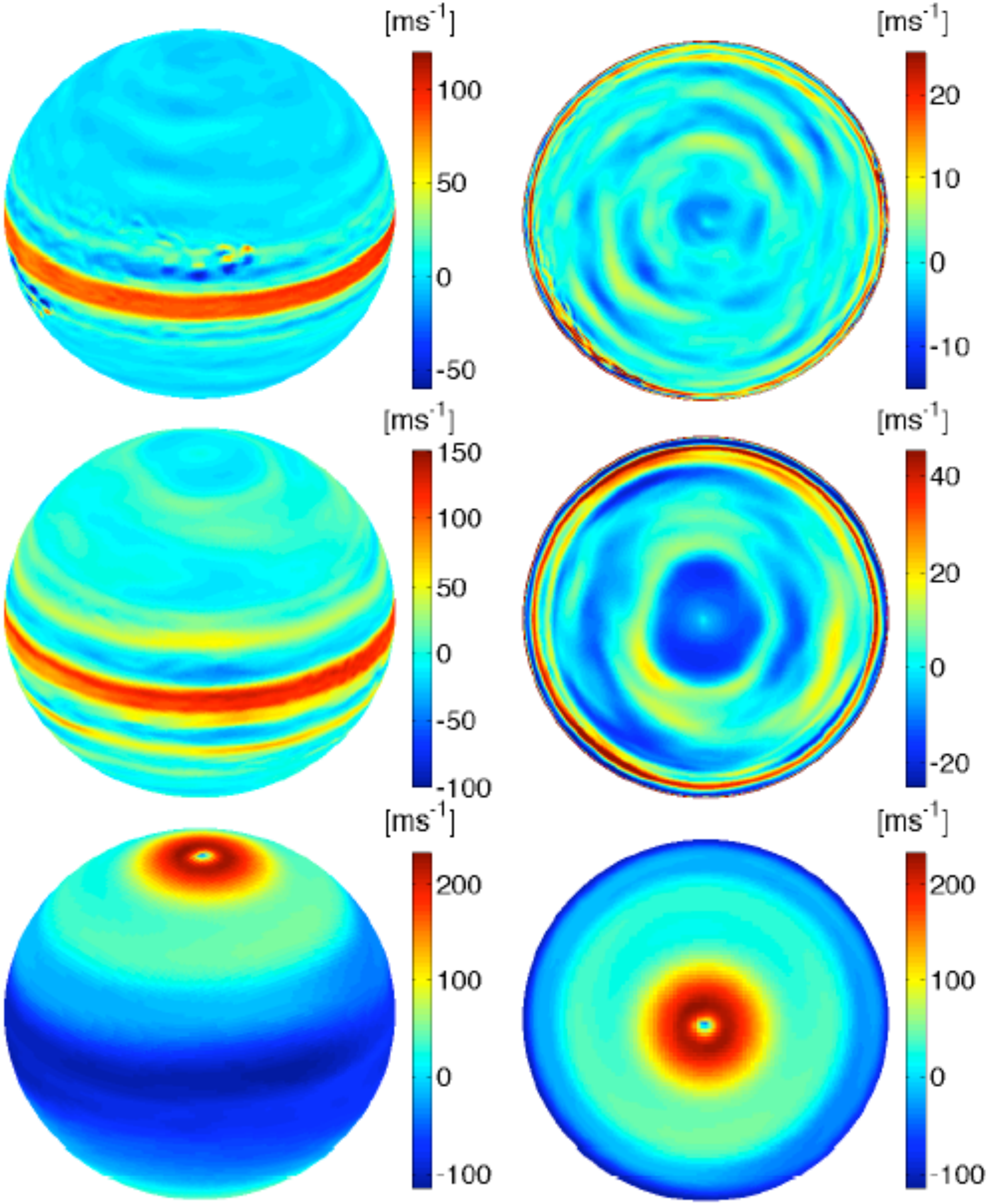
Thick shell
(Christensen 2001, 2002;
Aurnou & Olson 2001;
Kaspi et al. 2009, etc.)





Thin shell
(Heimpel et al. 2005;
Heimpel & Aurnou 2007;
Aurnou et al. 2008)

Lian & Showman (2010); see also Schneider & Liu (2009, 2010) and Young poster (this conference)

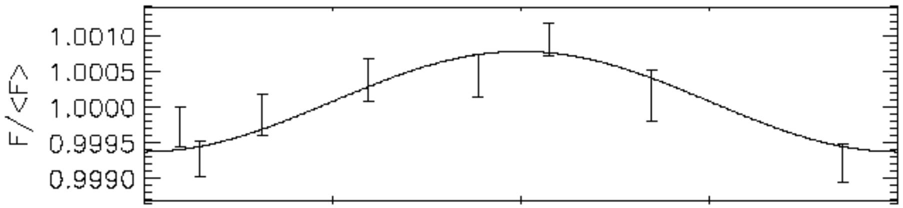


Jupiter

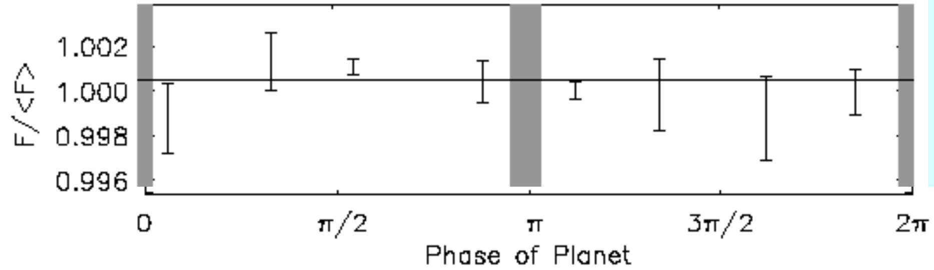
Saturn

Uranus/Neptune

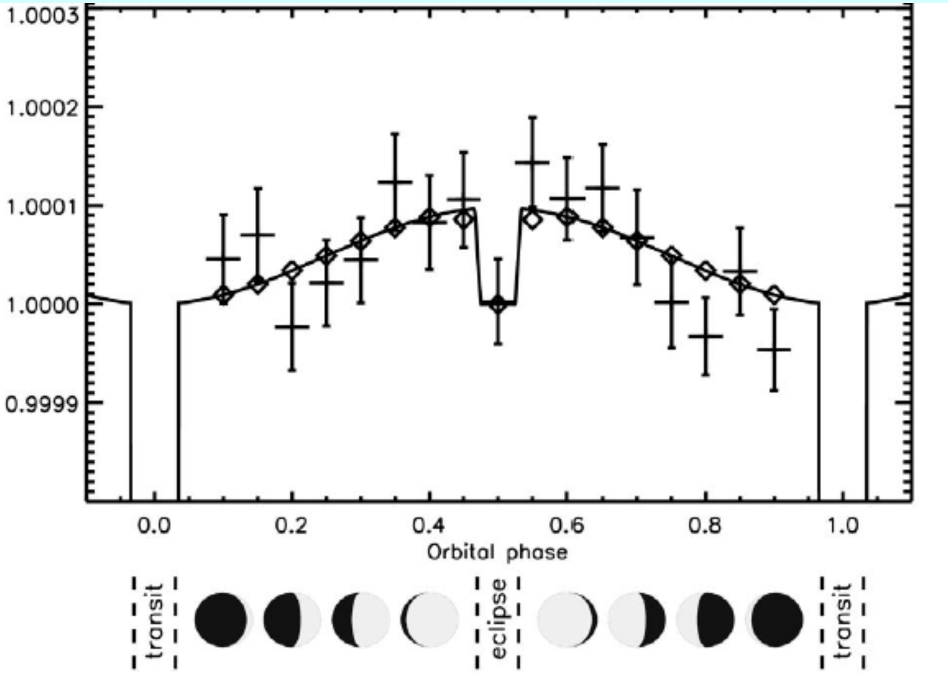
Spitzer and CoRoT lightcurves for hot Jupiters



HD179949b (Cowan et al. 2007)

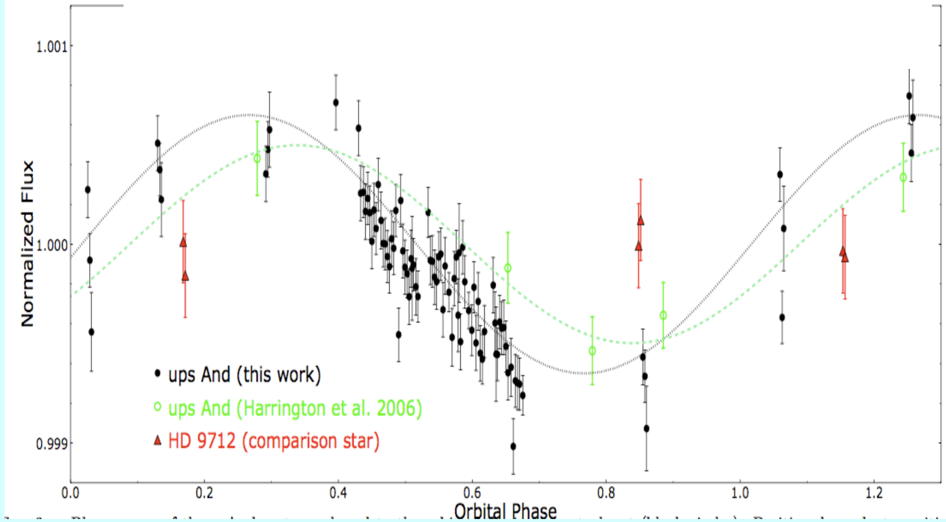


HD209458b (Cowan et al. 2007)



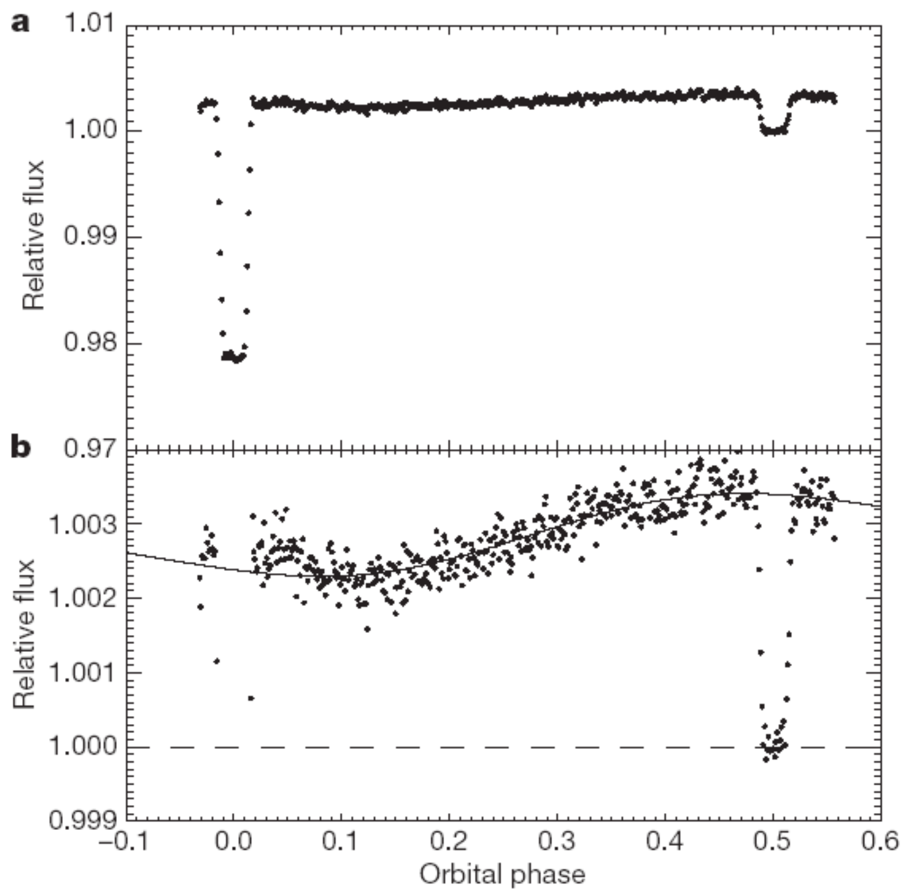
CoRoT-1b (Snellen et al. 2009)

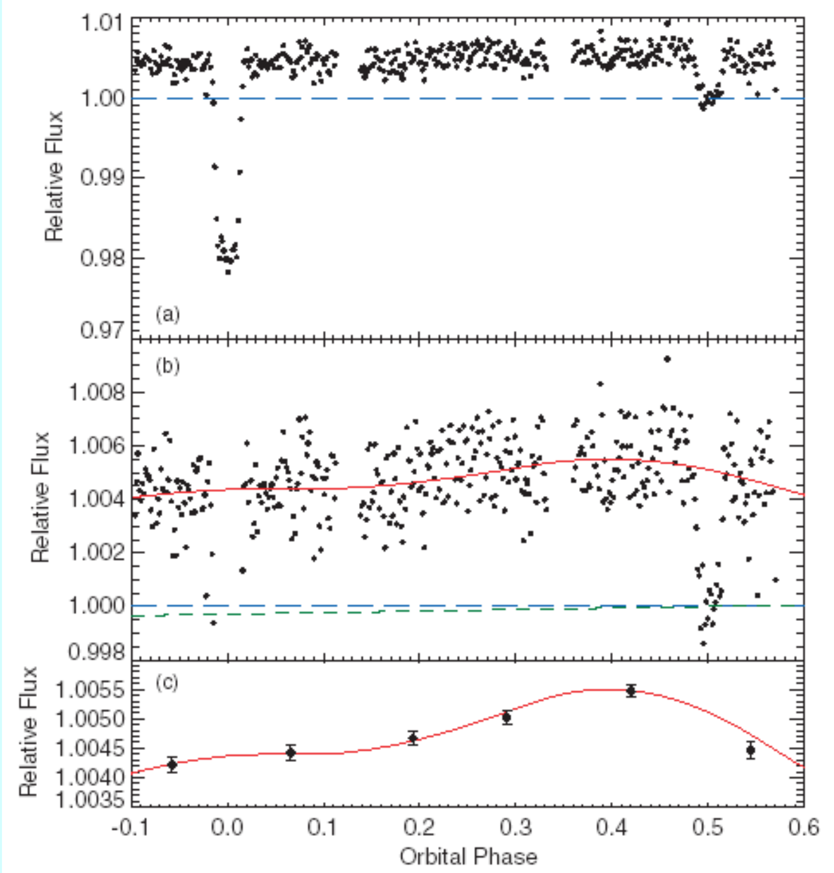
See Maxted poster (this conference), also Borucki et al. (2009), Welsh et al. (2010)



Ups And b (Crossfield et al. 2010, Harrington et al. 2006)

Spitzer light curves for HD 189733b

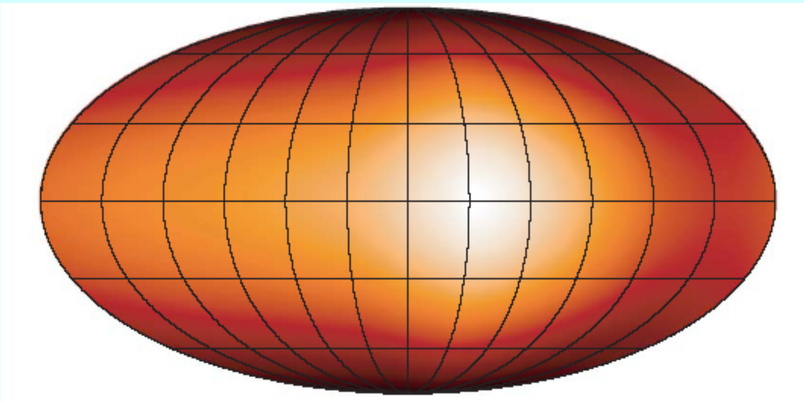




Knutson et al. (2007, 2009)

8 μm

24 μm



Doppler detection of winds

- **Snellen et al. (2010, Nature) report a detection of winds in HD 209458b via Doppler shift in CO lines during transit**

- **Suggests velocities of ~2 km/sec**

- **Similar to speeds obtained in current dynamical models**

Dynamical regime of hot Jupiters

- **Circulation driven by global-scale heating contrast: ~10^5 W/m^2 of stellar heating on dayside and IR cooling on nightside**

