Global Climate Models

I. What drives the circulation?
II. Tutorial on climate modeling
III. Examples of GCMs for solar-system planets and exoplanets

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Why study the circulation?

Many exoplanets will occupy dynamically unusual regimes unavailable in our Solar System. Studying them broadens our understanding of meteorology.

The circulation shapes the <u>IR spectra</u>, <u>lightcurves</u>, <u>cloudiness</u> (visible albedo), <u>evolution</u>, <u>climate</u>, and <u>chemistry</u>. To explain these, we must understand the circulation.

Existing spectra/lightcurves already challenge our understanding. Future Spitzer, Kepler, groundbased, and JWST data will revolutionize our opportunity to probe these worlds.

The wonder of it all: We're unveiling weather on planets dozens or hundreds of light years away!

Factors that shape the atmospheric circulation

Atmospheric Mass

Stellar flux

Rotation rate

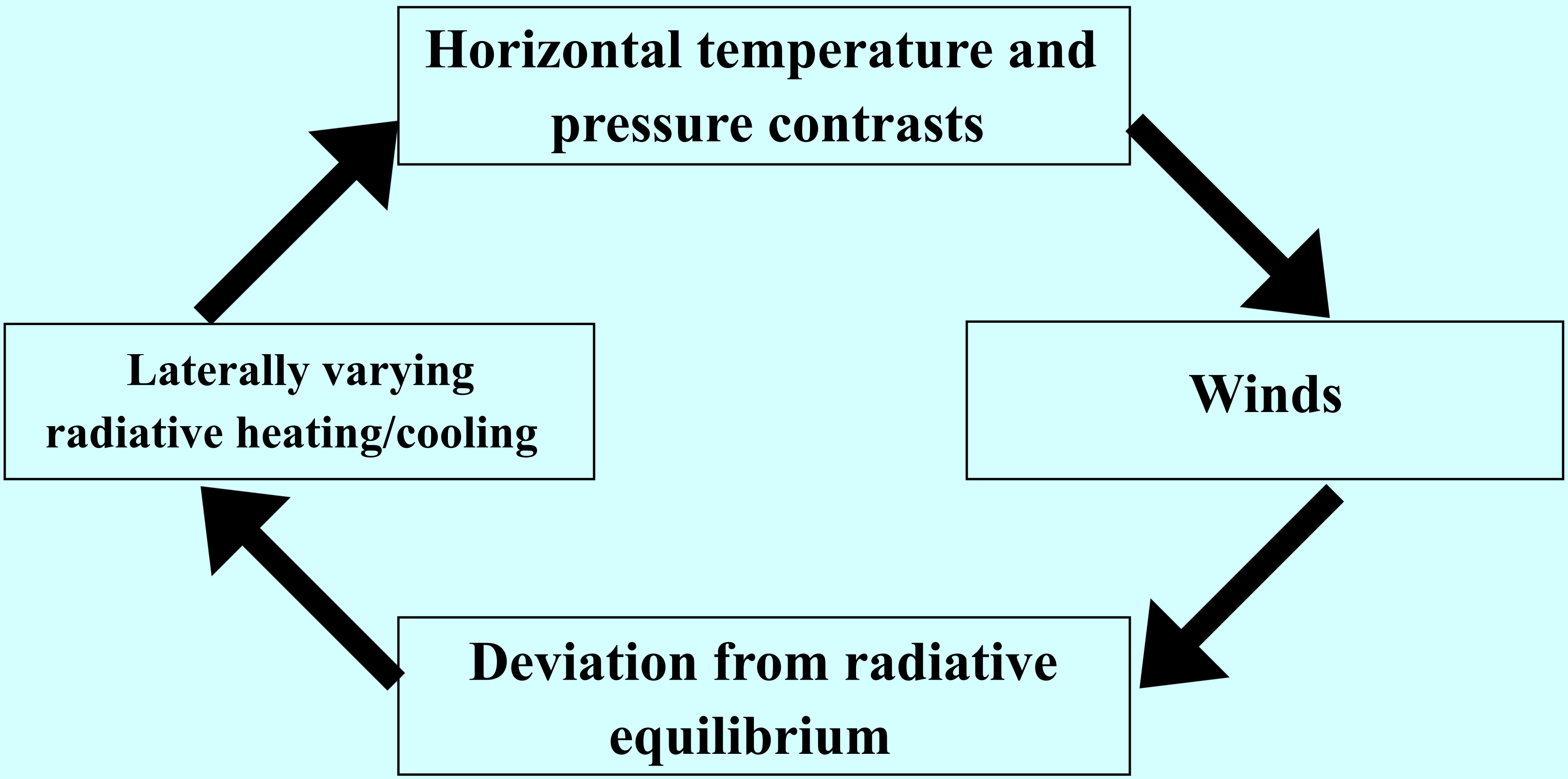
Heating pattern (equator-pole vs day-night)

Composition

Topography? Is there an ocean?

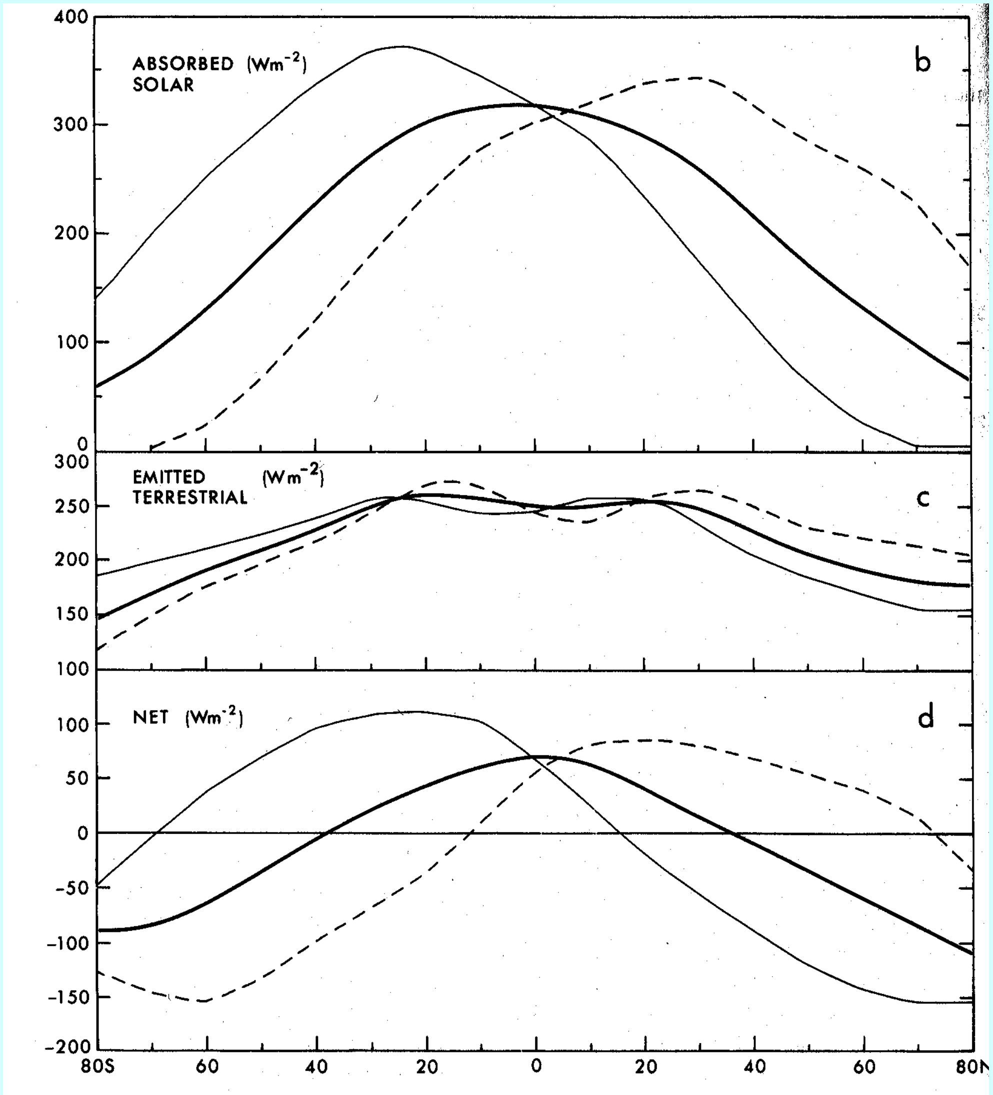
Interaction with interior

What drives the atmospheric circulation?



This is a coupled radiation/hydrodynamics problem!

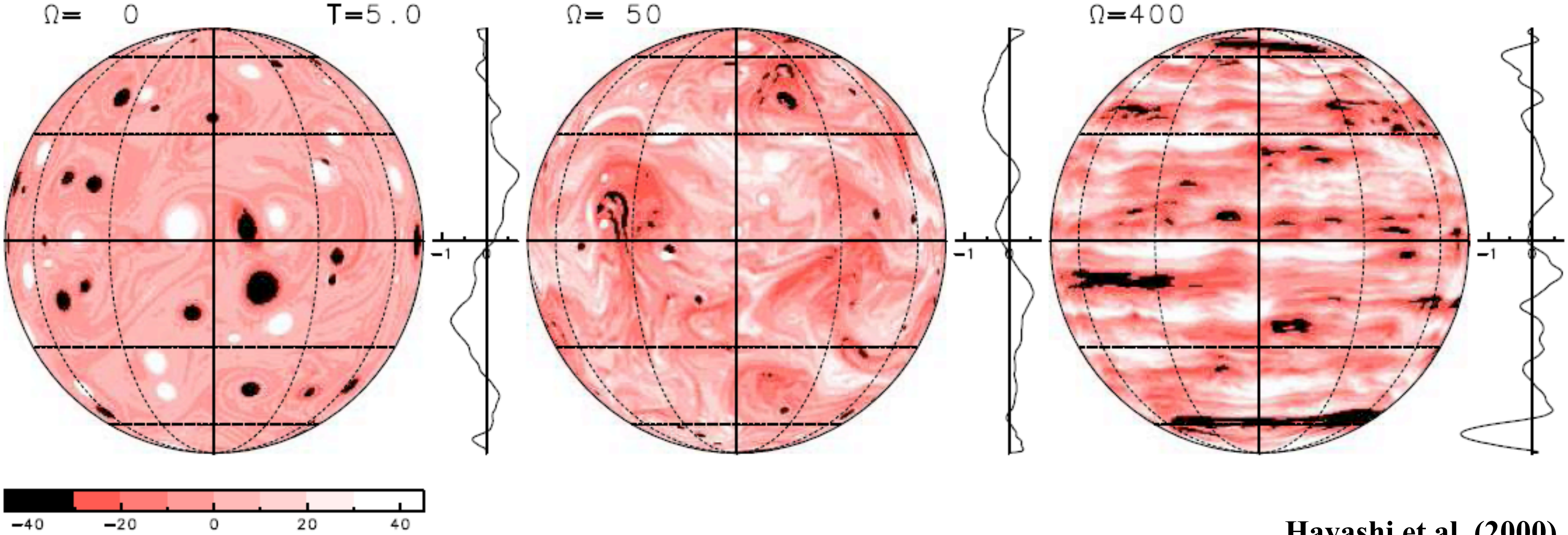
What drives the atmospheric circulation?