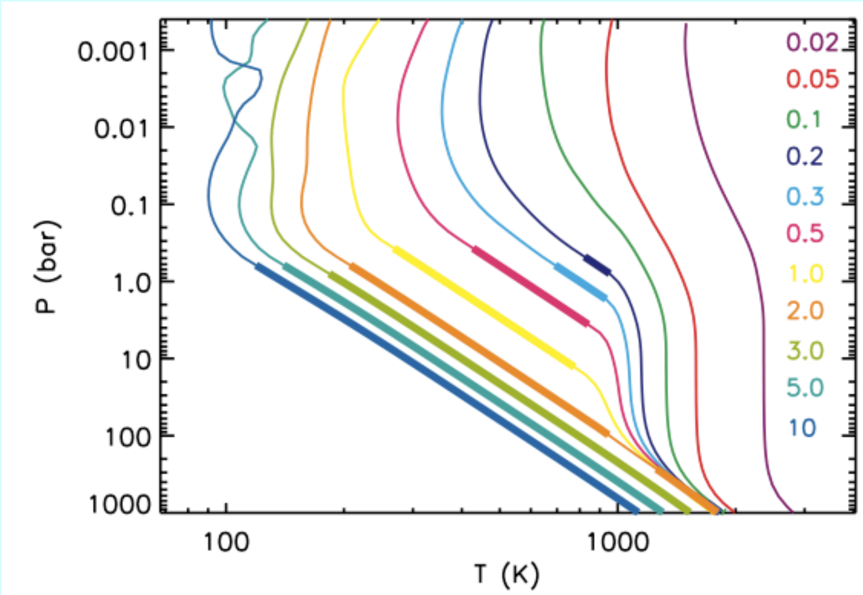
- **Rotation expected to be synchronous with the 1-10 day orbital periods; Coriolis forces important but not dominant**

- **Weather occurs in a statically stable radiative zone extending to ~100-1000 bar**

- **Timescale arguments:**

  $\tau_{rad} << \tau_{dyn}$ for $p < 1$ bar; large temperature contrasts

  $\tau_{rad} >> \tau_{dyn}$ for $p > 1$ bar; temperatures homogenized



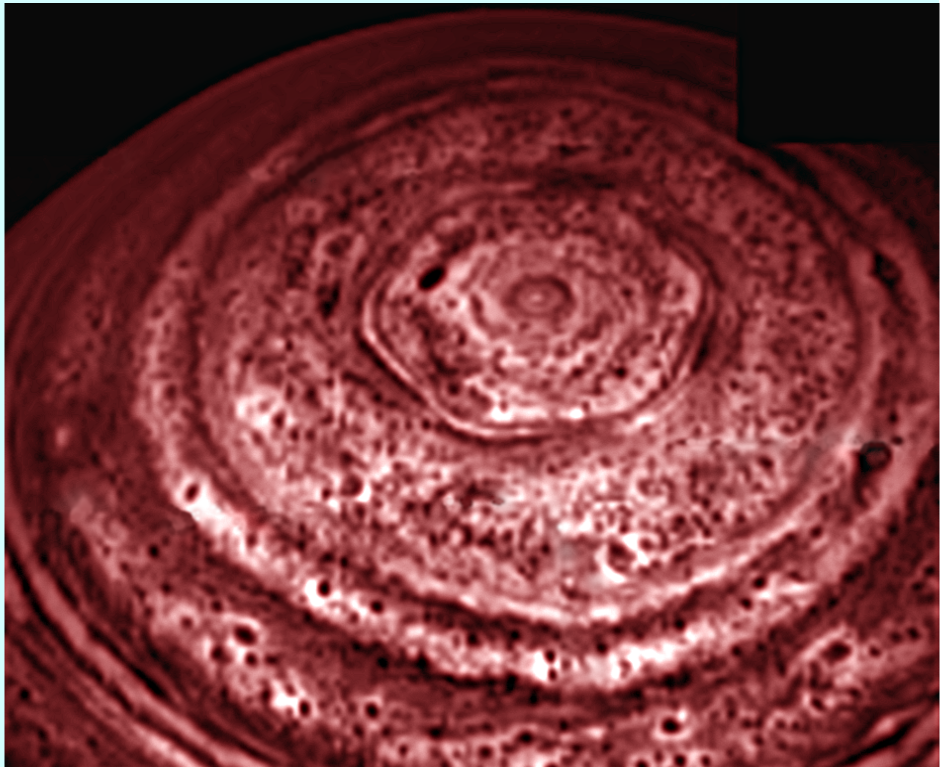
Fortney et al. (2007)

What controls the size and shape of flow structures?

- **<u>Rhines length</u>**, $(U/\beta)^{1/2}$, is the scale at which planetary rotation causes east-west elongation (jets).
- **<u>Deformation radius</u>**, c/Ω, is a natural scale of vortex formation and flow instability

On Jupiter/Saturn, these lengths are << planetary radius

On most hot Jupiters, they are close to planetary radius. Jets and vortices should therefore be global in scale.

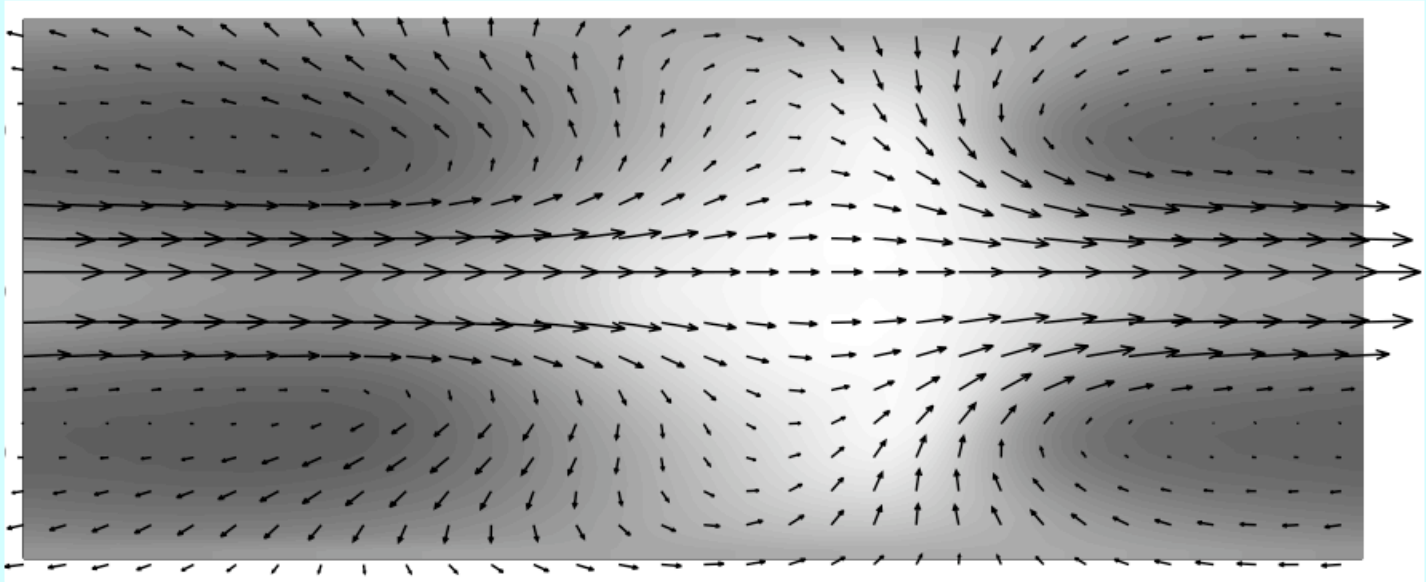


Motivation

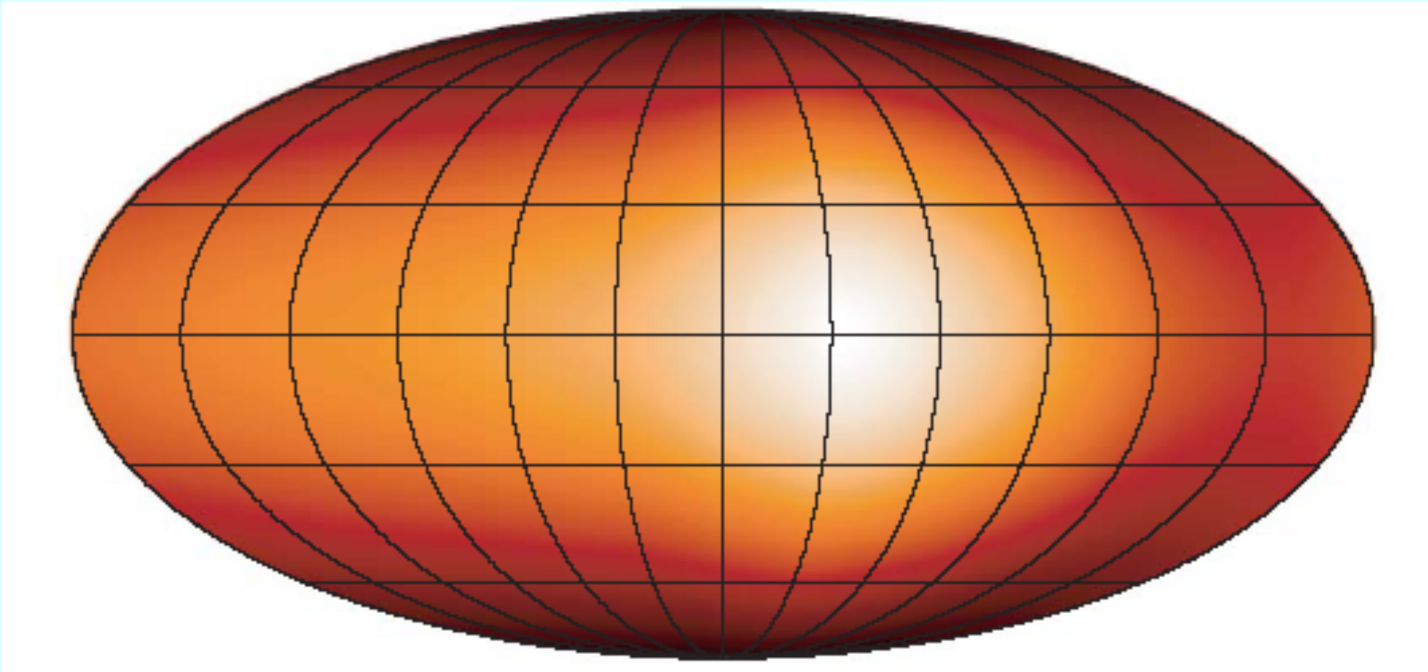
- **Light curves show evidence for atmospheric circulation, and the circulation will affect other observations (secondary eclipse photometry/spectra, etc) too. Can we explain these observations?**

- **What are the fundamental dynamics of this novel circulation regime? How is it similar/different to that on Solar-System planets?**

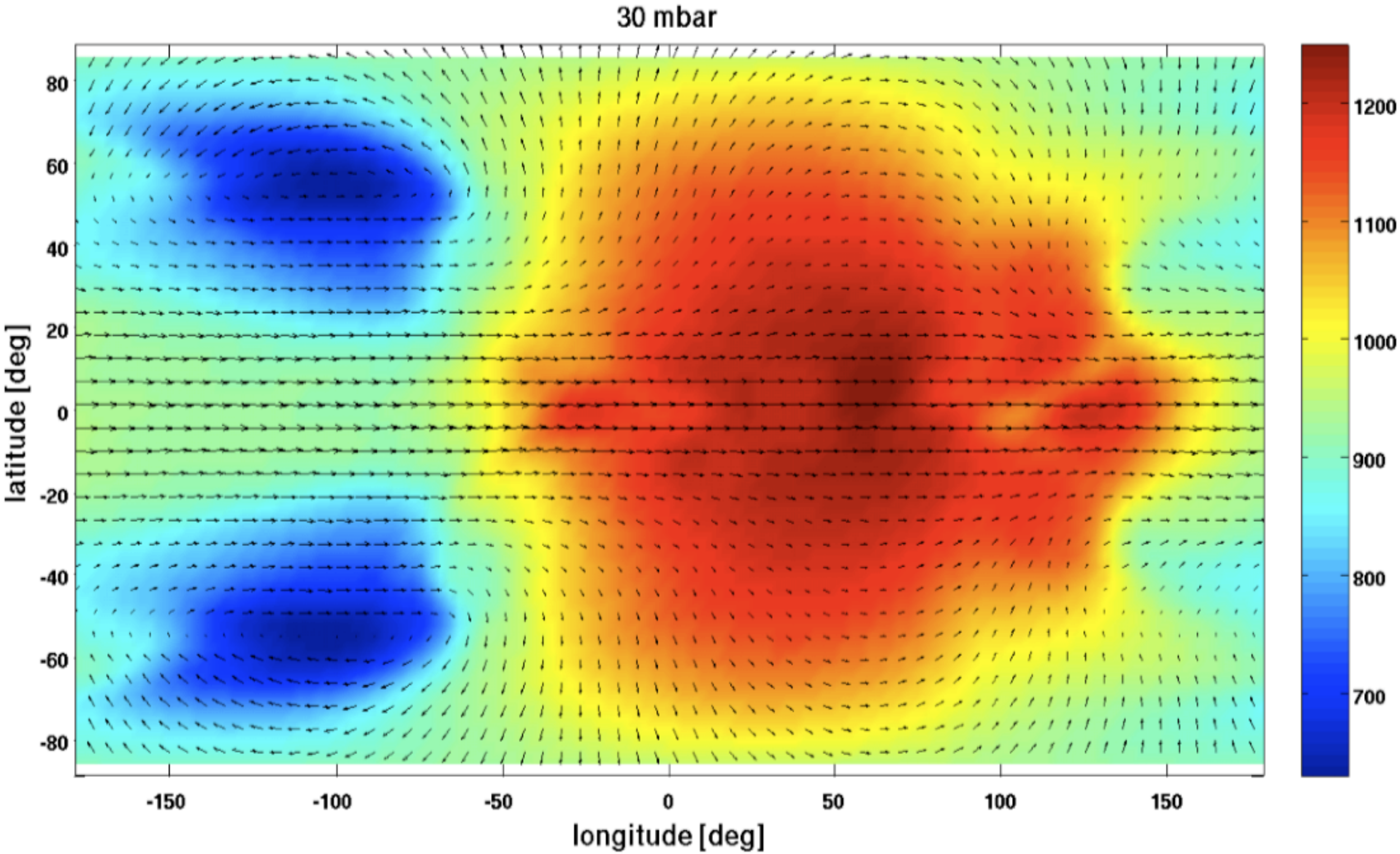
- **How do dynamics depend on planetary rotation rate, stellar irradiation, atmospheric metallicity, etc? Are there multiple dynamical regimes, and if so, what governs them? What are implications for observations?**



Showman & Guillot (2002)

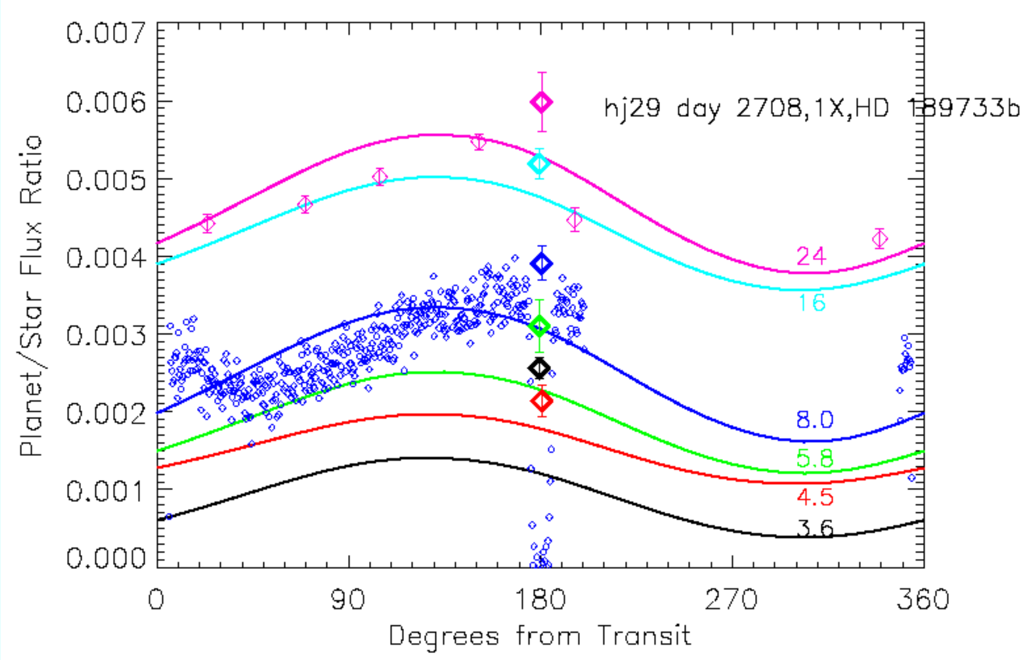


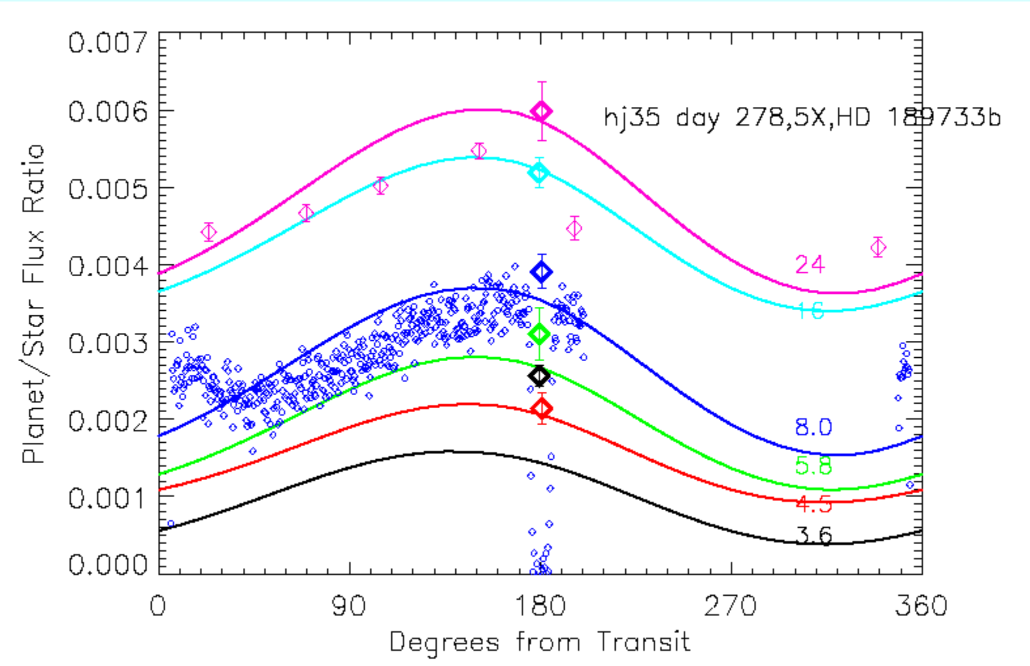
Knutson et al. (2007)



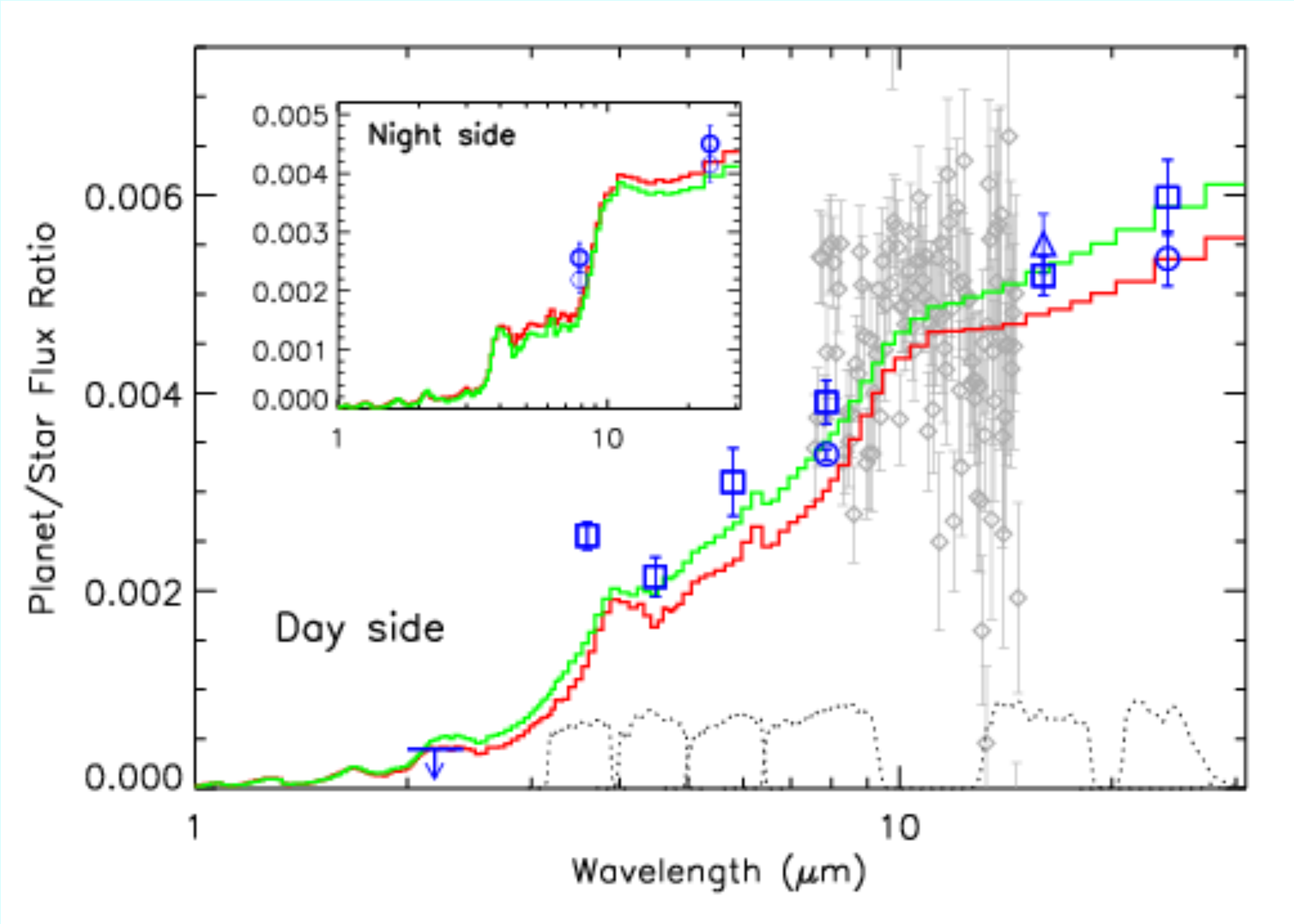
Showman et al. (2009)

Lightcurves: HD 189733b, solar (top) and 5 x solar (bottom)

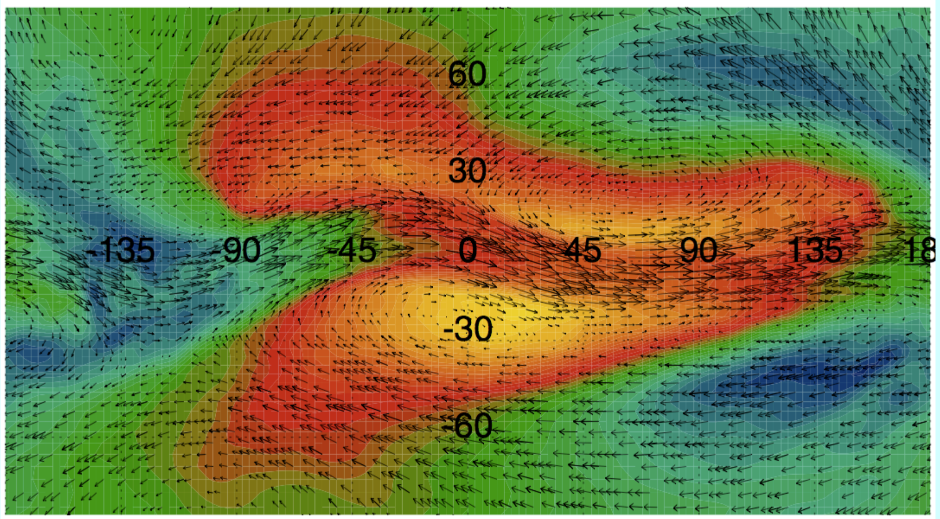




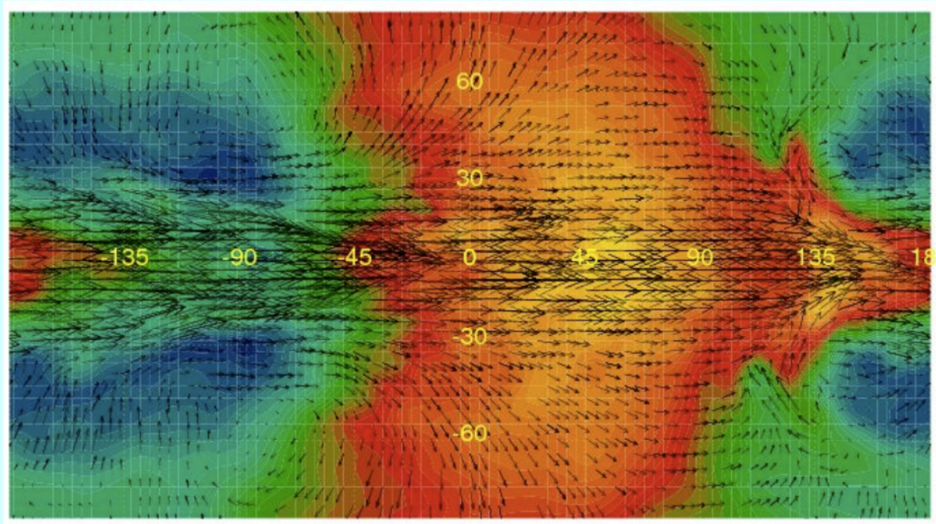
Secondary eclipse spectra: HD 189733b



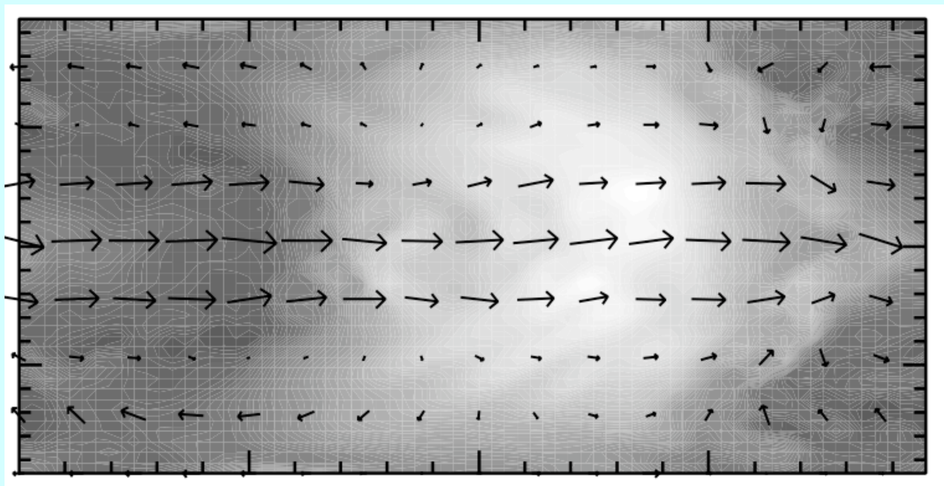
Equatorial superrotation is a common outcome of hot Jupiter circulation models



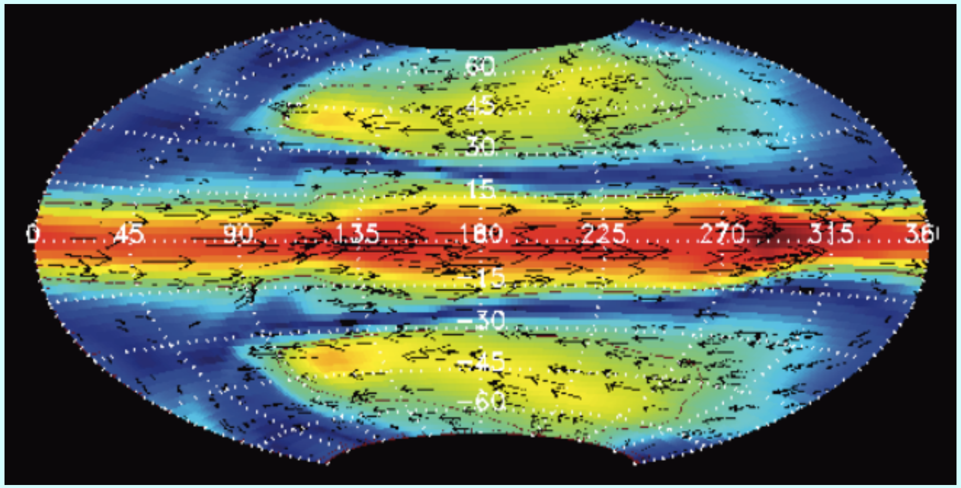
Menou & Rauscher (2009)



Rauscher & Menou (2010)



Cooper & Showman (2005, 2006)



Dobbs-Dixon & Lin (2008, 2010)

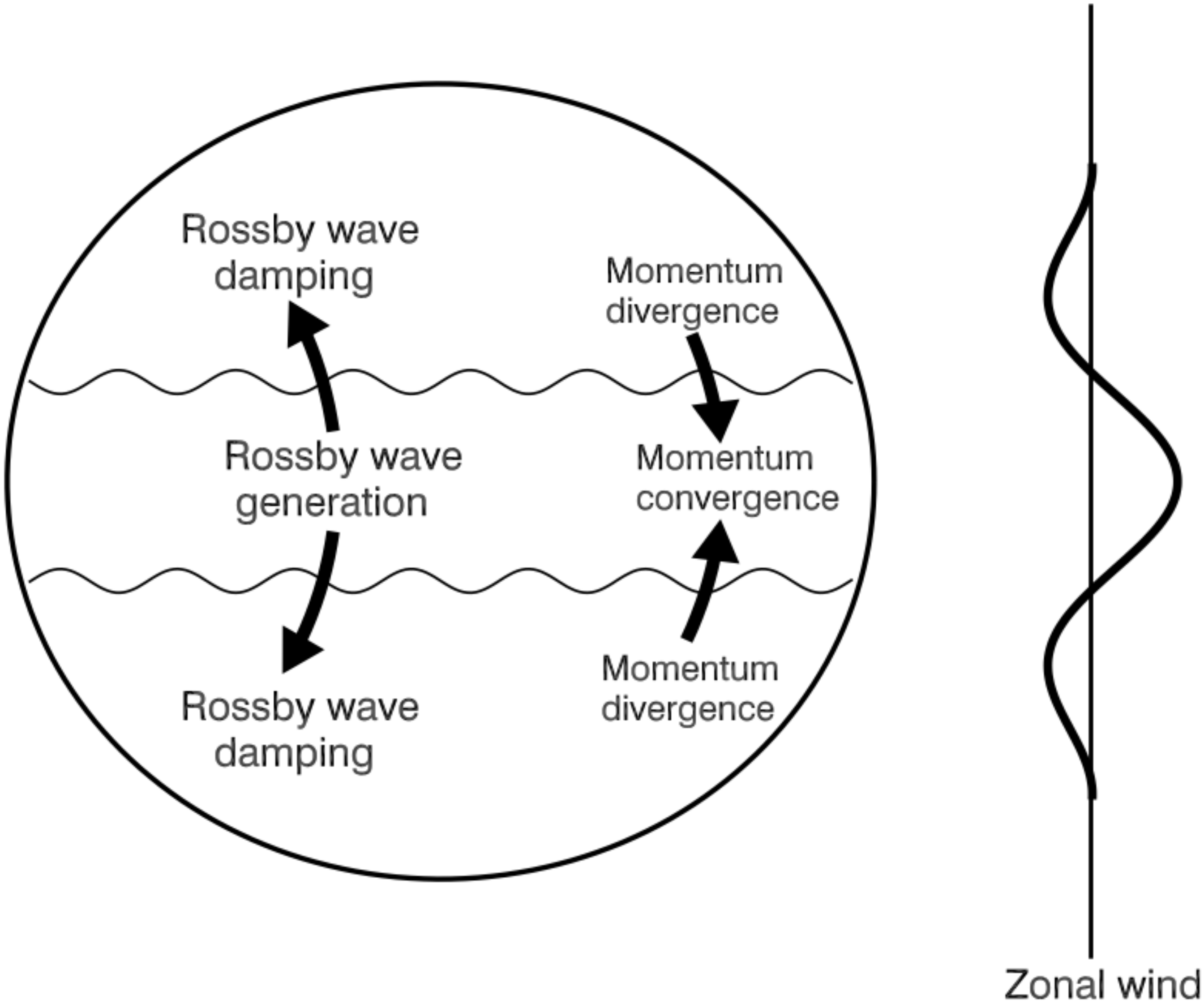
What causes the equatorial superrotation?