Latitude (deg)

Earth -- Peixoto and Oort (1992)

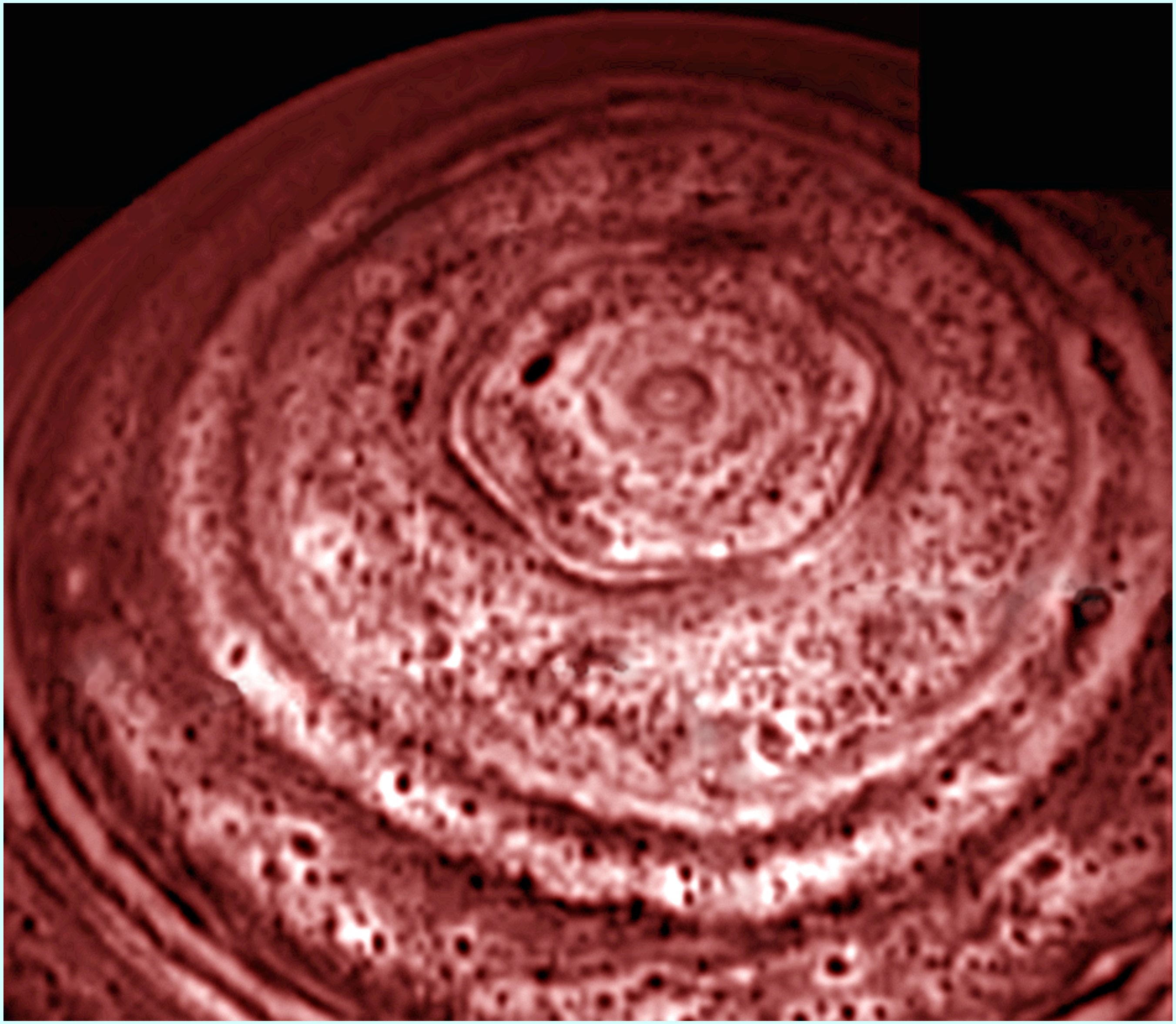
Rotation causes banding (east-west jet streams) in planetary atmospheres



Hayashi et al. (2000)

Even Venus (rotation period 243 Earth days) is banded, suggesting that transition to a banded flow happens at *very low* rotation rates

Most planetary atmospheres should exhibit a banded flow pattern!



Saturn

Temperature contrasts can be understood with timescale arguments

- If $\tau_{rad} << \tau_{advect}$: large temperature contrasts
  $\tau_{rad} >> \tau_{advect}$: temperatures homogenized

- Terrestrial planets fit expectations: longer τ_{rad} leads to smaller ΔT; faster longitudinal advection implies smaller ΔT in longitude than latitude.

	τ_{rad}	$\tau_{advect, lon}$	ΔT_{lon}	$\tau_{advect, lat}$	ΔT_{lat}
Venus	years	Days	< few K	Weeks	few K
Earth	Weeks-months	1 day	~10 K	Weeks	20-30 K
Mars	Days	1 day	~50 K	Weeks	~100 K

- Giant planet interiors: Convective mixing times are short (decades?) but radiative times are geological, so interior entropy is homogenized. On solar system giants, this constant-entropy interior “outcrops” at the photosphere, leading to nearly constant photospheric temperatures.

- Hot Jupiters: homogenized interior is hidden below a deep radiative zone, so large day-night temperature contrasts are possible depending on τ_{rad} and τ_{advect} near the photosphere.

Of course, one must understand something about the dynamics to estimate τ_{advect}!

Atmospheric collapse on synchronously rotating terrestrial planets?

- **Time scales:**

$$\tau_{advect} \approx \frac{a}{U} \qquad\qquad \tau_{rad} \approx \frac{p}{g}\frac{c_p}{4\sigma T^3}$$

- **Large fractional temperature differences should occur when**

$$p \leq \frac{4\sigma T^3 a g}{U c_p}$$

~0.1 bars (for Earth parameters)

These crude arguments are consistent with full GCM simulations (Joshi et al 1997, Joshi 2003)

Purpose of climate models

- **Explain observations of atmospheric circulation and climate**
- **Understand mechanisms by turning various processes on and off to see what minimal set of physics is necessary to explain a given phenomenon**
- **Determine sensitivity of system to changes in parameters**
- **Test hypotheses about how the system works**
- **Make predictions**

Hierarchy of climate models

- **Zero-dimensional energy balance models**

- **1D (latitude-dependent) energy balance models**

- **Models that involve dynamics:**
  - **One-layer models (e.g., barotropic-vorticity equation, shallow-water equations, equivalent-barotropic equations)**
  - **2D models in (say) latitude and height**
  - **3D models with realistic dynamics but simplified “physics”**
  - **3D general circulation models (GCMs)**

A wide range of approaches, from simple to complex, is needed to understand the circulation of any planet

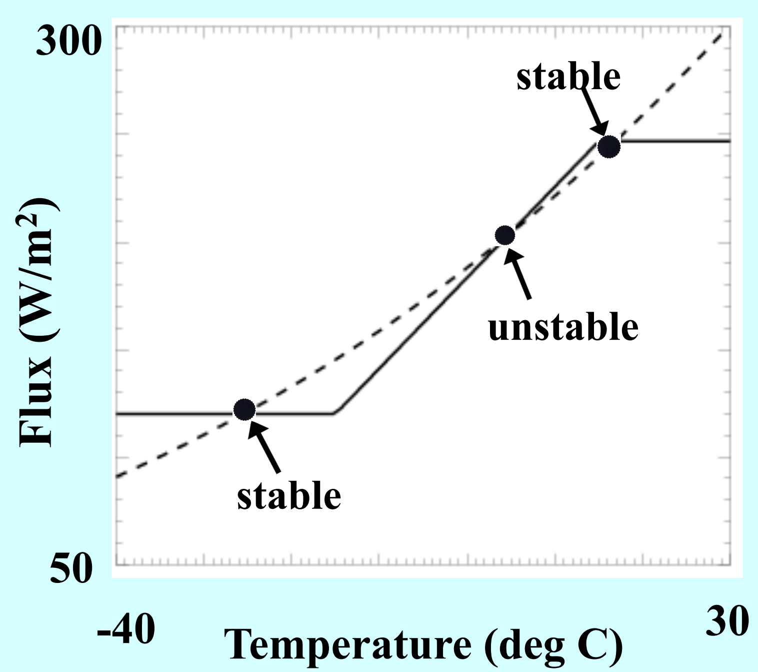
Zero-dimensional energy balance model

- **Equate global-mean absorbed solar and emitted IR fluxes**

$$4\sigma T^4 = (1 - A)F_\Theta$$

where A is albedo and F_Θ is the incident stellar flux (1372 W/m^2 for Earth).

- **If albedo increases with decreasing T in the temperature range where ice forms, this model can describe the ice-albedo feedback**
  - Assume albedo of 0.28 for T > 15 C, 0.65 for T < -15 C, varying linearly in between
  - Let surface T be 33 C greater than T for emission to space to account for greenhouse effect
- **This leads to 2 stable equilibria: one cold and ice-covered, the other hot and ice-free. A third equilibrium is unstable.**



Lesson: Even simple models can inform our understanding of climate equilibria and sensitivity!

One-dimensional energy balance models

- **Solve for surface temperature as a function of latitude, parameterizing latitudinal heat transport as diffusion:**

$$c\frac{\partial T}{\partial t} = \nabla \cdot (cD\nabla T) + S - I$$

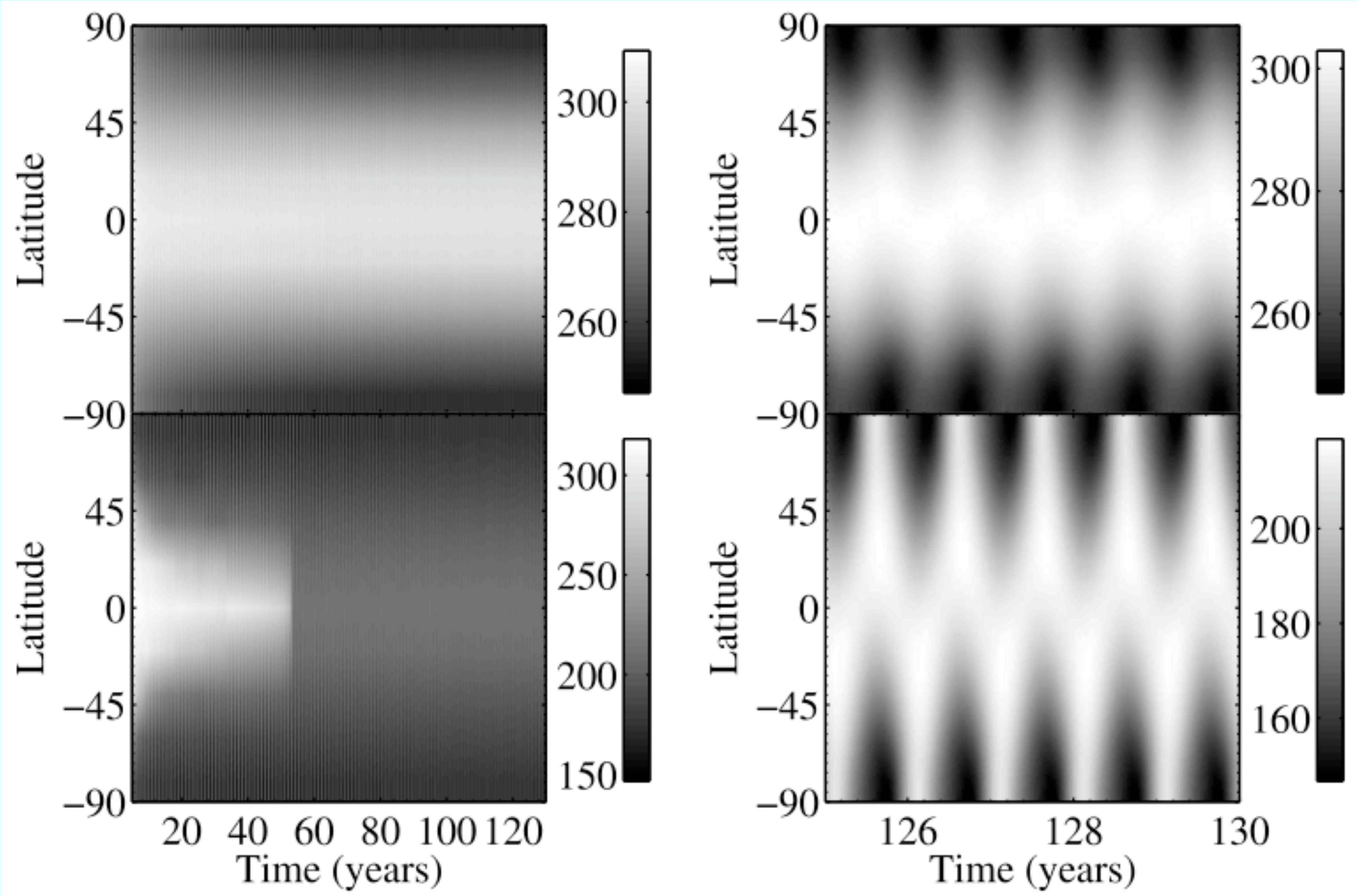
where *D* is diffusivity of heat transport, *c* is heat capacity of atmosphere/ocean system, *S* is absorbed solar flux and *I* is emitted infrared flux