Hide’s theorem: **Superrotating equatorial jets (corresponding to local maxima of angular momentum) cannot result from axisymmetric circulations (e.g., angular-momentum conserving Hadley cells).**

Such jets must instead result from up-gradient momentum transport by waves and/or turbulence

Rossby waves are a possible candidate (Held 1999, 2000): they cause eastward acceleration where they are generated and westward acceleration where they dissipate/break

For a hot Jupiter, the asymmetric forcing (dayside heating, nightside cooling) is a natural generator of Rossby waves that propagate away from the equator…thus causing the equatorial superrotation!


Rossby wave
damping
Momentum
divergence
Rossby wave
generation
Momentum
convergence
Momentum
divergence
Rossby wave
damping
Zonal wind

Simple models to isolate superrotation mechanism

- **To capture the mechanism in the simplest possible context, adopt the shallow-water equations for a single fluid layer:**

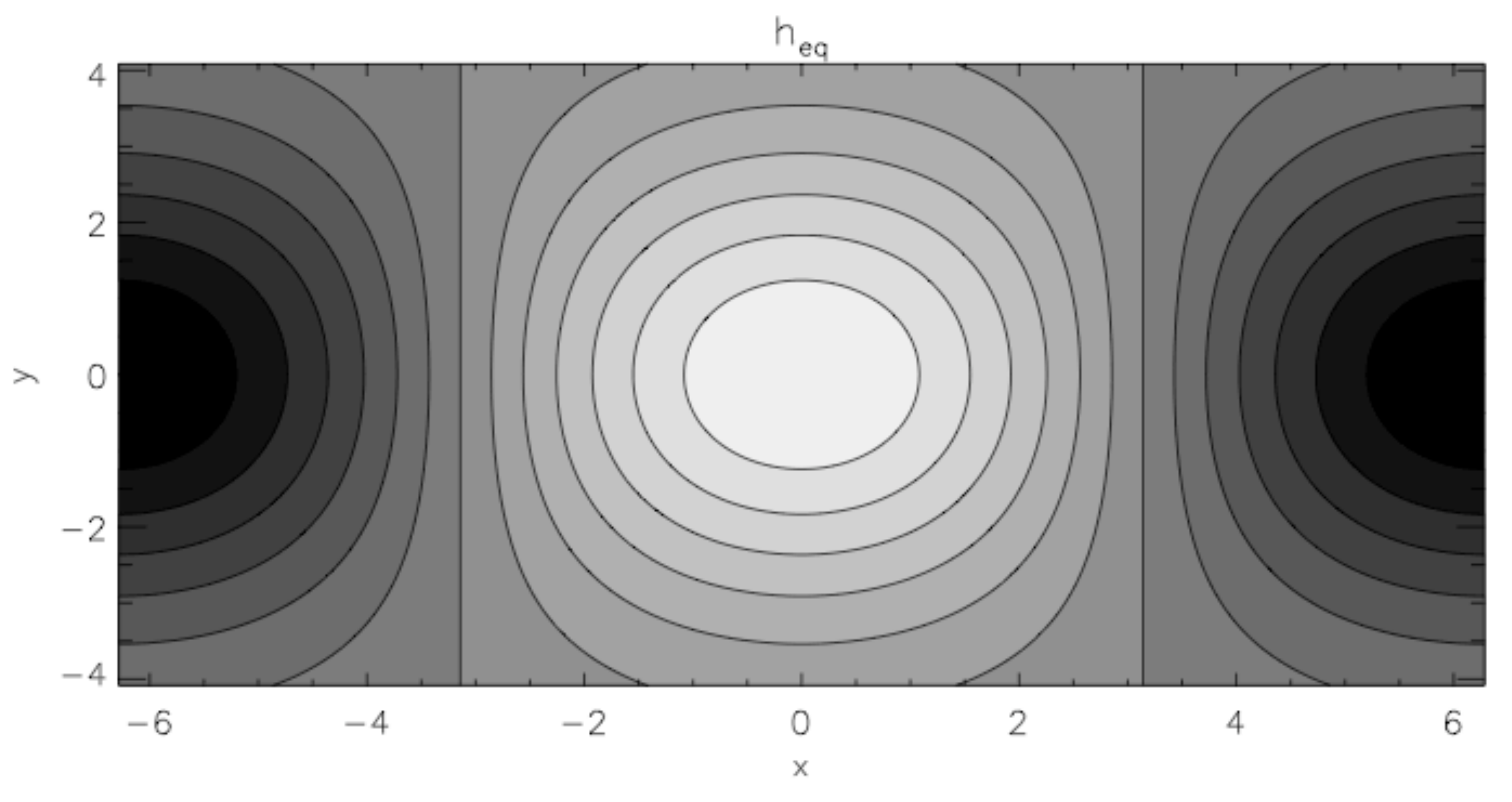
$$\frac{d\vec{v}}{dt} + g\nabla h + fk \times \vec{v} = -\alpha\vec{v} - \vec{v}\frac{Q_h}{h}\delta$$

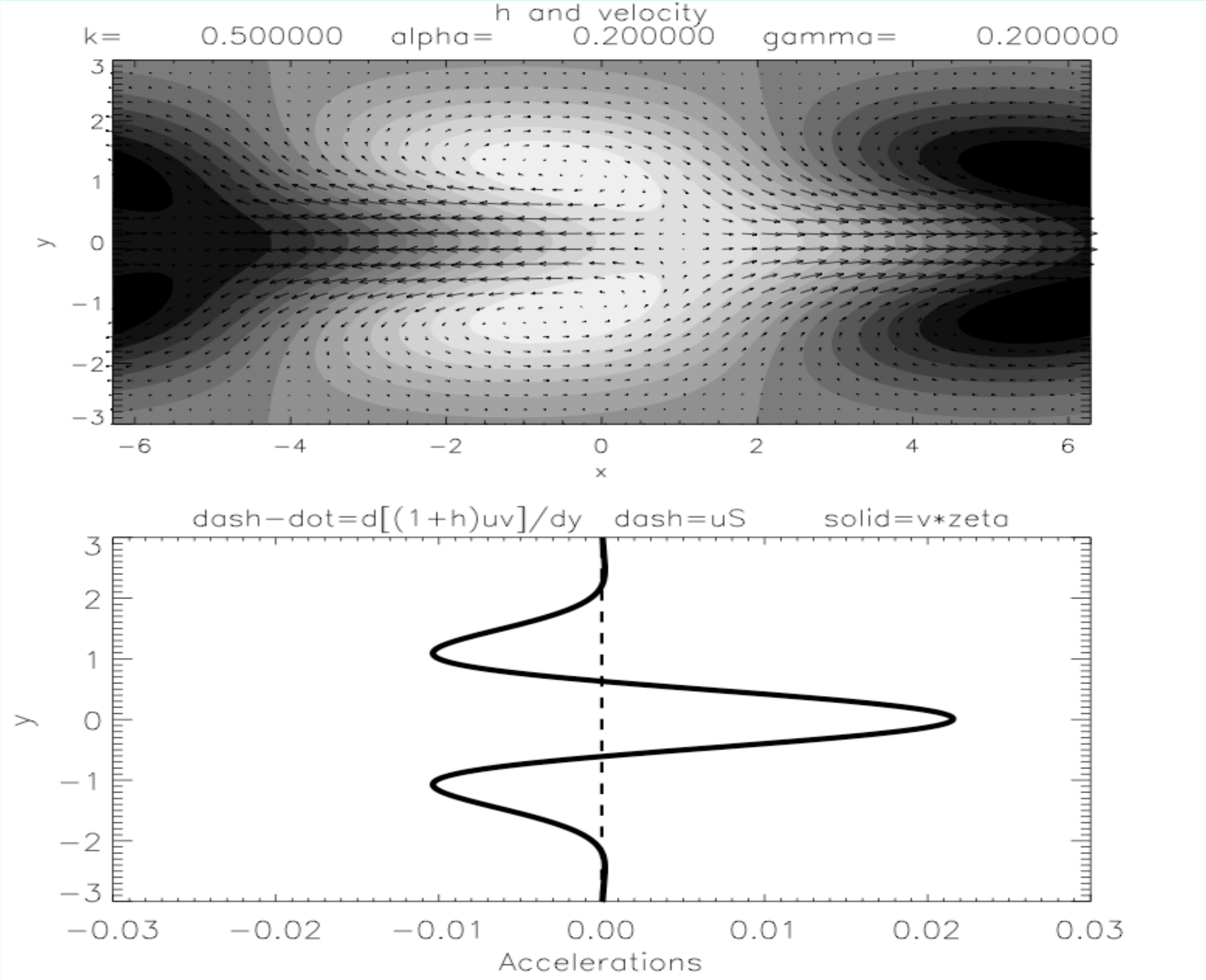
$$\frac{\partial h}{\partial t} + \nabla \cdot (h\vec{v}) = \gamma[h_{eq}(x,y) - h] \equiv Q_h$$

where $\gamma[h_{\mathrm{eq}}$-$h]$ represents thermal forcing/damping, αv represents drag, and where δ=1 when Q_h>0 and δ=0 otherwise

- **First consider linear, steady analytic solutions and then consider full nonlinear solutions on a sphere.**

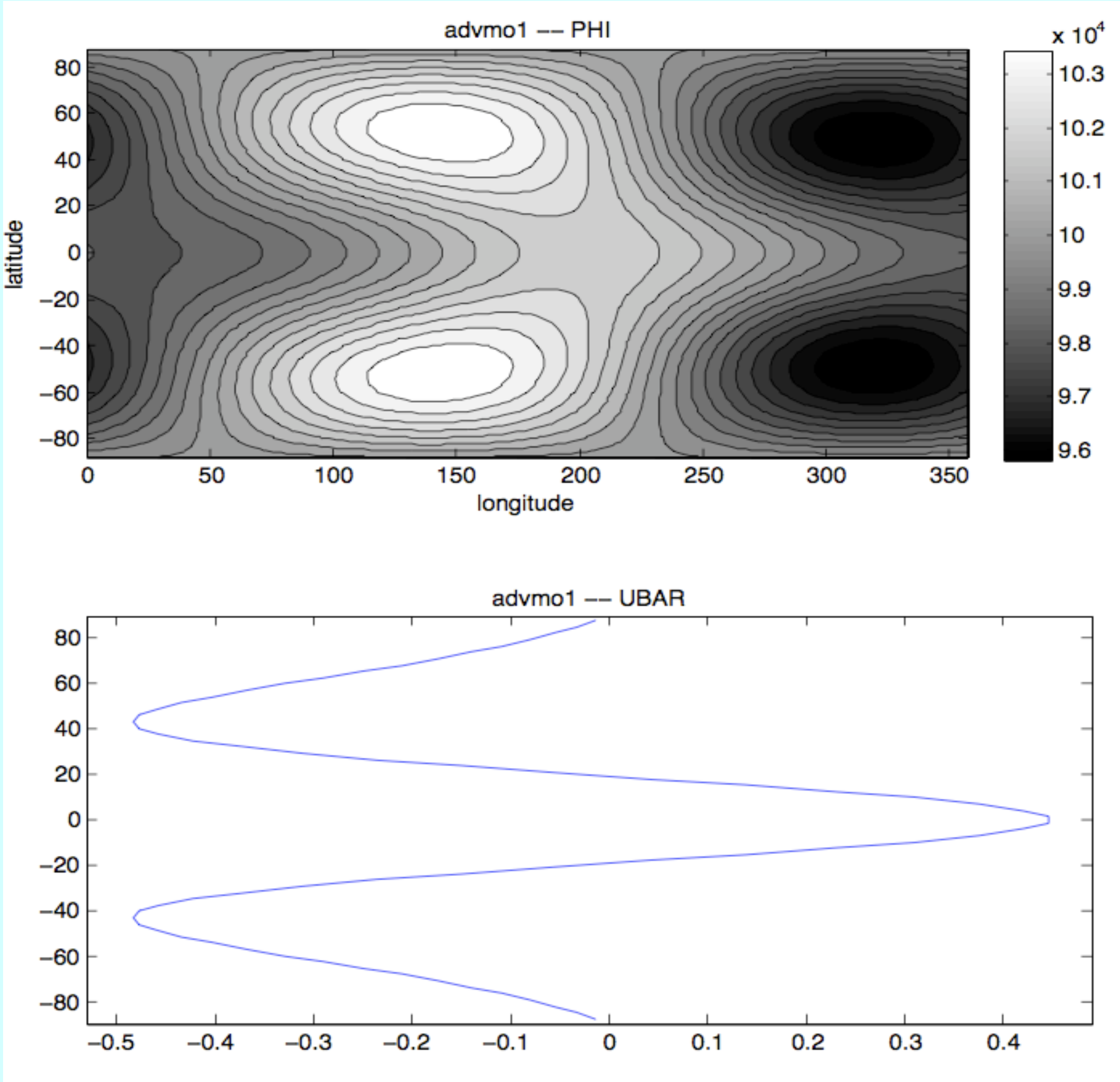
Forcing



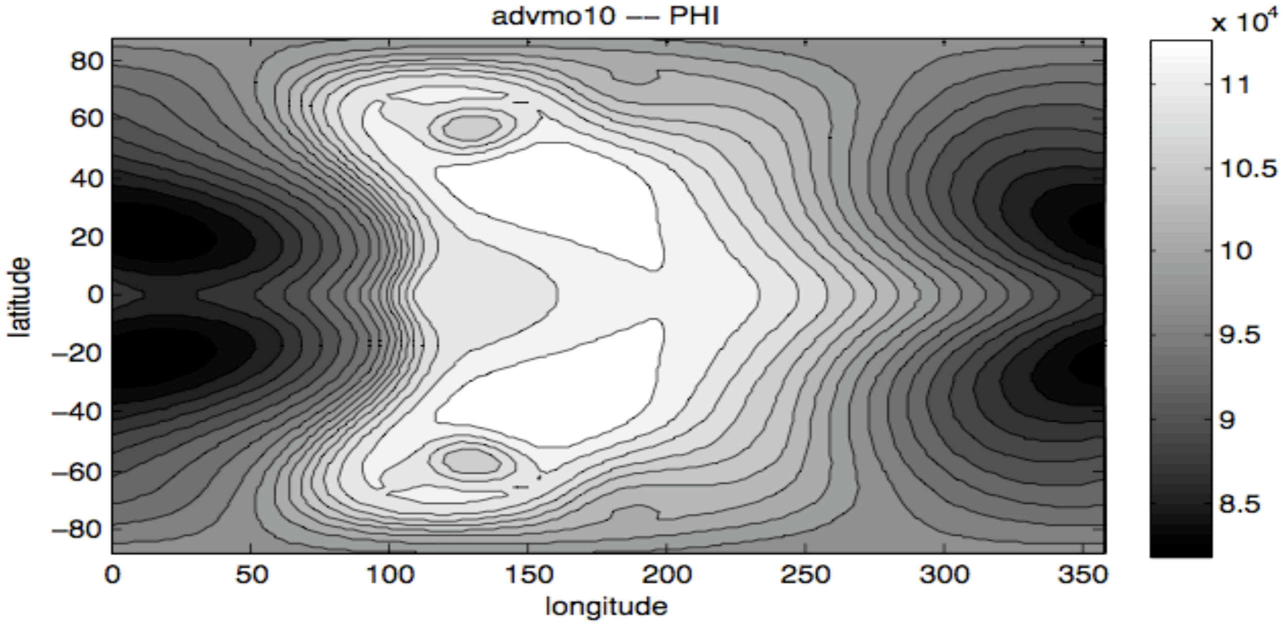


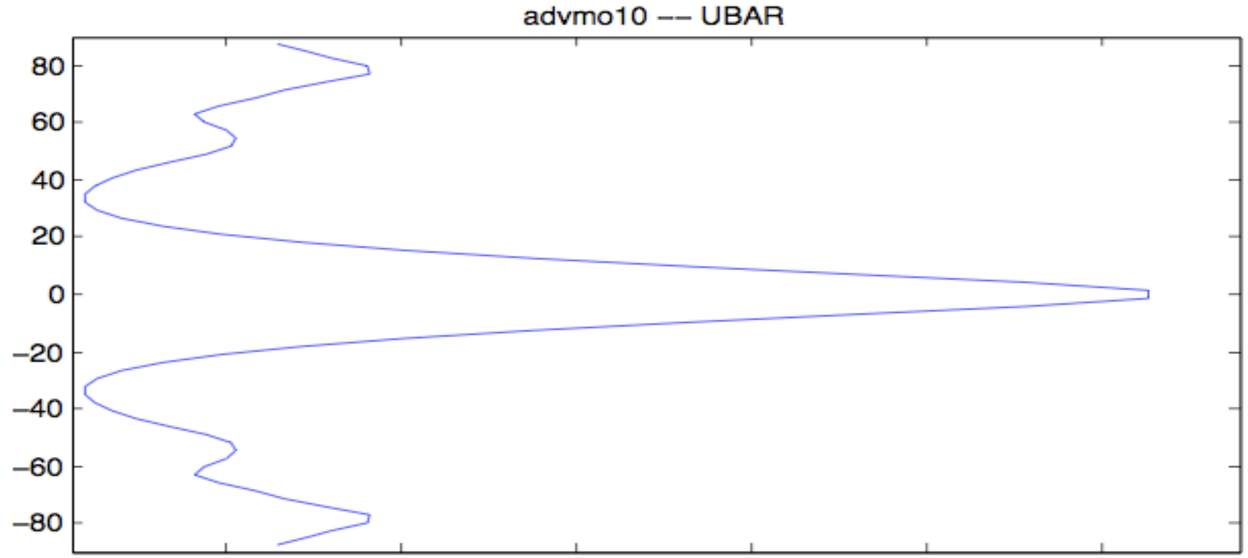
$$\frac{\partial \overline{u}}{\partial t} = -\frac{1}{\overline{h}}\frac{\partial}{\partial y}[\overline{(hv)'u'}] + \ldots$$