- **Such models show that atmospheric transport becomes important when diffusivity exceeds a critical value (~10^6 m^2/sec for Earth).**

- **They can be used to study how latitudinal heat transport affects climate sensitivity, e.g., the transition to a Snowball-Earth state**

- **Limitation: There exists no robust theory for how *D* should depend on vertical stratification, latitudinal temperature gradient, planetary rotation rate, and other parameters**

Example of 1D energy balance model: sensitivity of climate to Snowball Earth transitions depends on latitudinal heat transport



Spiegel et al. (2008)

- **ddd**

General Circulation Models (GCMs)

- **Solve the 3D dynamical equations, such as the primitive equations:**

$$\frac{d\vec{v}}{dt} = -\nabla_p \Phi - f\vec{k} \times \vec{v} + F_v$$ Horizontal momentum

$$\frac{\partial \Phi}{\partial p} = -\frac{1}{\rho}$$ Hydrostatic balance

$$\nabla \cdot \vec{v} + \frac{\partial \omega}{\partial p} = 0$$ Continuity

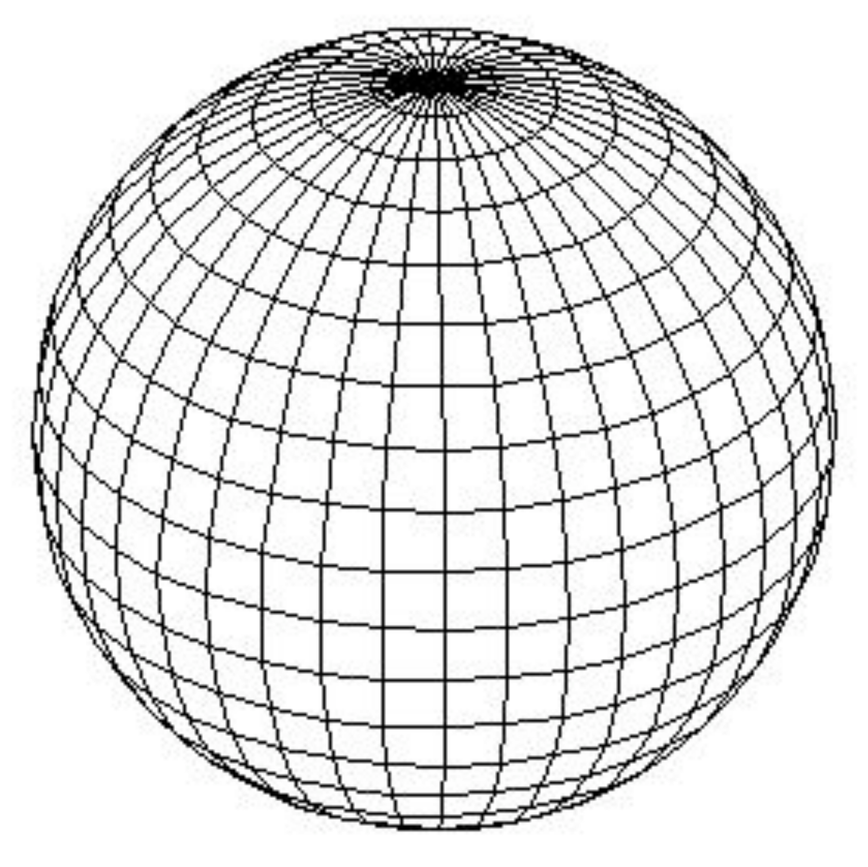
$$\frac{dT}{dt} = \frac{Q}{c_p} + \frac{\omega}{\rho c_p}$$ Thermodynamic energy

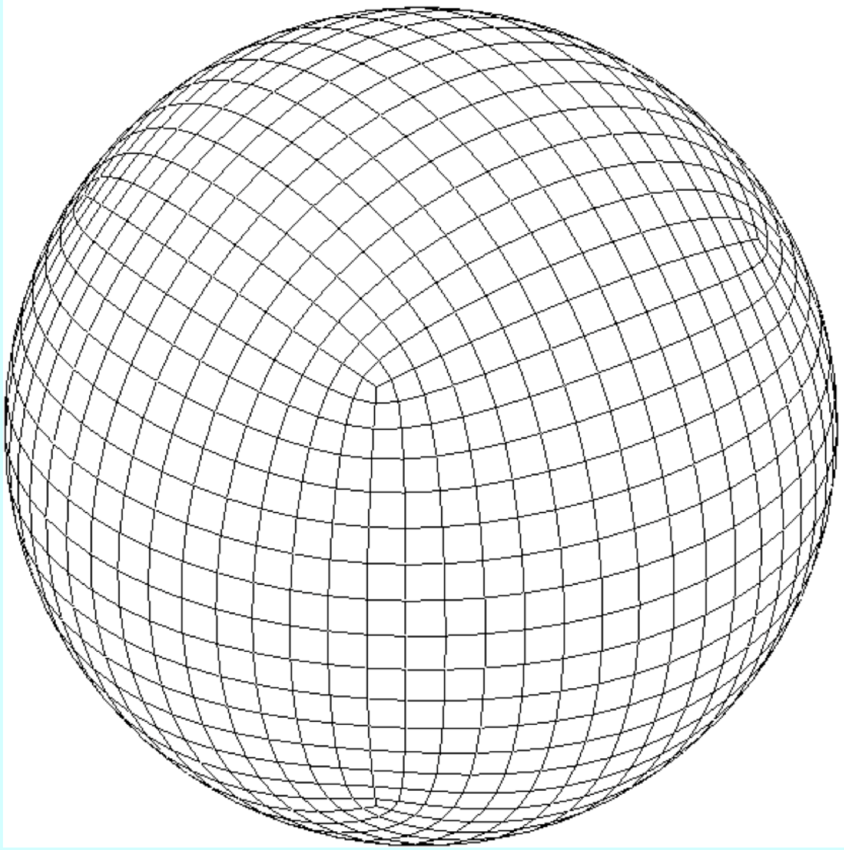
$$p = \rho R T$$ Equation of state (usually ideal gas)

with horizontal velocity $\vec{v}$, gravitational potential Φ (on isobars), temperature T, density ρ, vertical velocity ω, and independent variables longitude, latitude, pressure p, and time t. F_v and Q represent sources/sinks of momentum and thermal energy.

- **Need to select initial and boundary conditions and decide how to represent the source terms F_v and Q**

GCM grids





General Circulation Models

- **"Simplified" GCMs solve the equations with highly idealized representations of radiation, surface drag, etc. In the simplest case:**

$$Q = \frac{T_{eq} - T}{\tau_{rad}}$$ **"Newtonian cooling"**

$$F_v = -\frac{u}{\tau_{\mathrm{drag}}}$$ **"Rayleigh drag"**

- **Full GCMs solve the 3D dynamics with "realistic" representations of**
  - **Radiative transfer**
  - **Clouds**
  - **Transports due to sub-grid-scale turbulence**
  - **Moist convection (thunderstorms)**
  - **Surface/atmosphere interactions, e.g., heat/moisture exchange, formation of surface ice, etc**

- **Excellent for understanding a planet's 3D circulation and testing hypotheses about how the circulation interacts with various processes to determine the climate**

Challenges with GCMs

- **Sensitivity to initial conditions and numerics**
- **Degeneracy: Multiple circulation patterns explaining the observations**
- **Understanding the simulations**
- **Sub-grid-scale parameterizations**

Challenges with GCMs

- **Spin-up: Getting simulations to reach a statistical steady state is a major challenge for planets with massive atmospheres and/or low heat fluxes.**
  - **Characteristic spin-up time for an atmosphere of wind speed *u*, pressure *p*, and heat flux *F* that transfers a fraction *ε* of its heat flux into kinetic energy:**

$$\tau_{spinup} \approx \frac{u^2 p}{2\varepsilon F g}$$

  - **For *ε*~0.01 this yields**

~10 days	**Earth atmosphere**
~3 years	**Venus**
~10 years	**Jupiter (down to 10 bars)**
~10^6 years	**Jupiter (down to 1 Mbar)**

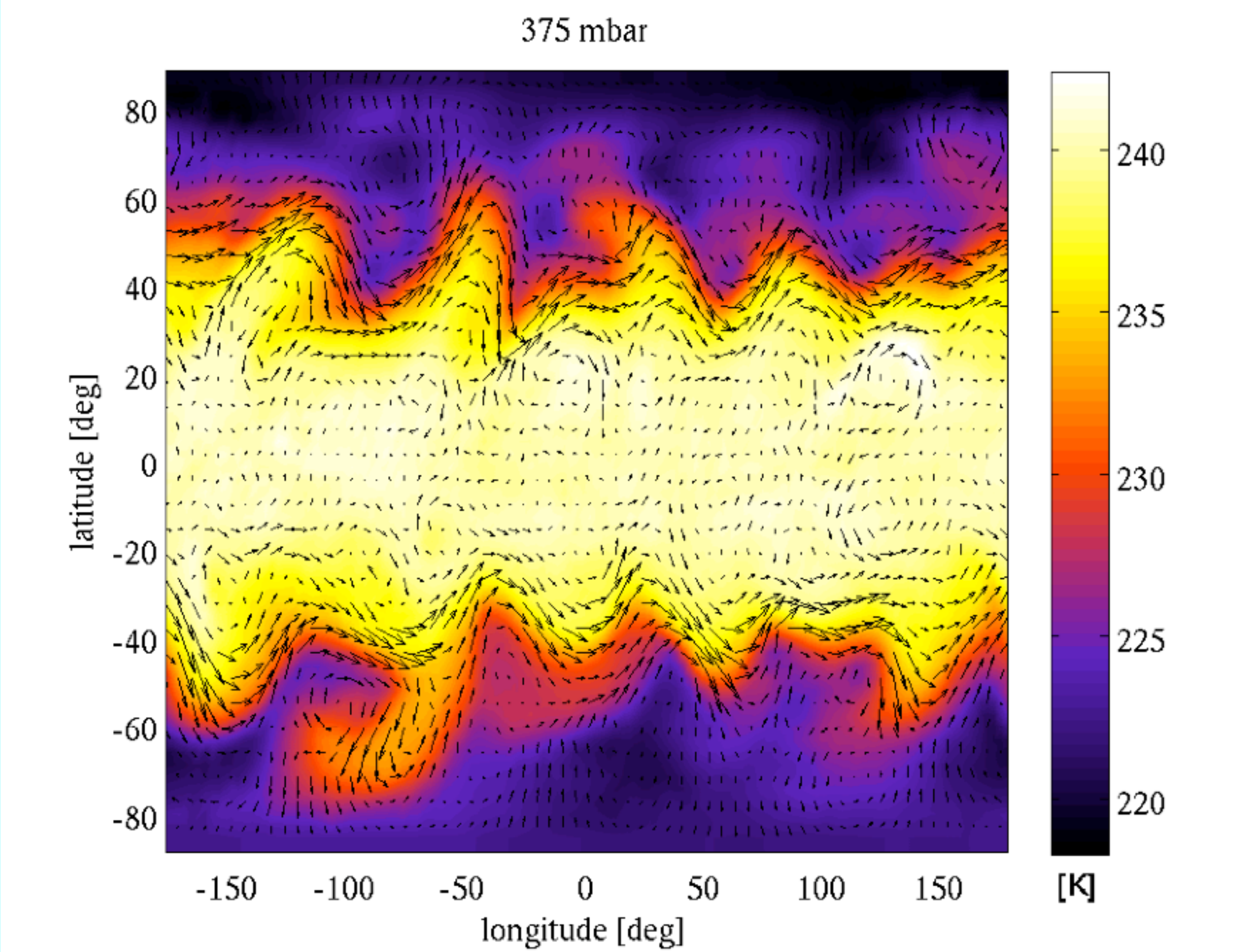
These are lower limits! Angular momentum equilibration time scales can be longer, and one may have to integrate 10 times longer yet to ensure equilibration.

But GCMs can generally only integrate for years to centuries!

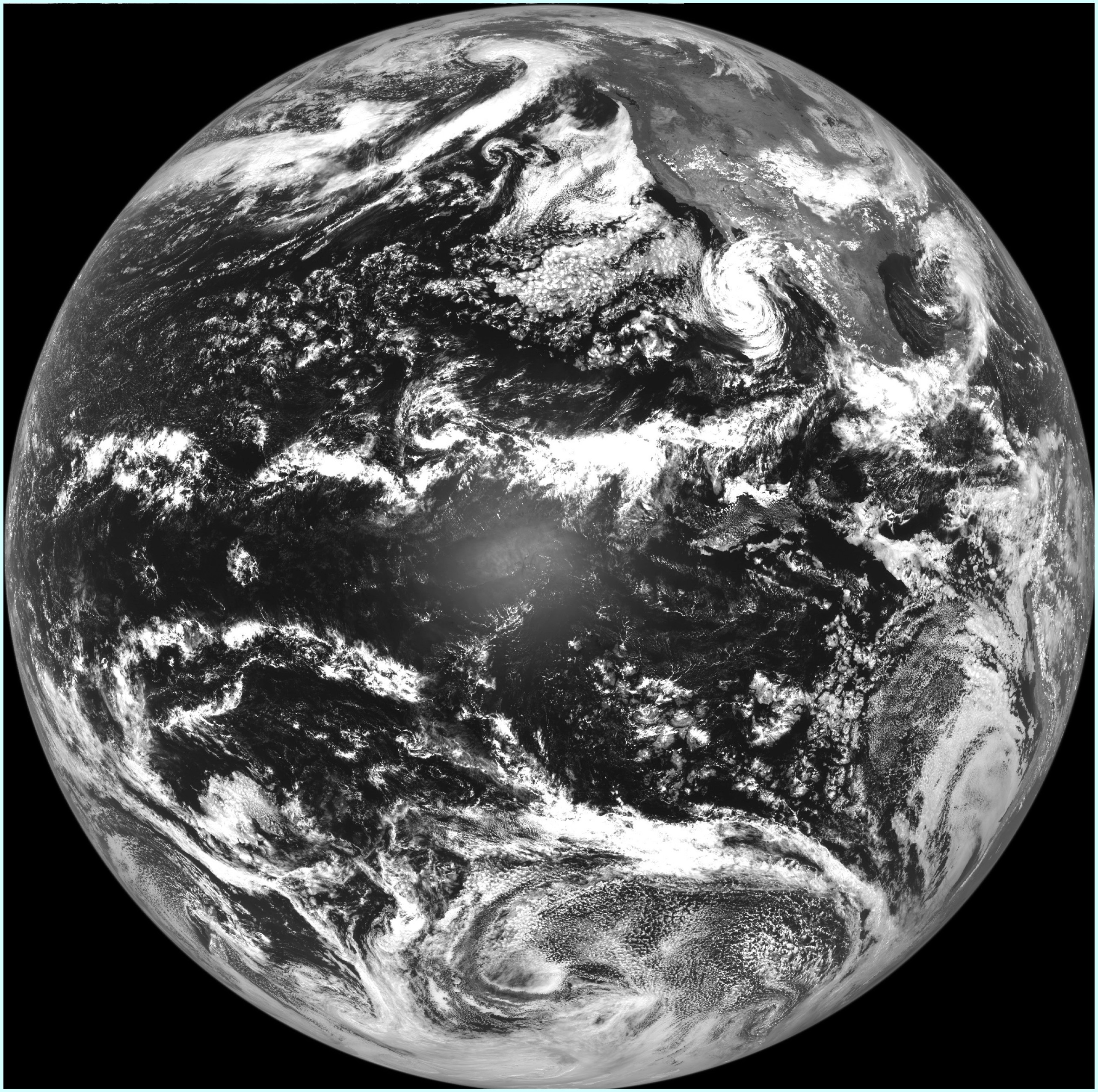
Some publicly available GCMs:

- **Community Climate System Model (CCSM), including the Community Atmosphere Model (CAM), supported at NCAR: http://www.ccsm.ucar.edu/ and http://www.ccsm.ucar.edu/models/atm-cam/**
- **Flexible Modeling System (FMS), supported at NOAA's Geophysical Fluid Dynamics Lab (GFDL) located at Princeton: http://www.gfdl.noaa.gov/fms**
- **Built on Beowulf (BOB) dynamical core: http://www.cisl.ucar.edu/css/compsci/dynamical_cores/**
- **MITgcm, supported at MIT: http://mitgcm.org**
- **University of Reading Intermediate General Circulation Model (IGCM): http://www.met.rdg.ac.uk/~mike/dyn_models/igcm/**
- **NASA Goddard Institute for Space Studies (GISS) GCM: http://www.giss.nasa.gov/tools/modelE/**
- **Max Planck Institute's atmosphere model ECHAM: http://www.mpimet.mpg.de/en/wissenschaft/modelle/model-distribution/available-models.html**
- **Explicit Planetary Isentropic Coordinate (EPIC) Model, supported at Univ. Louisville, available via http://louisville.edu/cpl/ and the NASA PDS node http://atmos.nmsu.edu/data_and_services/software/ software.htm**
- **Institute Pierre Simon Laplace (IPSL) GCM: http://igcmg.ipsl.jussieu.fr/**

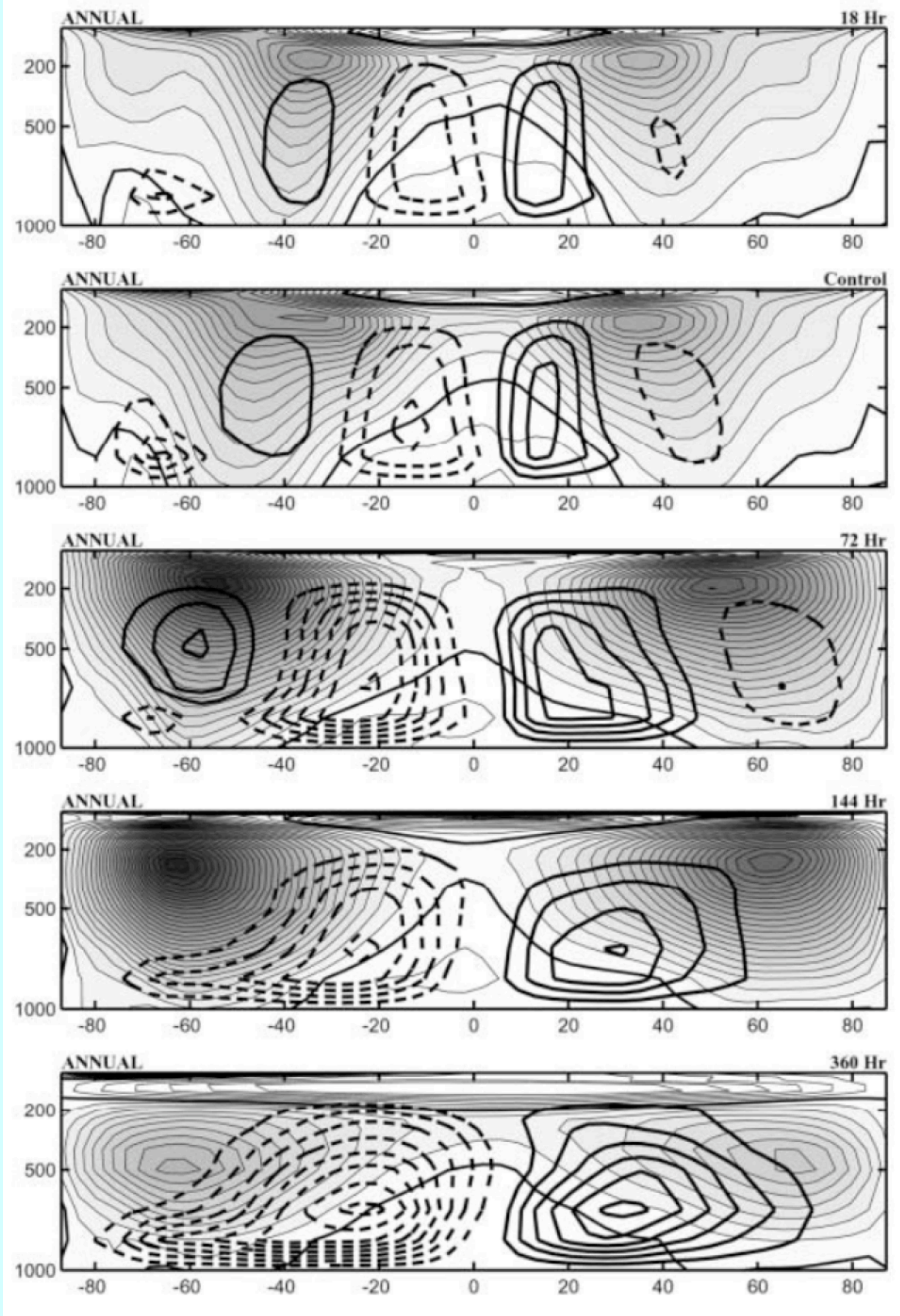
Earth tropospheric circulation – simplified GCM