Full nonlinear spherical shallow-water simulation for Gill forcing



Zonal-mean zonal wind

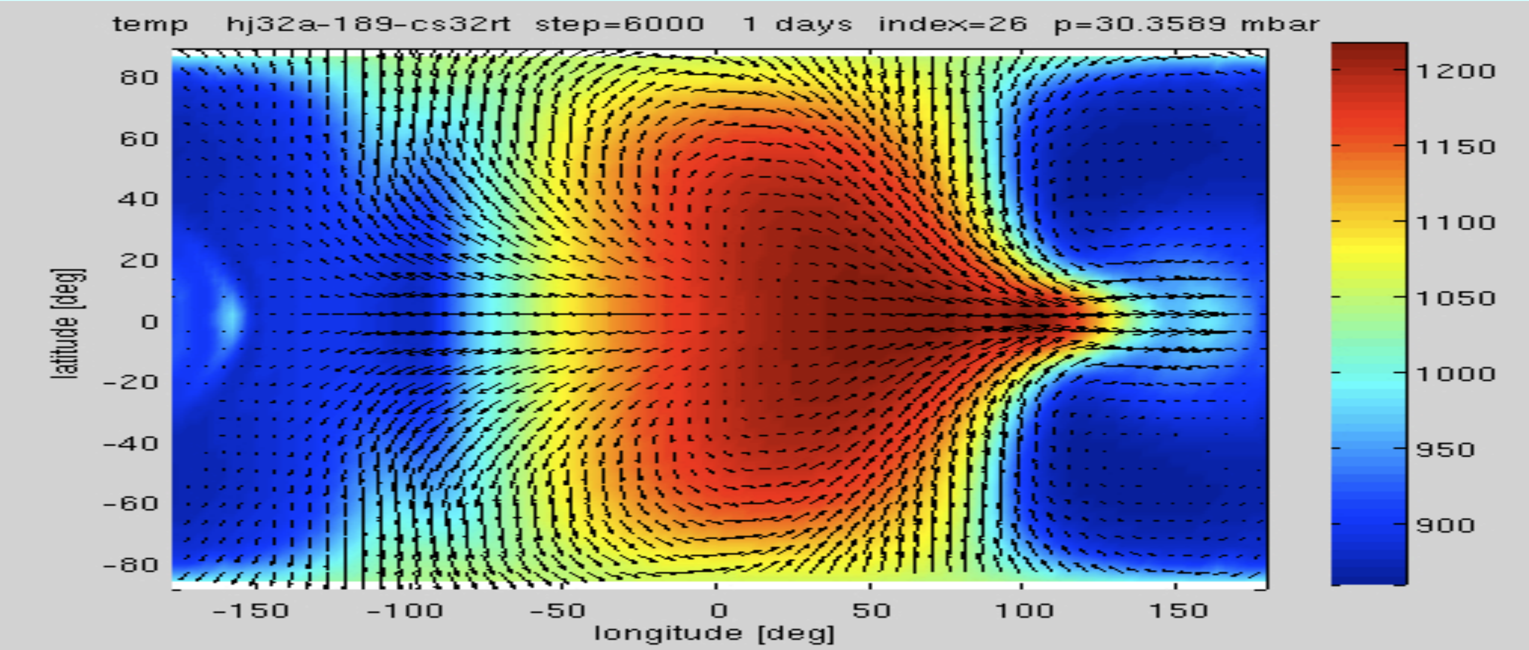


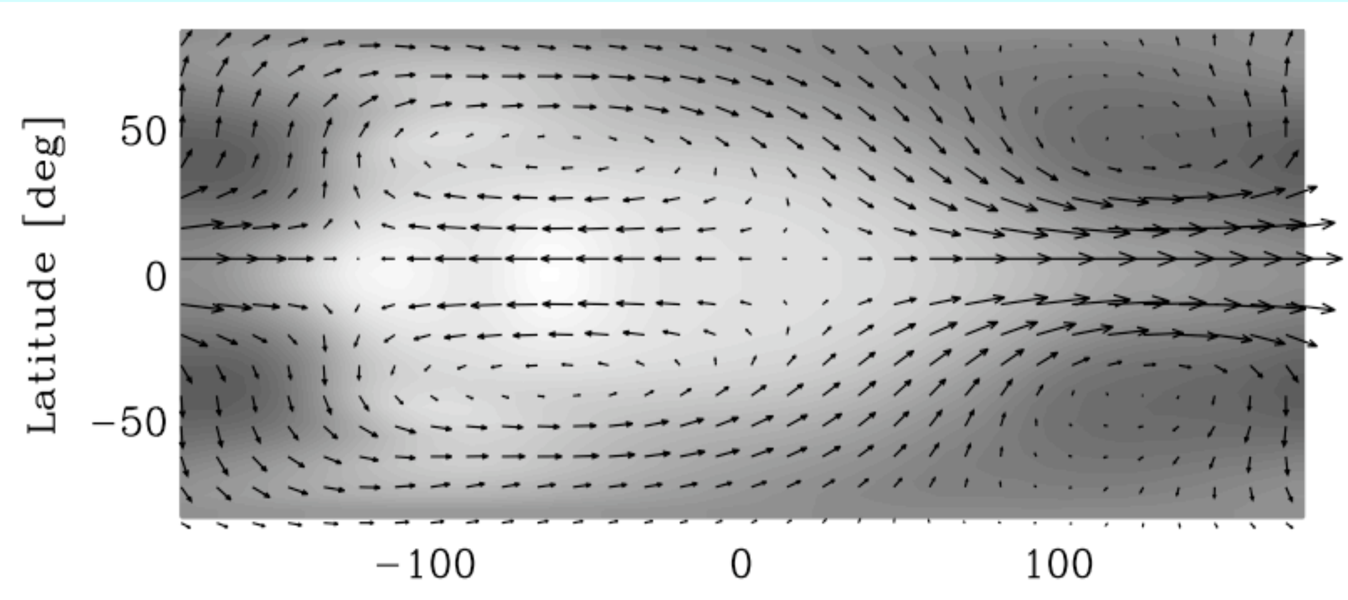


Zonal-mean zonal wind

Showman & Polvani (in prep)

“Gill” pattern is clearly evident in spin-up phase of 3D hot Jupiter simulations

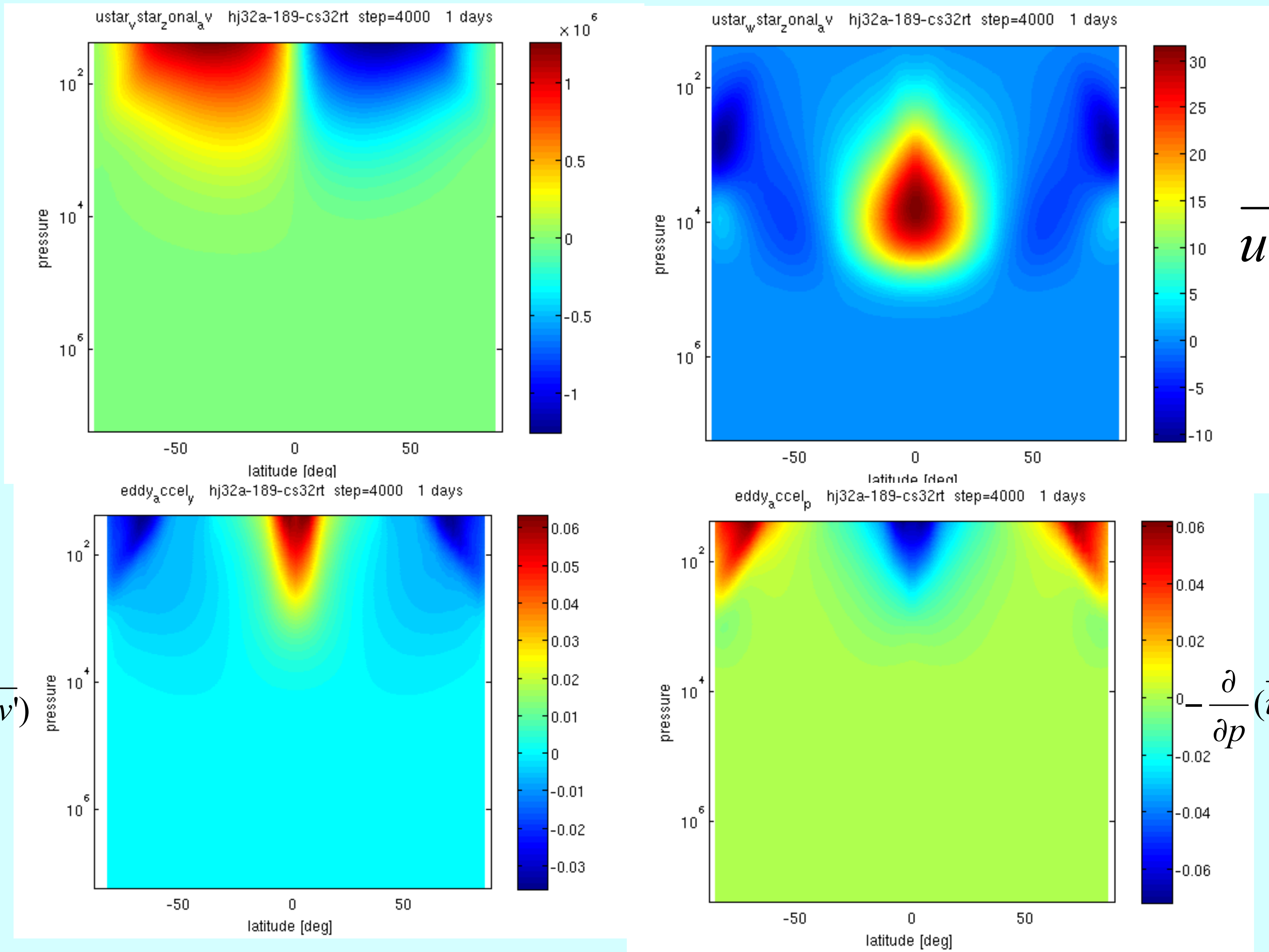


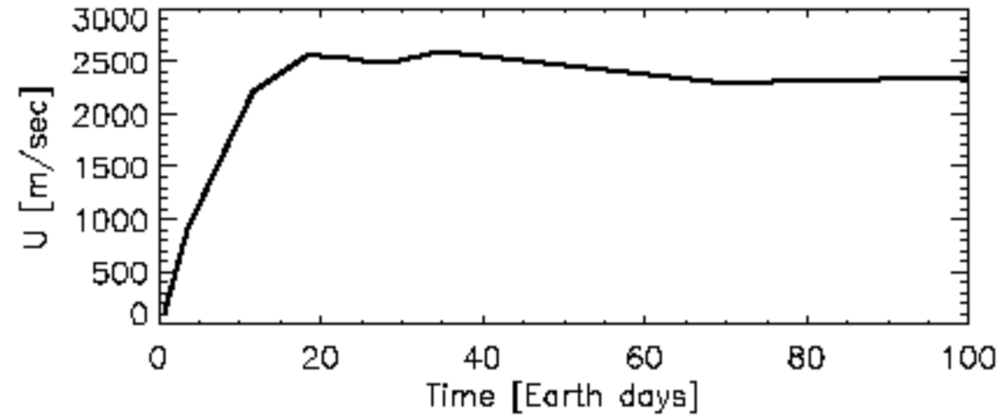


Showman & Guillot (2002)

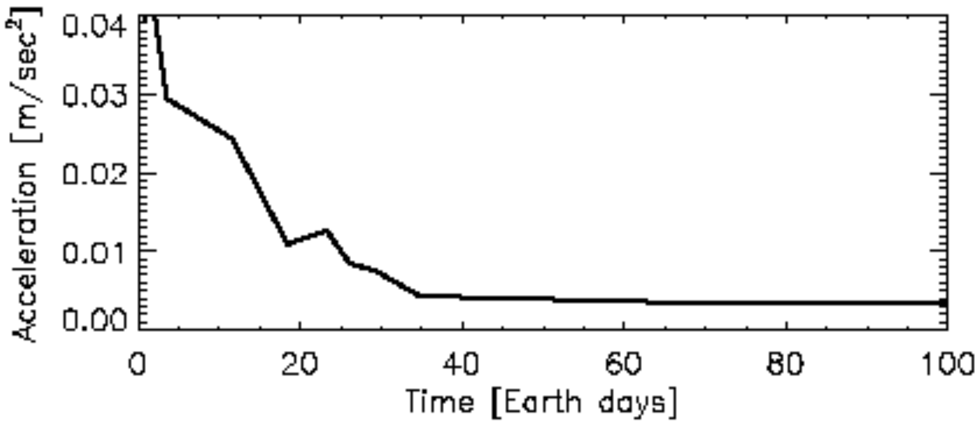
$$\overline{u'v'} \qquad \overline{u'\omega'}$$

$$-\frac{\partial}{\partial y}(\overline{u'v'}) \qquad -\frac{\partial}{\partial p}(\overline{u'\omega'})$$