Courtesy Nikole Lewis

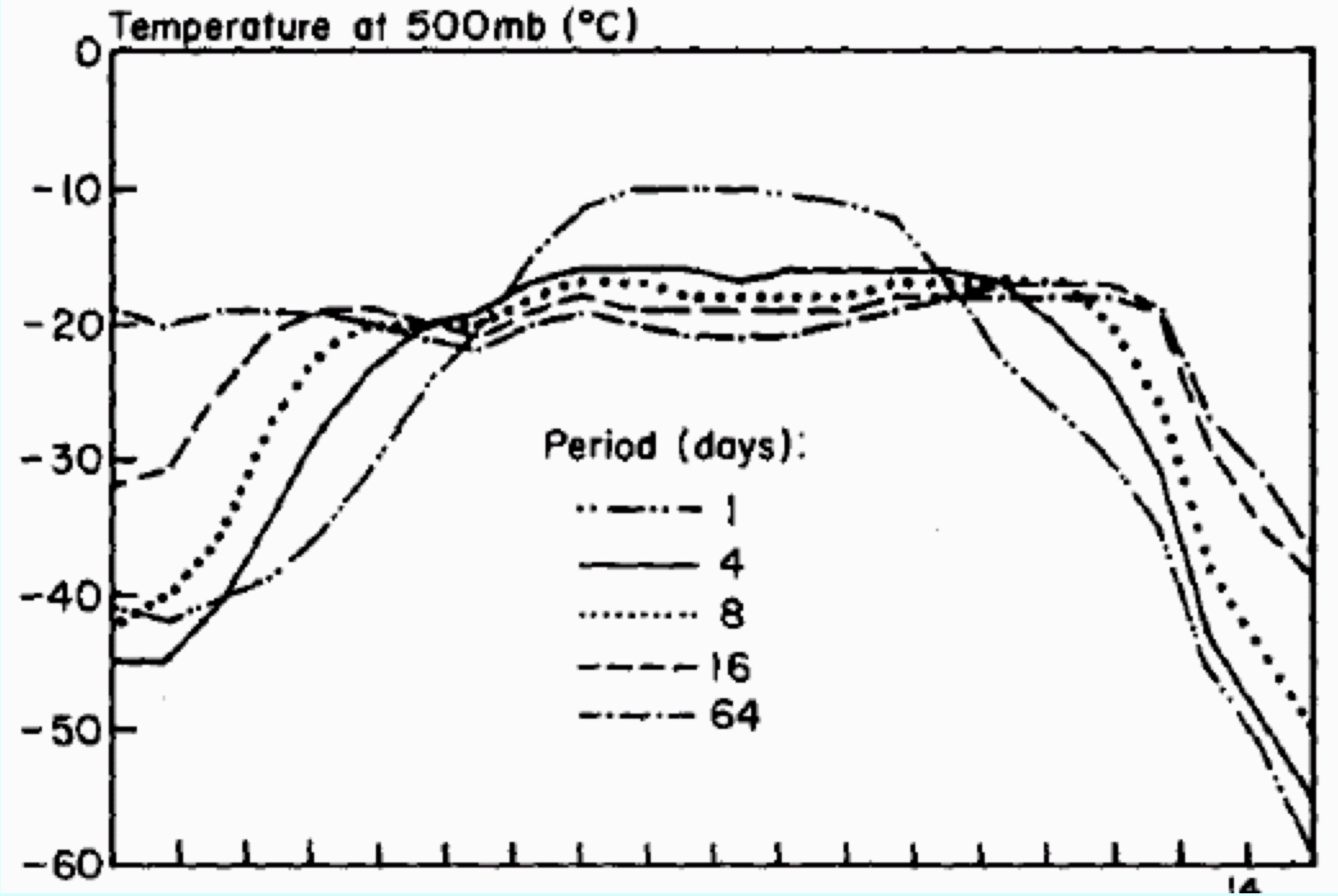


Increasing rotation period



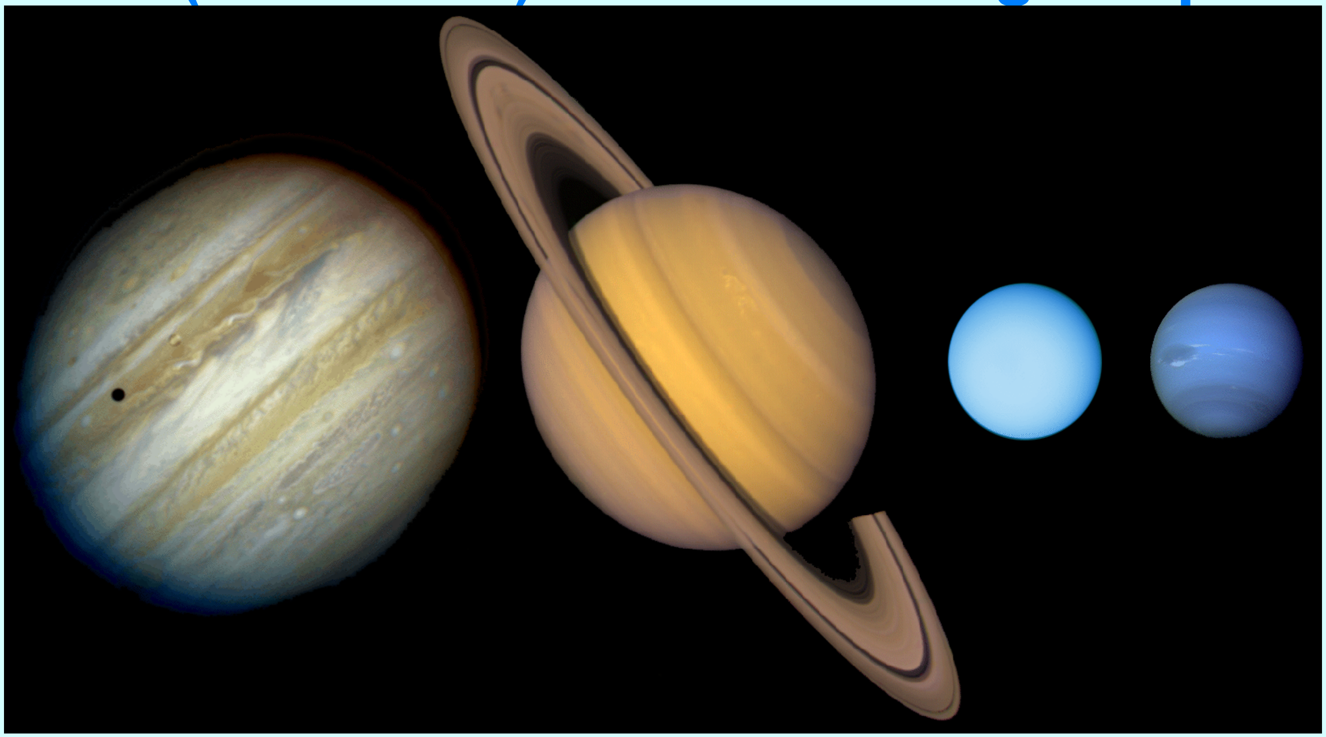
Latitude (deg)

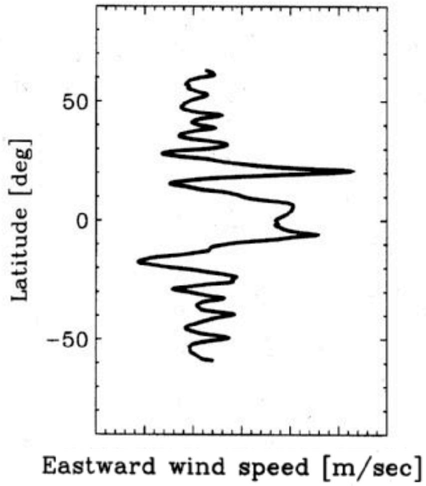
Navarra & Bocaletti (2002)

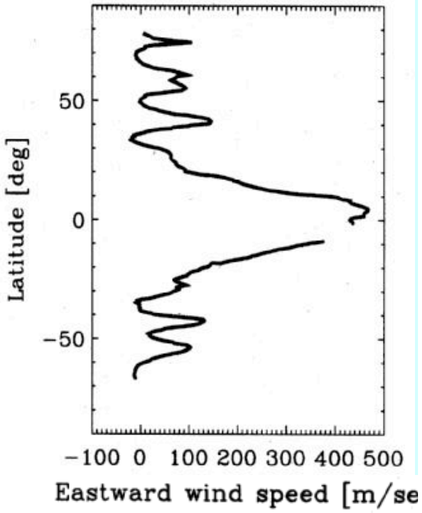


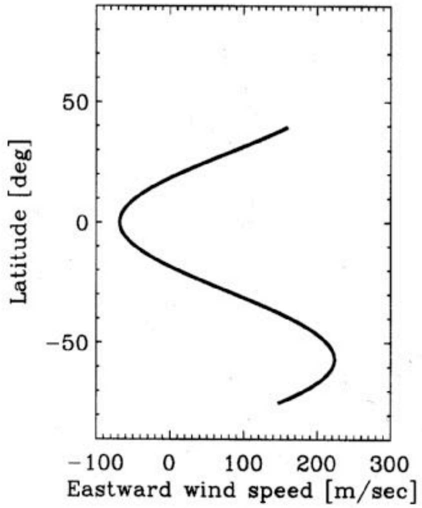
Del Genio & Suozzo (1987)

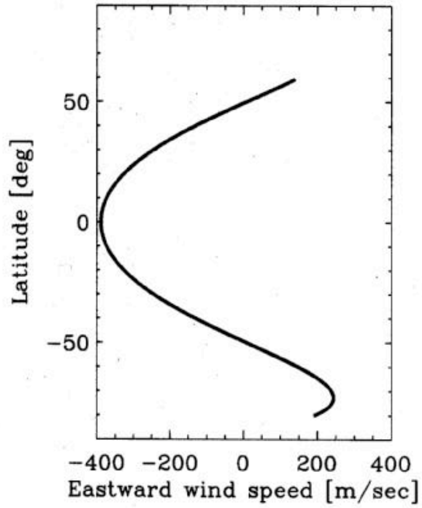
Zonal (east-west) winds on the giant planets







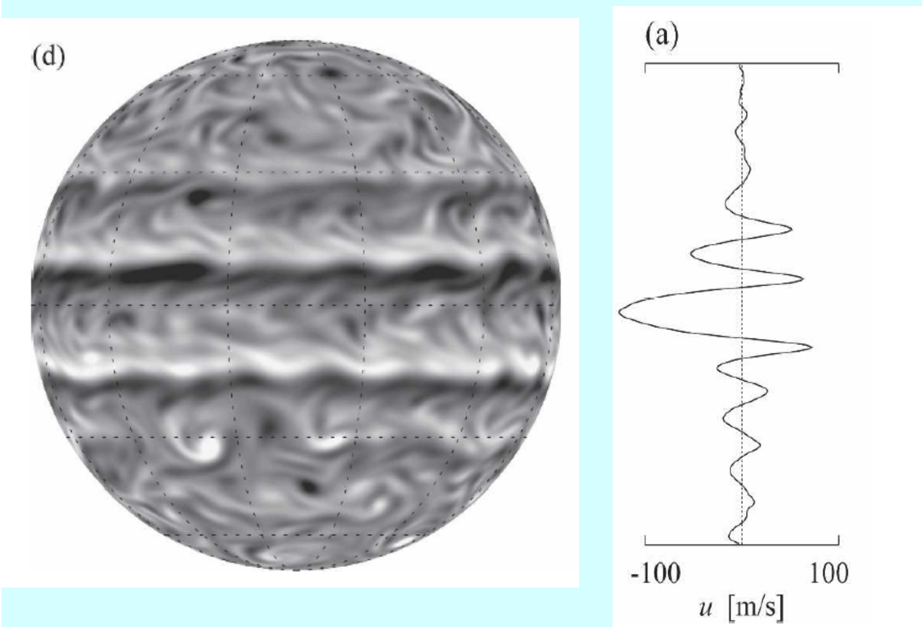


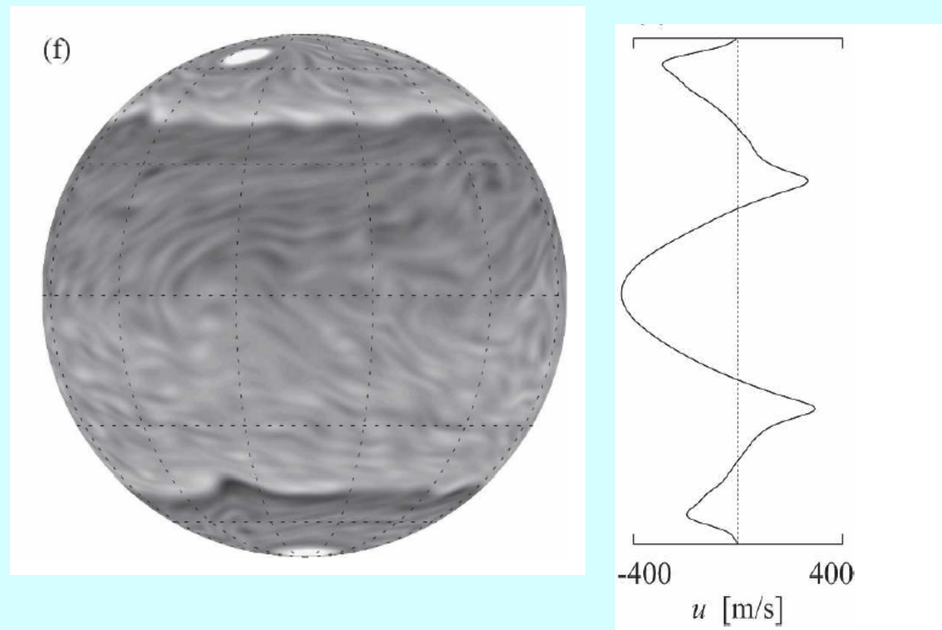


One-layer shallow-water models of the giant planets

Jupiter

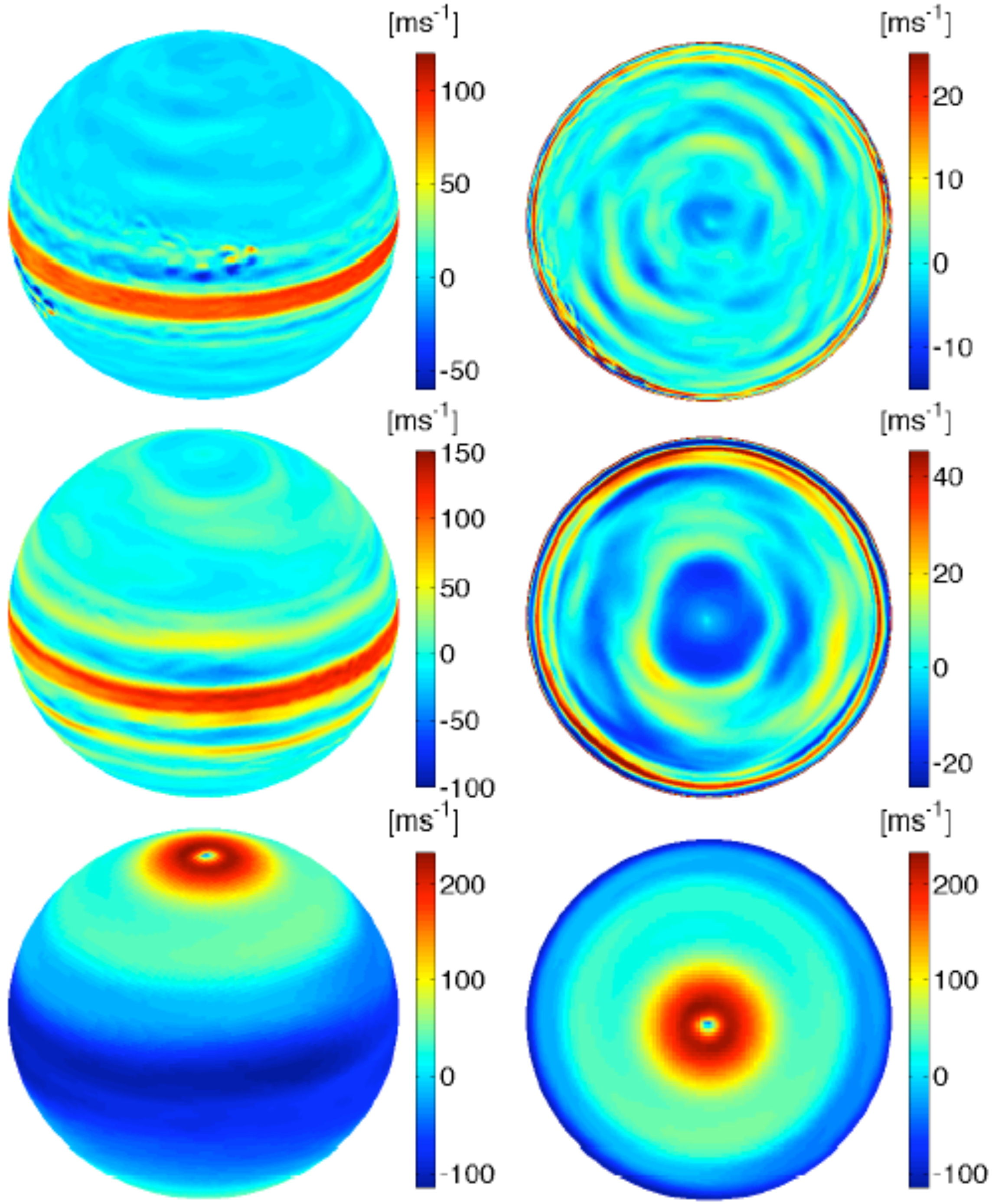
Uranus/Neptune





Scott & Polvani (2007); see also Showman (2007) and Cho & Polvani (1996)

Lian & Showman (2009)



Jupiter

Saturn

Uranus/Neptune

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**

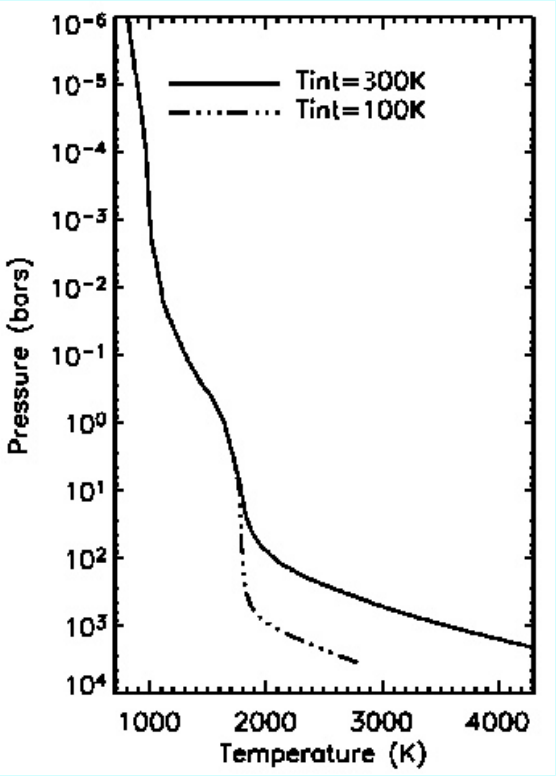
- **Rotation expected to be synchronous with the 1-10 day orbital periods; Coriolis forces important but not dominant**