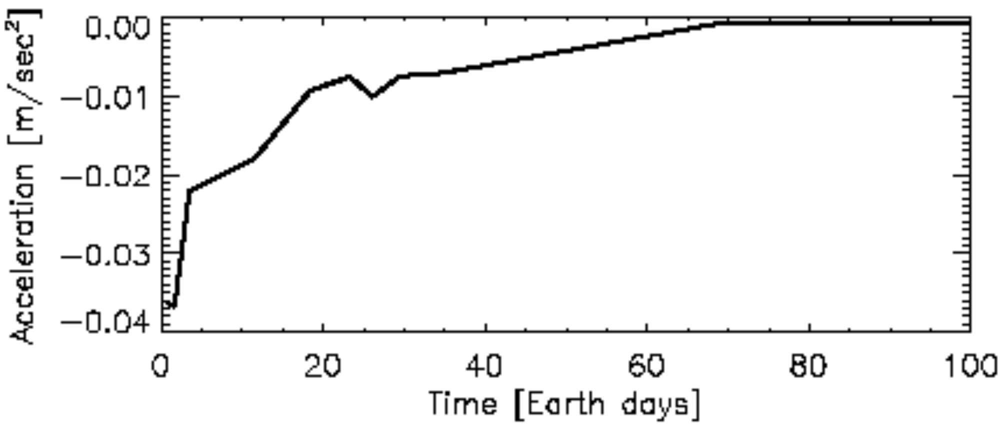




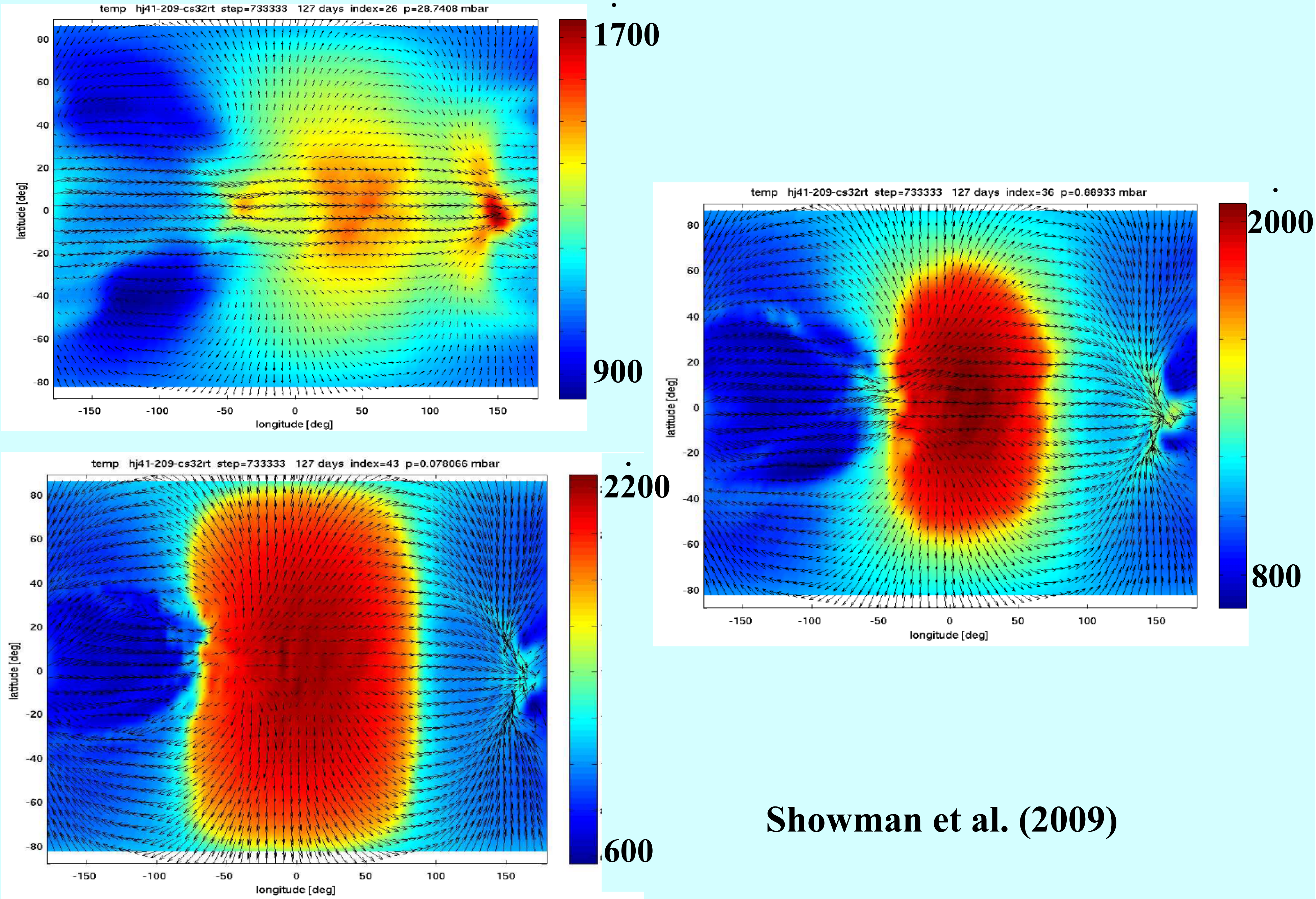
$$-\frac{\partial}{\partial y}(\overline{u'v'})$$



$$-\frac{\partial}{\partial p}(\overline{u'\omega'})$$



HD 209458b, solar, with TiO/VO

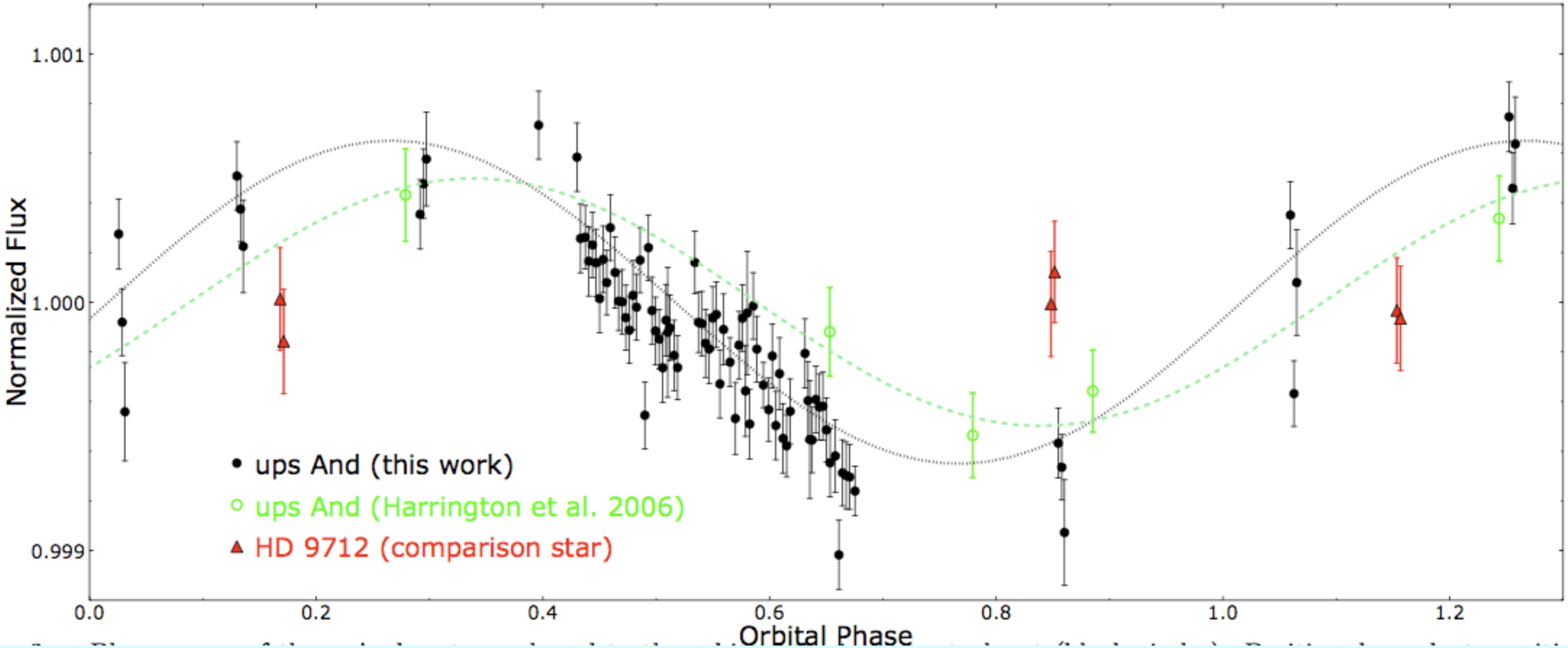


Showman et al. (2009)

Hints of diversity

- **Simple arguments and 3D models suggest a correlation between day-night temperature contrasts and offset (if any) of hottest regions from substellar point**

- **But recent light curves suggest that the reality may be more complicated!**

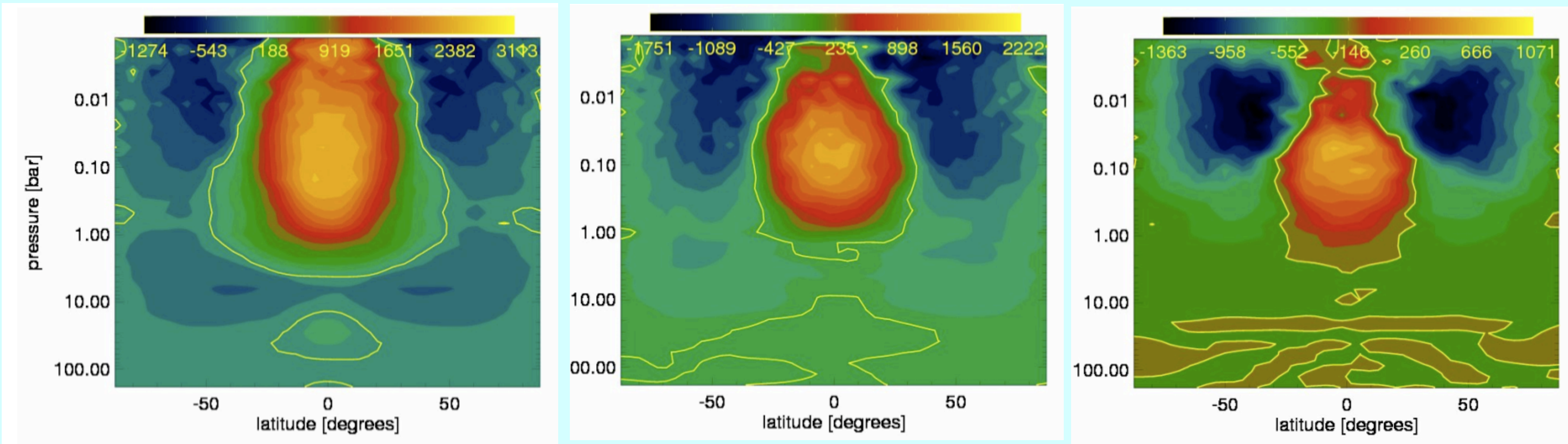


Ups And b (Crossfield et al. 2010, arXiv)

Friction

- **Sources of frictional damping are poorly understood. Possibilities:**
  - **Sub-grid-scale turbulence**
  - **Sub-grid-scale wave generation/breaking/absorption (e.g., Watkins & Cho 2010)**
  - **Drag and dissipation associated with MHD effects (Perna et al. 2010, Batygin & Stevenson 2010)**

Weak drag | **Medium drag** | **Strong drag**



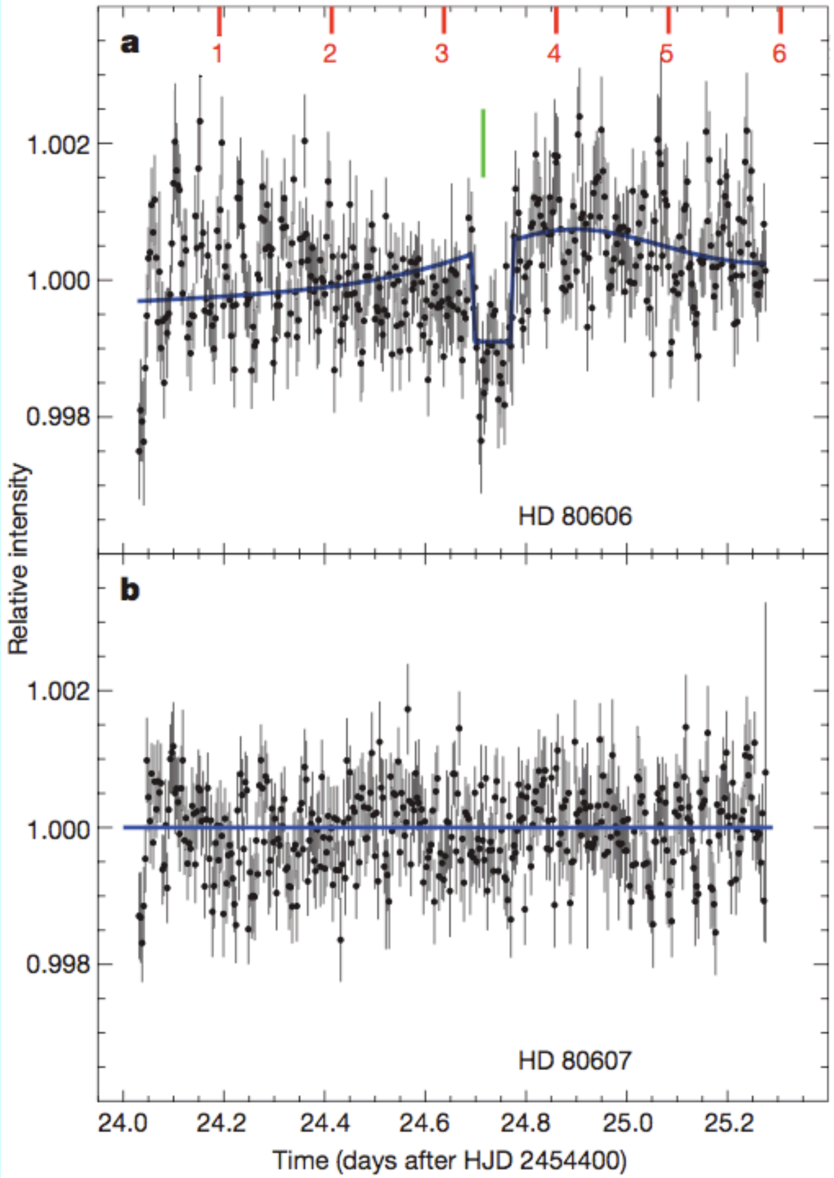
Perna et al. (2010)

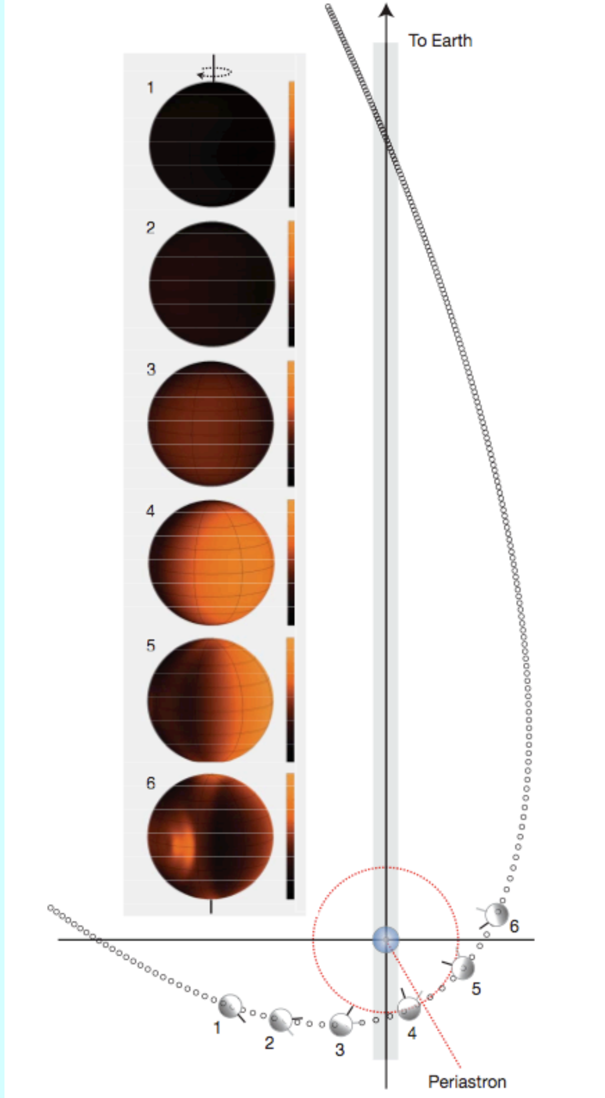
- **Note that equilibration of jet speeds a given level—say the photosphere-- need not require drag *at those levels* (e.g., drag could occur at bottom, with eddy-jet pumping at the photosphere balanced by Coriolis acceleration/ advection).**

Eccentric Planets

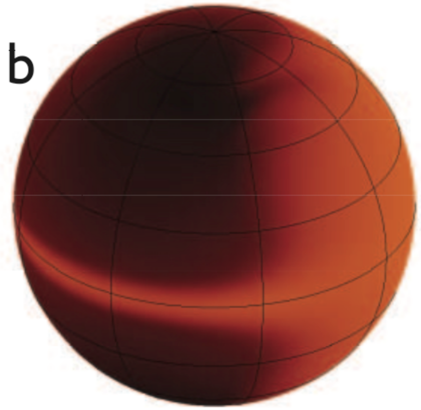
HD 80606b: *e*=0.93, stellar flux varies by factor of ~800!