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

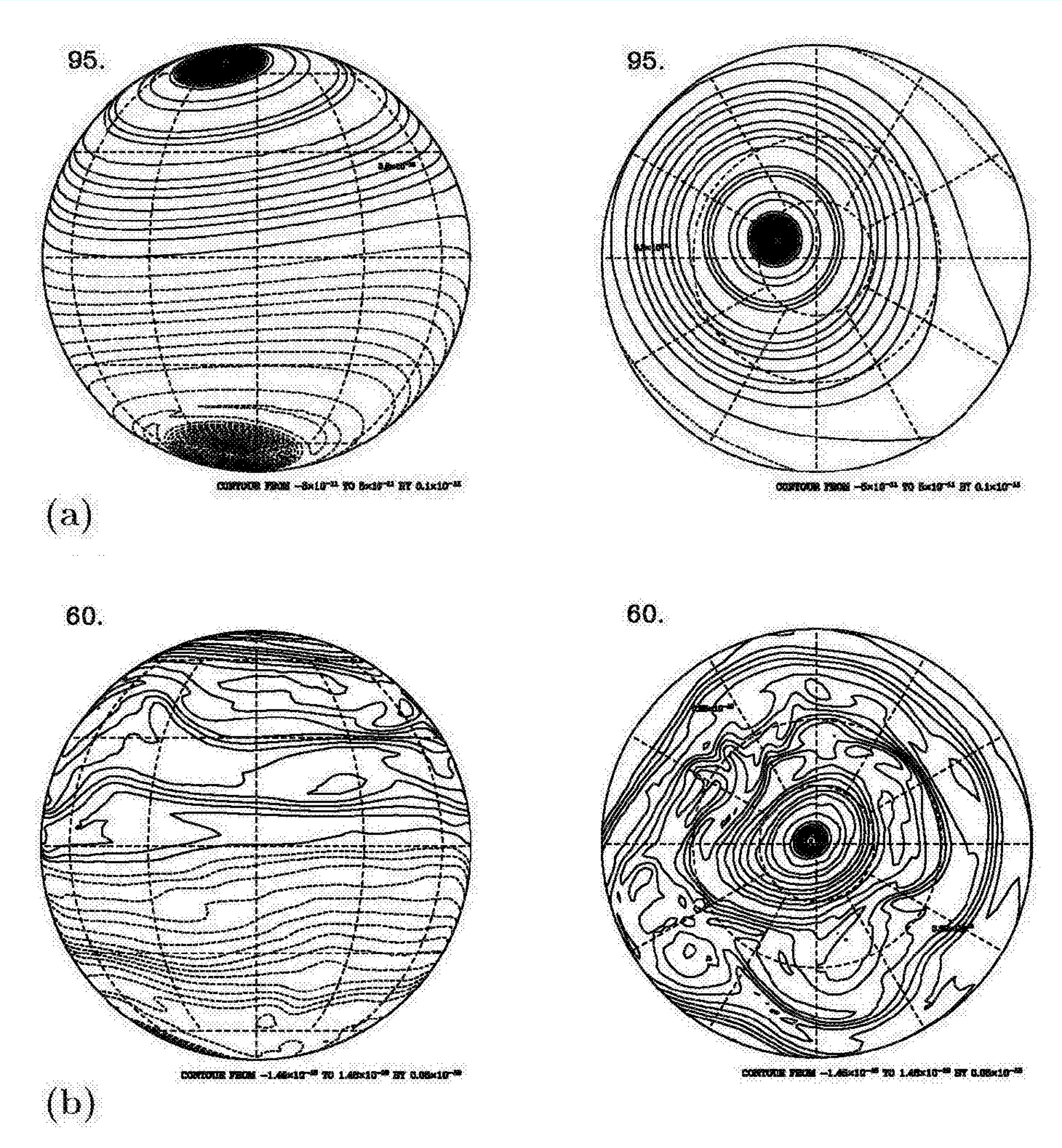
- **For km/sec winds,**

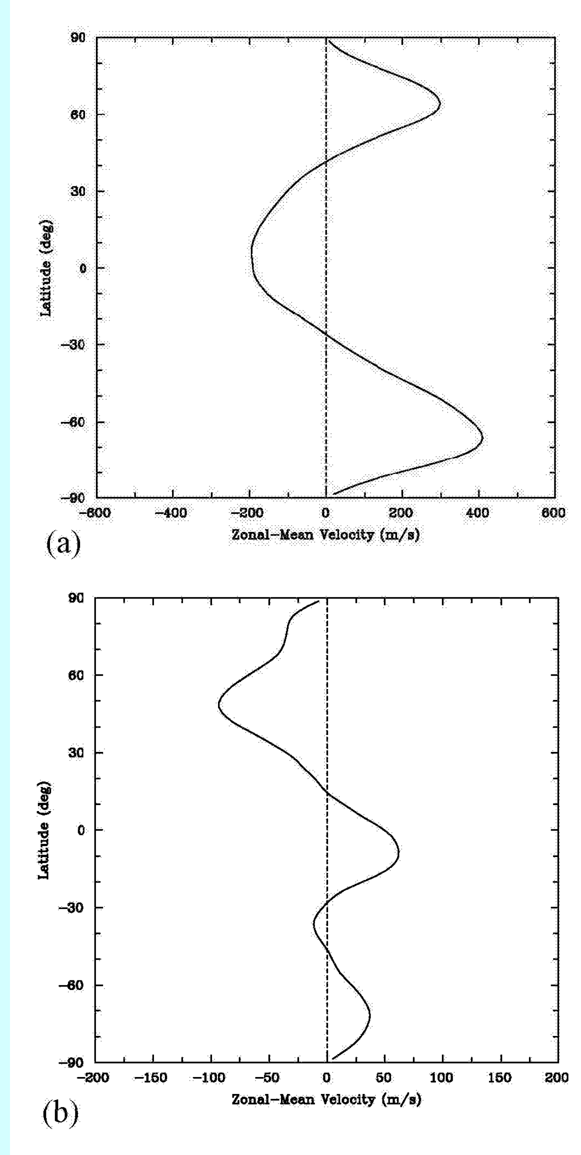
  $\tau_{rad} \ll \tau_{advect}$ for $p < 1$ bar; large temperature contrasts

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

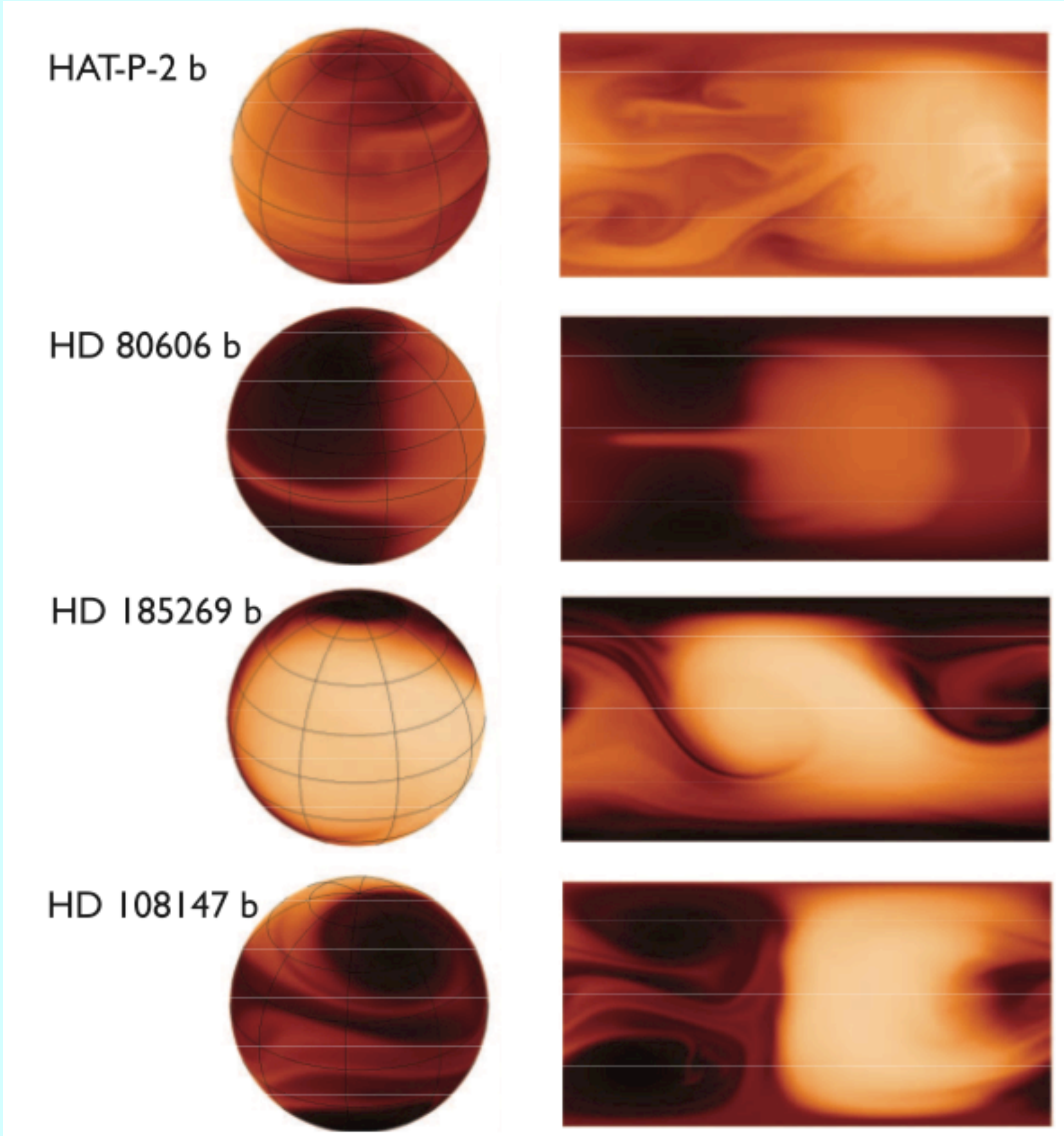


Iro et al. (2005)