Other examples: HAT-P-2b (*e*=0.5), HD 17156b (*e*=0.67)



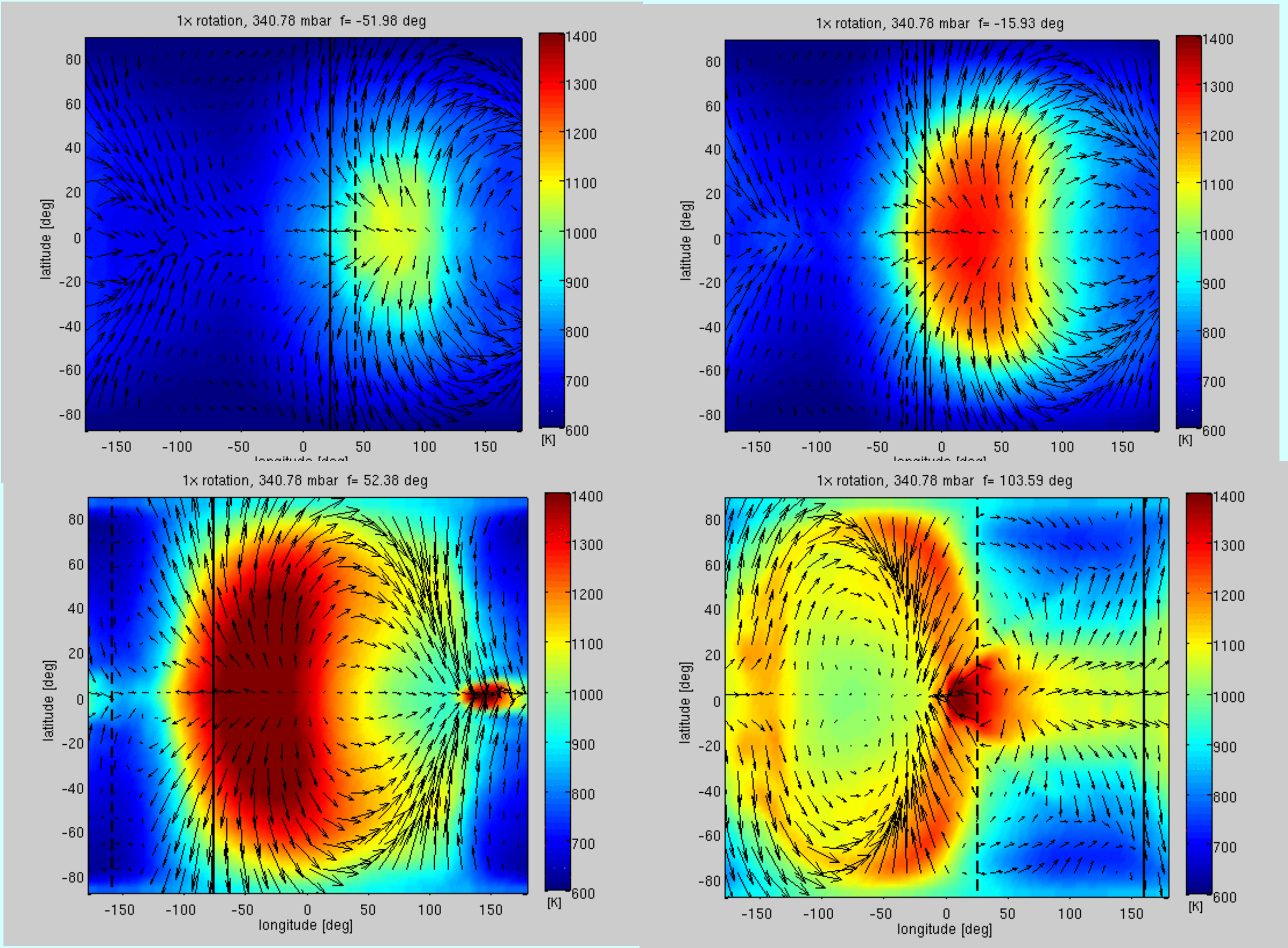


Laughlin et al. (2009)



Langton & Laughlin (2008)

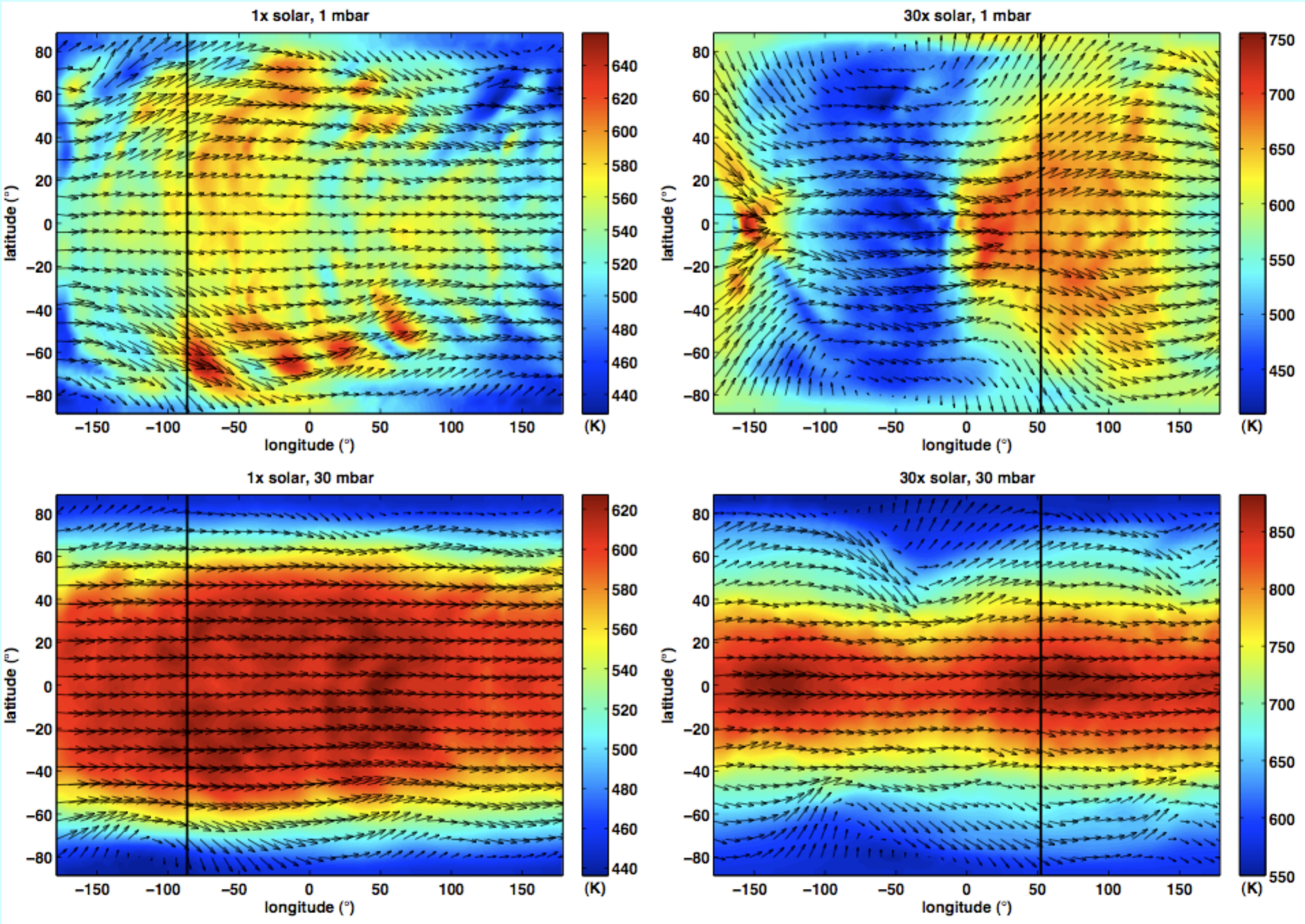
Dynamical models of eccentric planets



Lewis et al. (2010, in preparation); see also Kataria poster

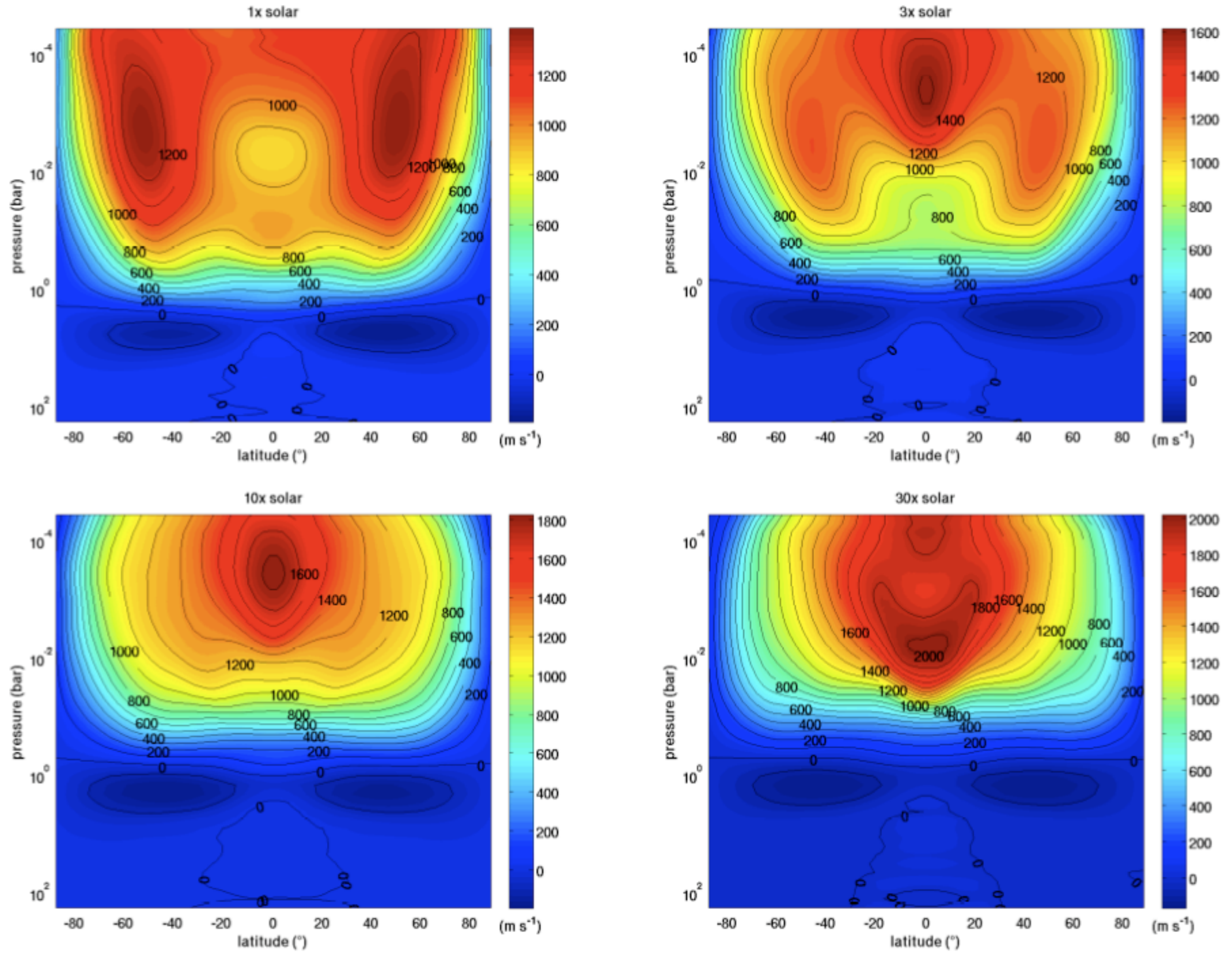
Hot Neptunes

- **Smaller sizes and possible higher metallicity make these planets interesting laboratories for atmospheric circulation.**
- **GJ 436b receives less stellar flux than most transiting planets and is an interesting case study**



Lewis et al. (2010)

GJ 436b: influence of metallicity on dynamical regime



Lewis et al. (2010).

See also Beaulieu et al. (2010, arXiv) which includes 3D models from Cho

Conclusions

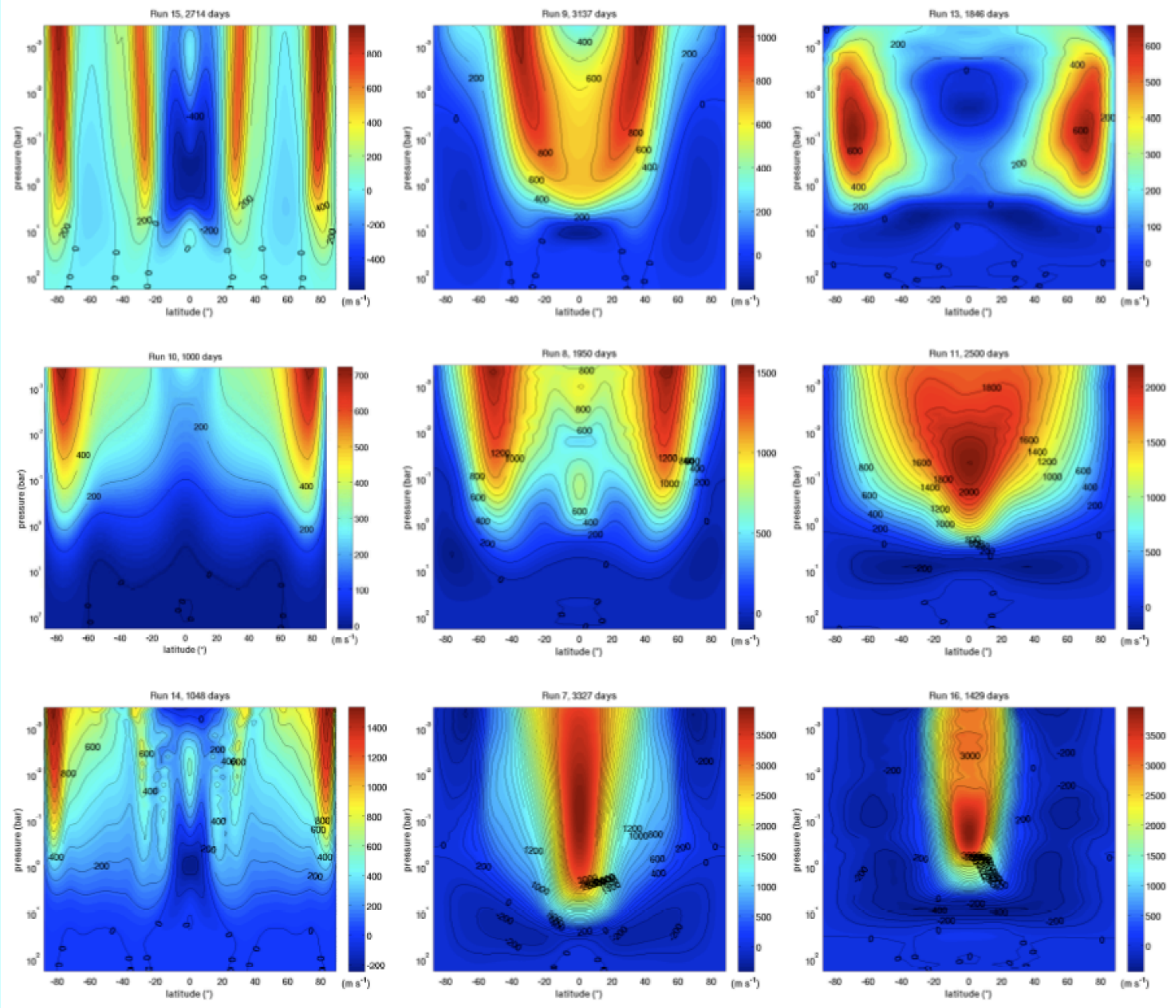
The intense radiation produces winds > 1 km/sec and temperature contrasts of ~200-1000 K. The winds can distort the temperature pattern in a complex manner, with important implications for lightcurves and spectra.

For synchronously rotating planets on few-day orbits, all of the 3D models produce equatorial superrotation. Under appropriate conditions (radiative timescale comparable to advective timescale), this displaces the hottest regions to the east of the substellar point, as observed on HD 189733b.

The equatorial superrotation results from the generation of standing, planetary-scale Kelvin and Rossby waves by the day-night heating gradient. We have demonstrated this mechanism in a sequence of linear and nonlinear one-layer (shallow-water) models and full 3D GCM runs.

There is likely a huge diversity of circulation regimes, hinted at in recent observations and models.

Dependence of wind on rotation rate and orbital distance

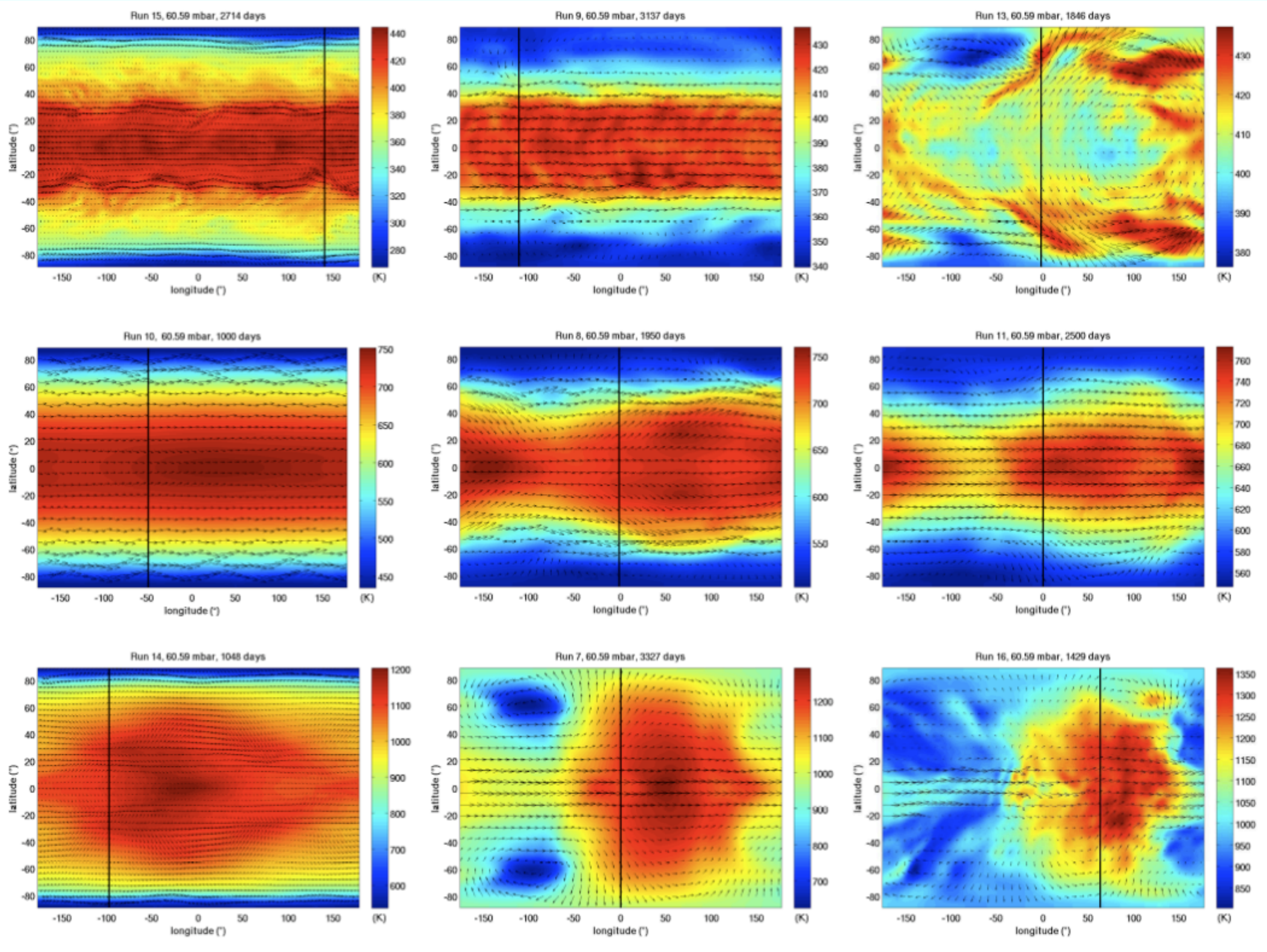


Orbital distance

Rotation rate

Lewis, Showman

Dependence of temperature on rotation rate and orbital distance



Orbital distance →

← Rotation rate

Lewis, Showman

Global-scale time variability on tidally locked hot Jupiters?

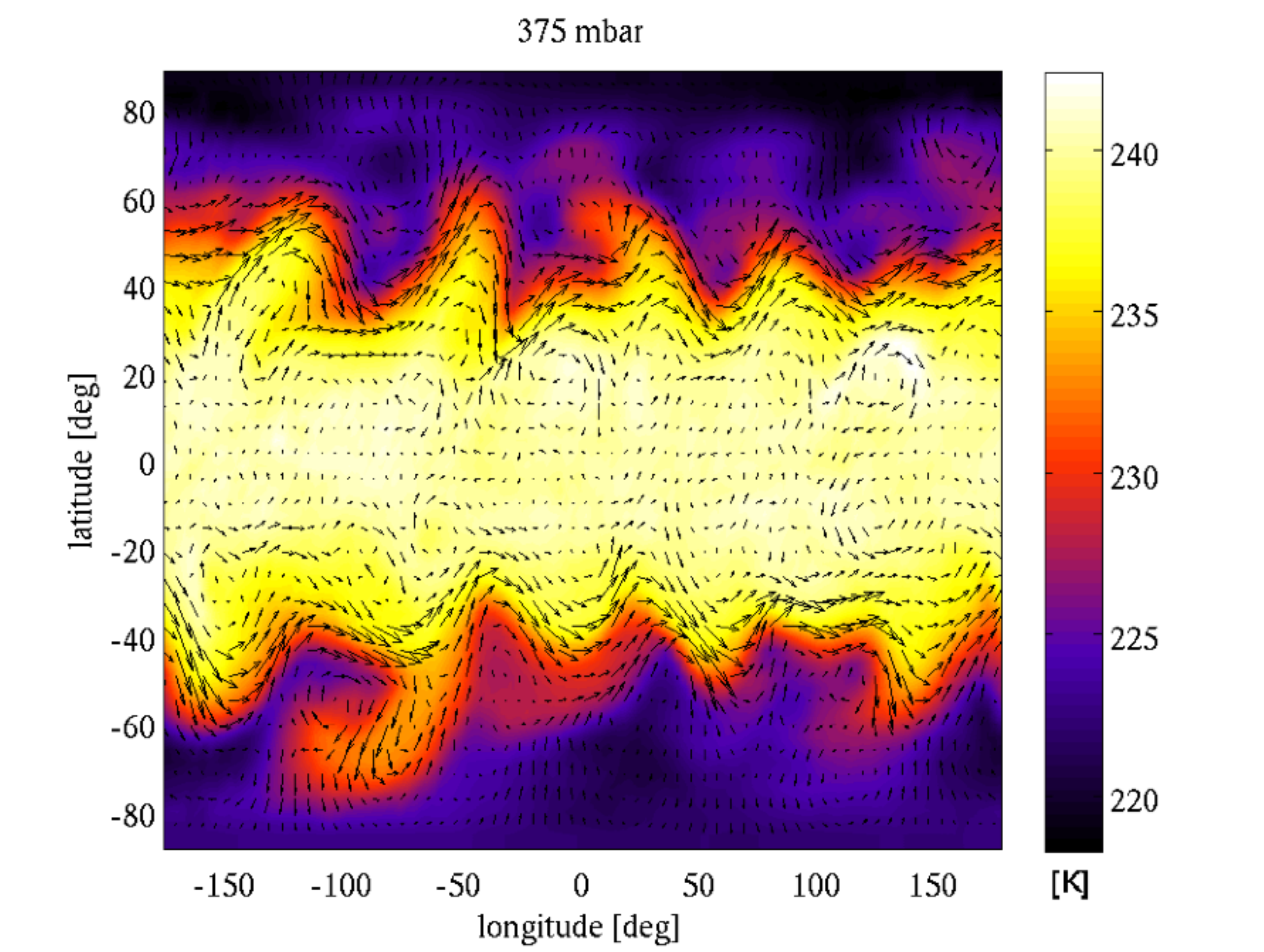
- **A necessary condition for instability is that latitudinal gradients of the "potential vorticity" (PV) change sign somewhere within the domain**

- **Entropy gradients along a lower impermeable surface induce a surface contribution to the PV and therefore promote the possibility of baroclinic instability in an atmosphere**

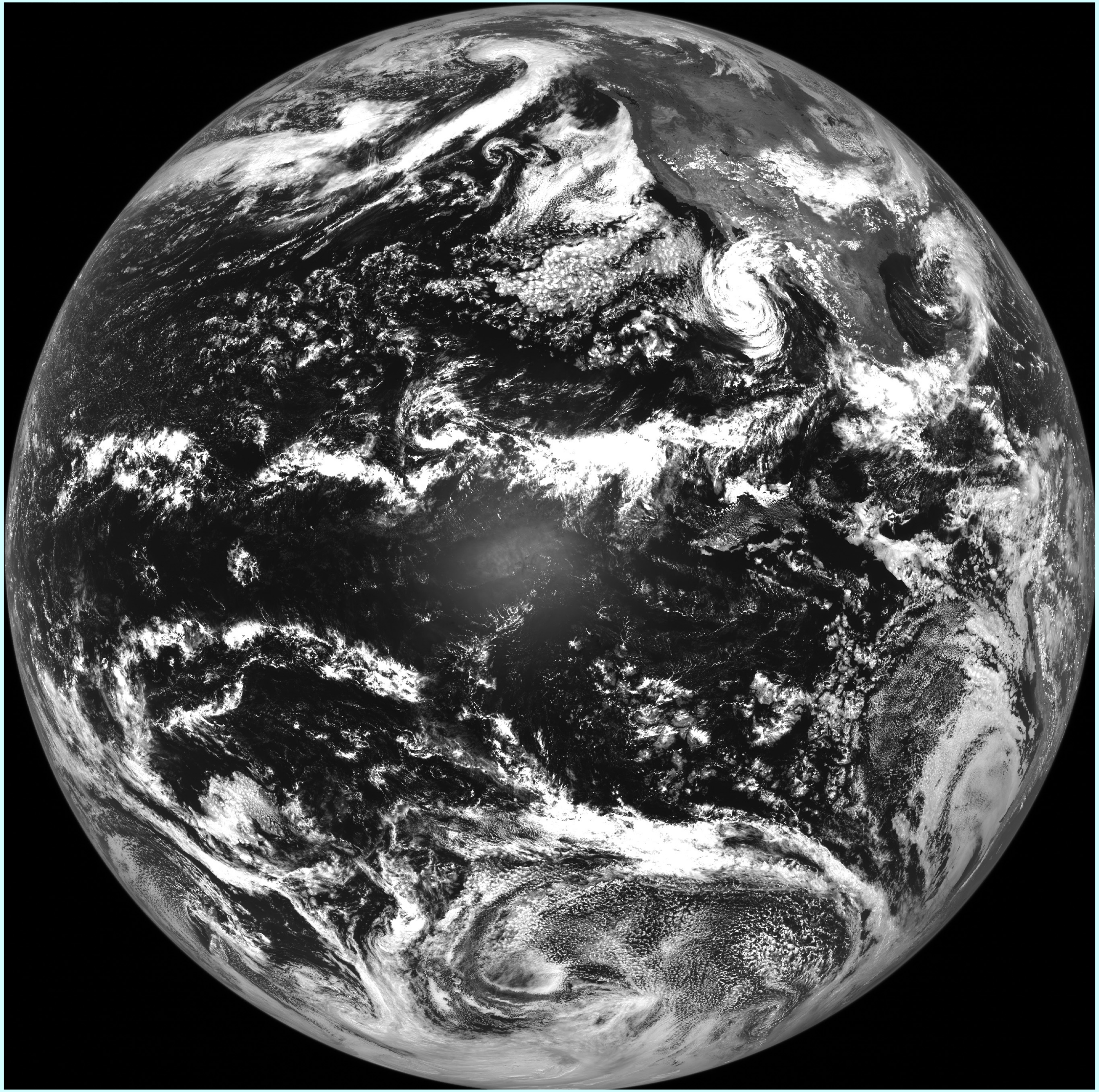
- **Baroclinic instability in Earth's atmosphere typically occurs *not* because of reversals of the interior PV gradient but because of the entropy gradients at the surface**

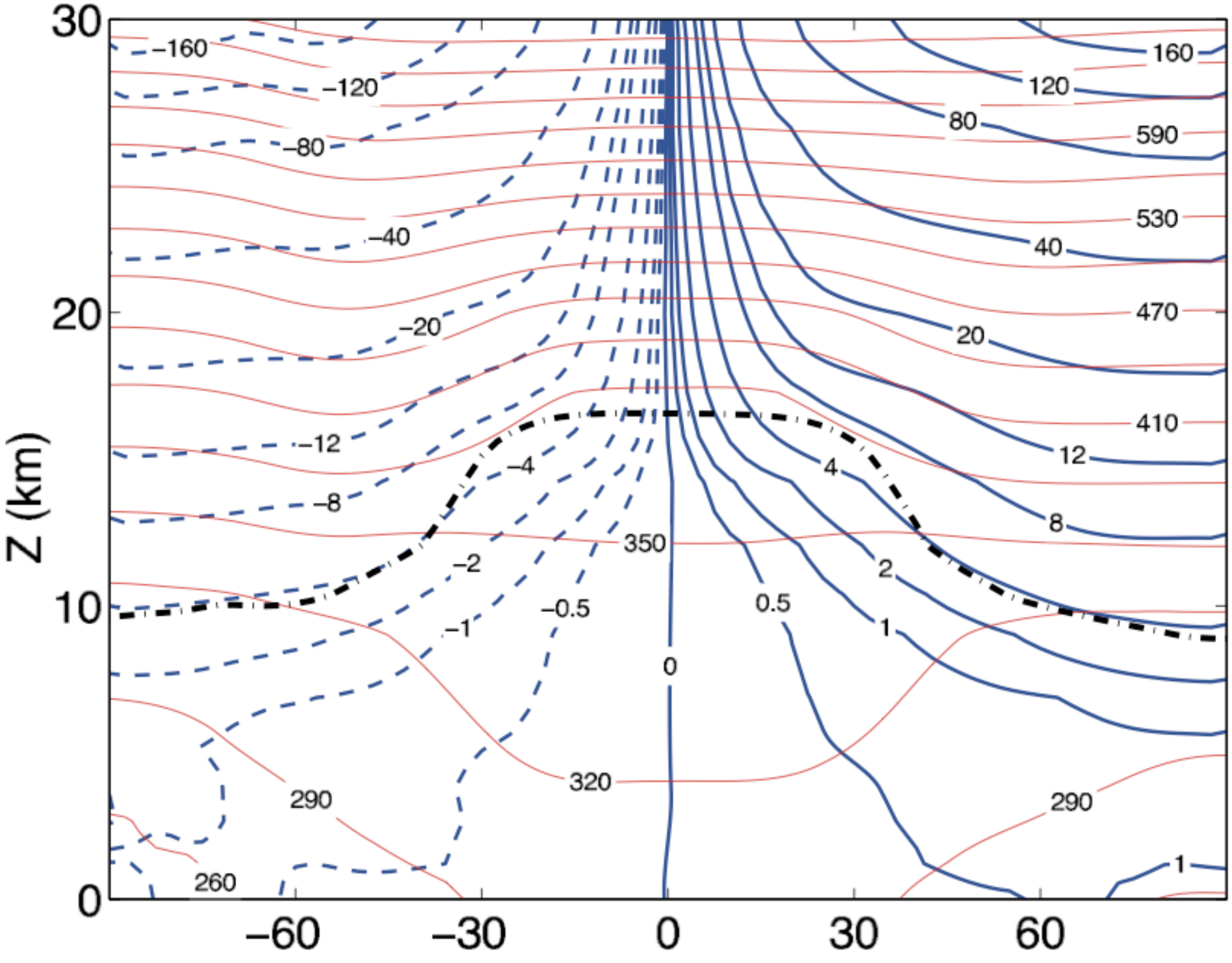
- **3D models of tidally locked hot Jupiters with relatively steady flows are those with deep lower boundaries (far below the stellar heating) whereas those with strong instabilities and time variability place the surface in the heating region where latitudinal entropy gradients exist**

Earth tropospheric circulation – simplified GCM



Courtesy Nikole Lewis





Latitude (deg)

Vallis (2006)