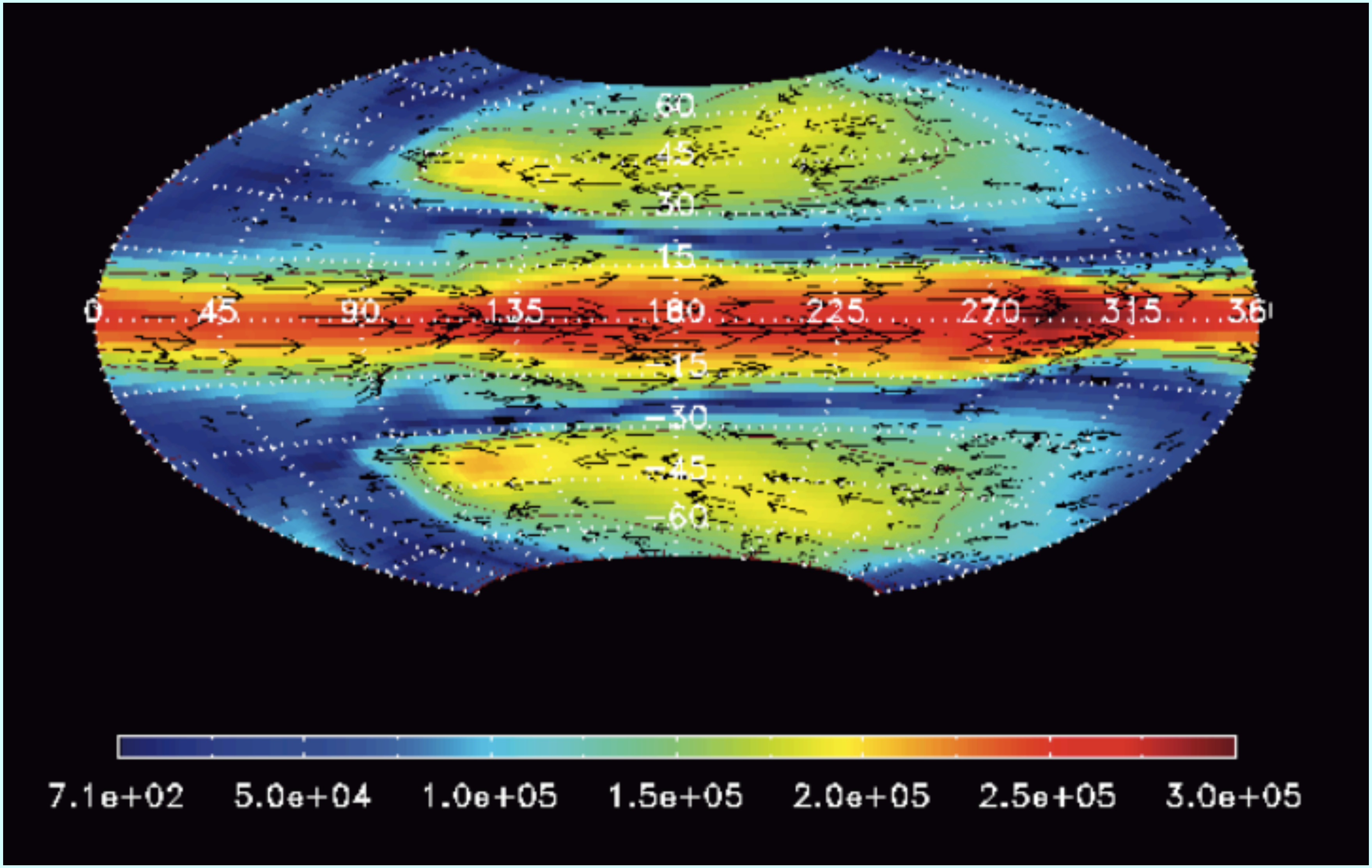




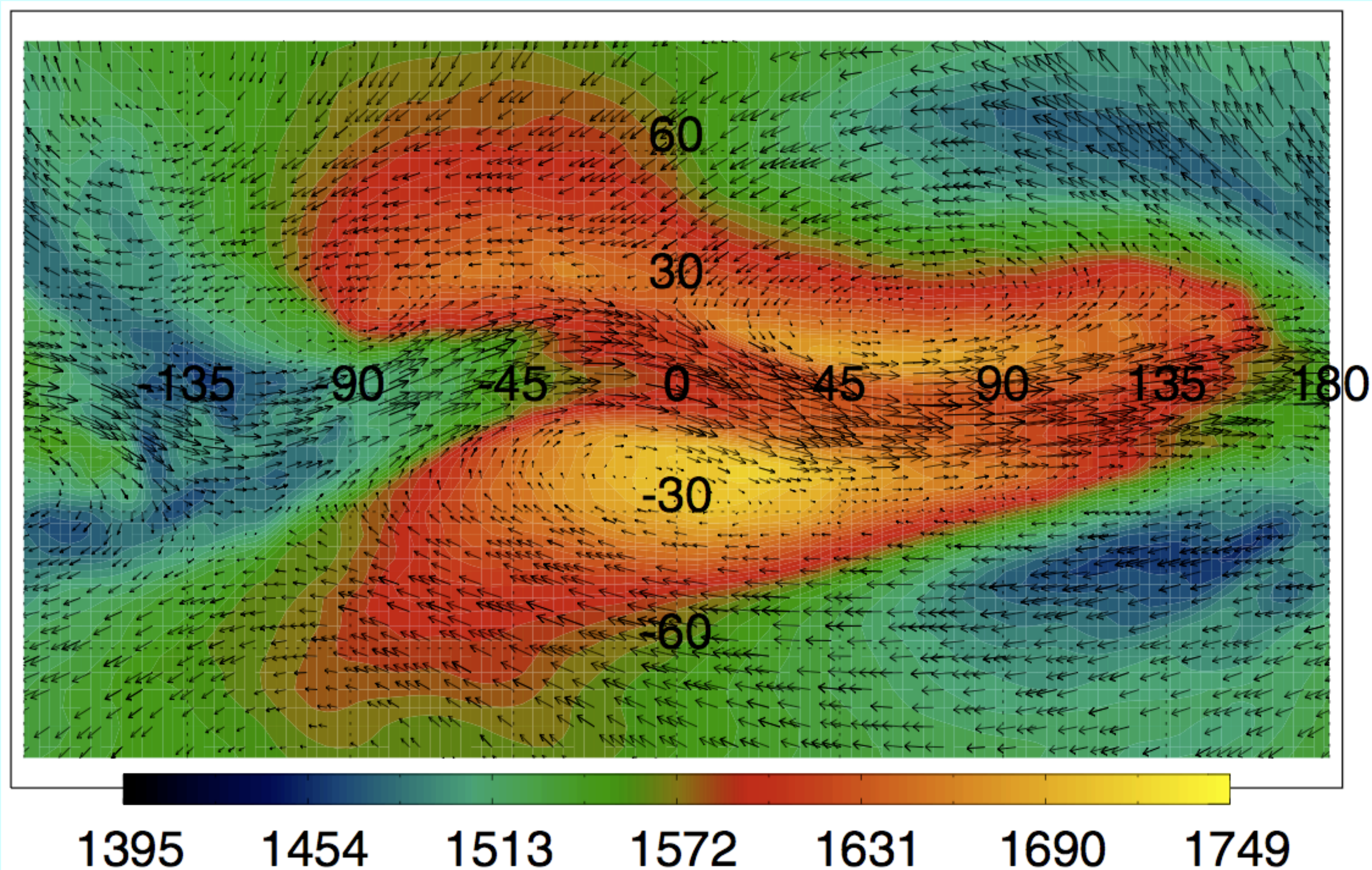
Hot Jupiters -- Cho et al. (2008)



Langton and Laughlin (2008)

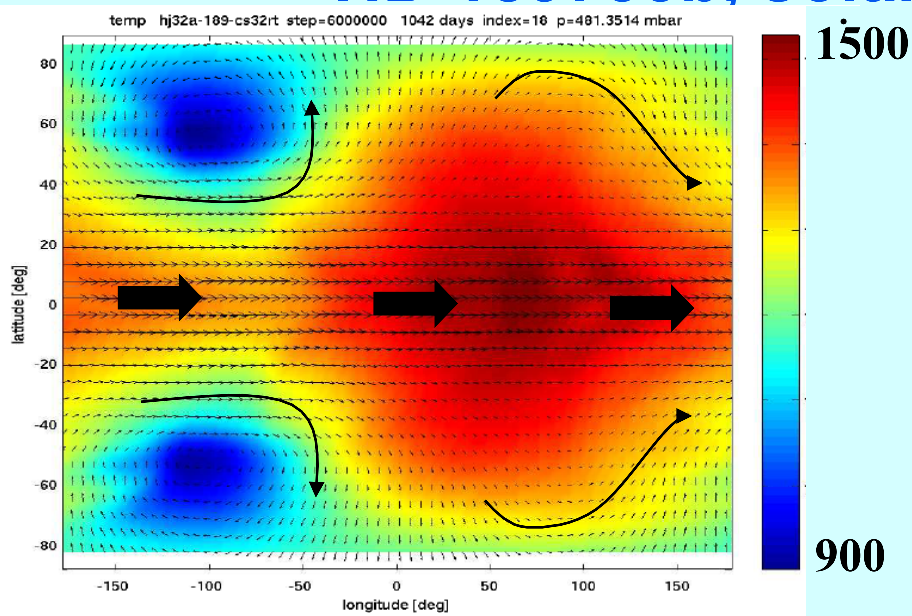


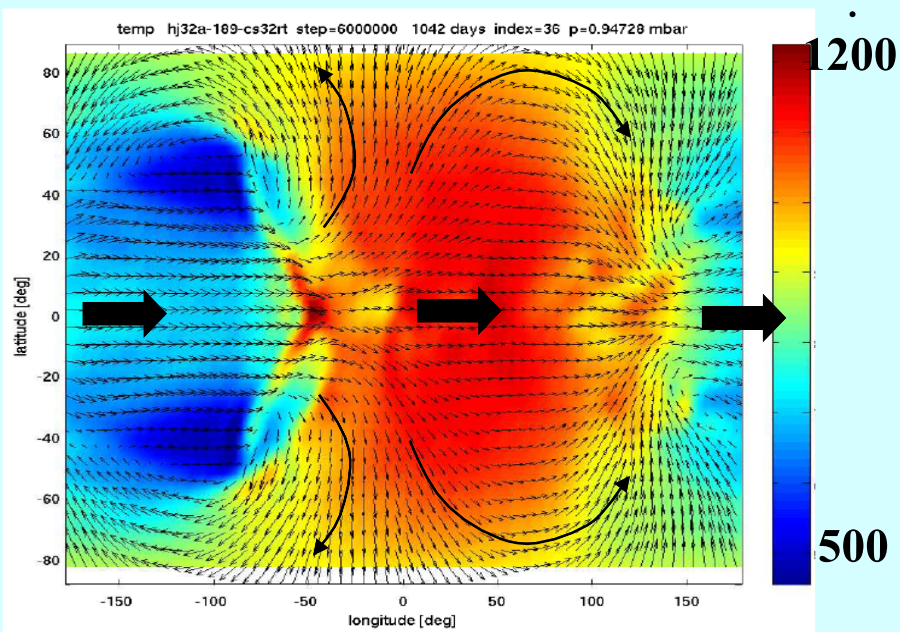
Dobbs-Dixon and Lin (2008)

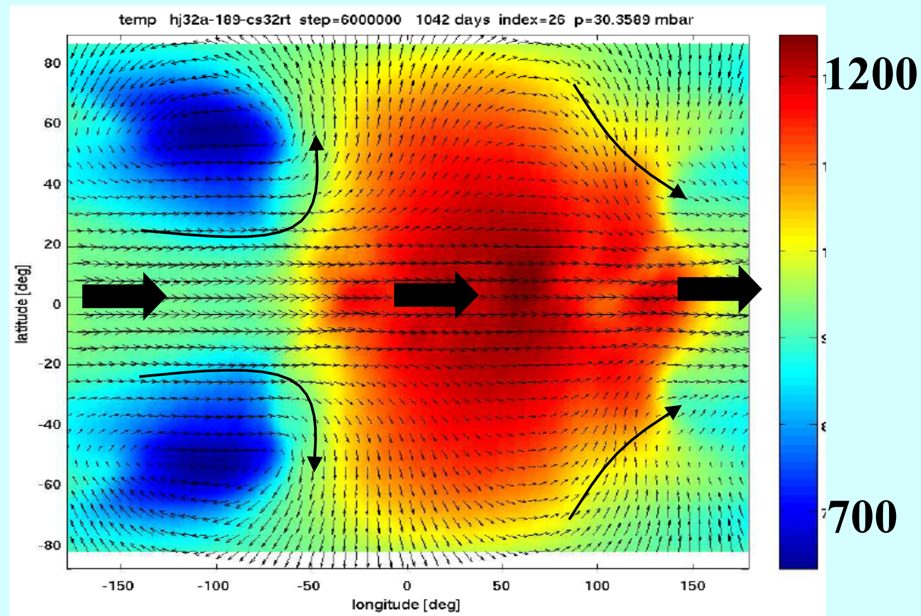


Menou & Rauscher (2008)

HD 189733b, solar, without TiO/VO

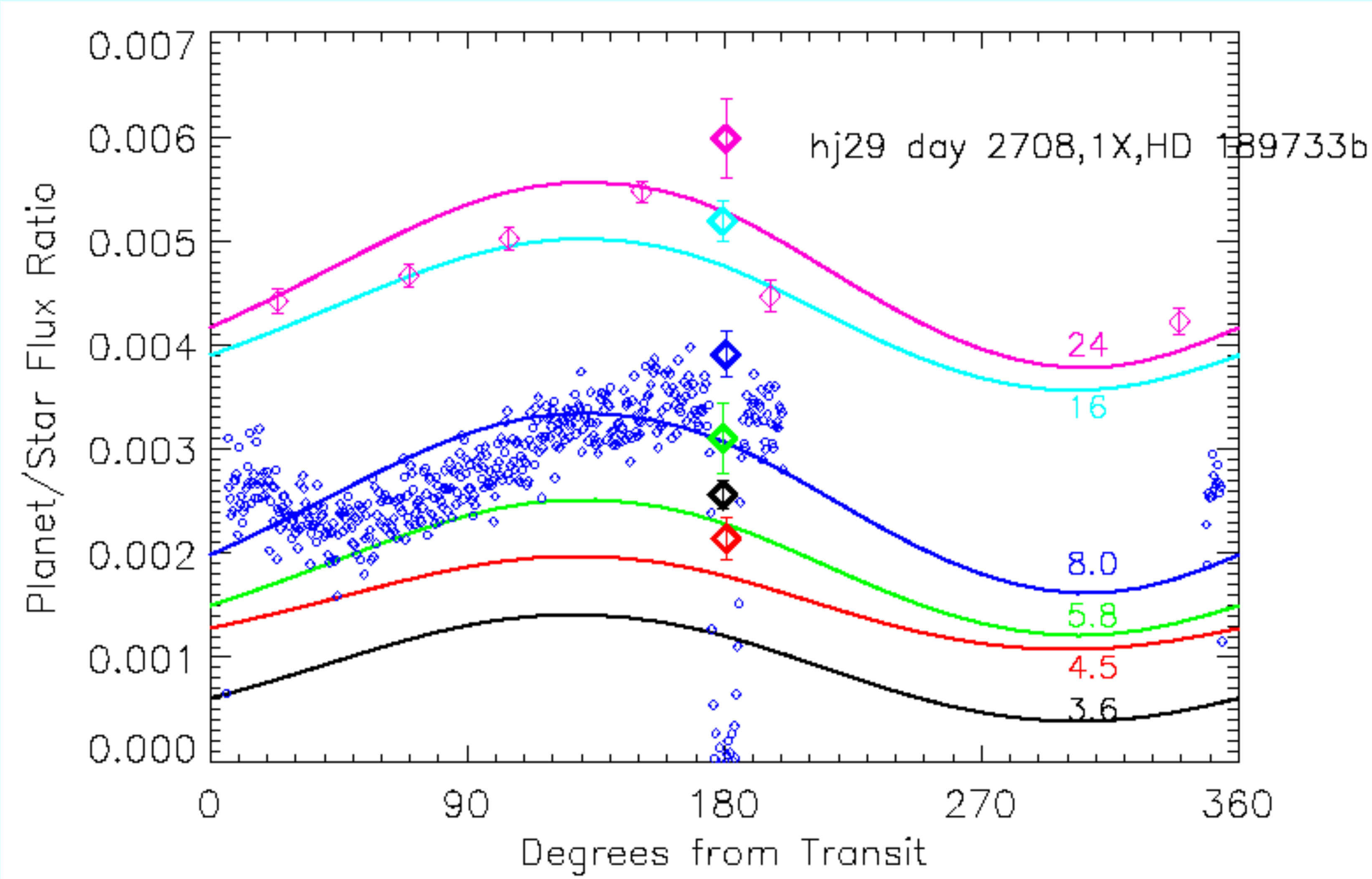






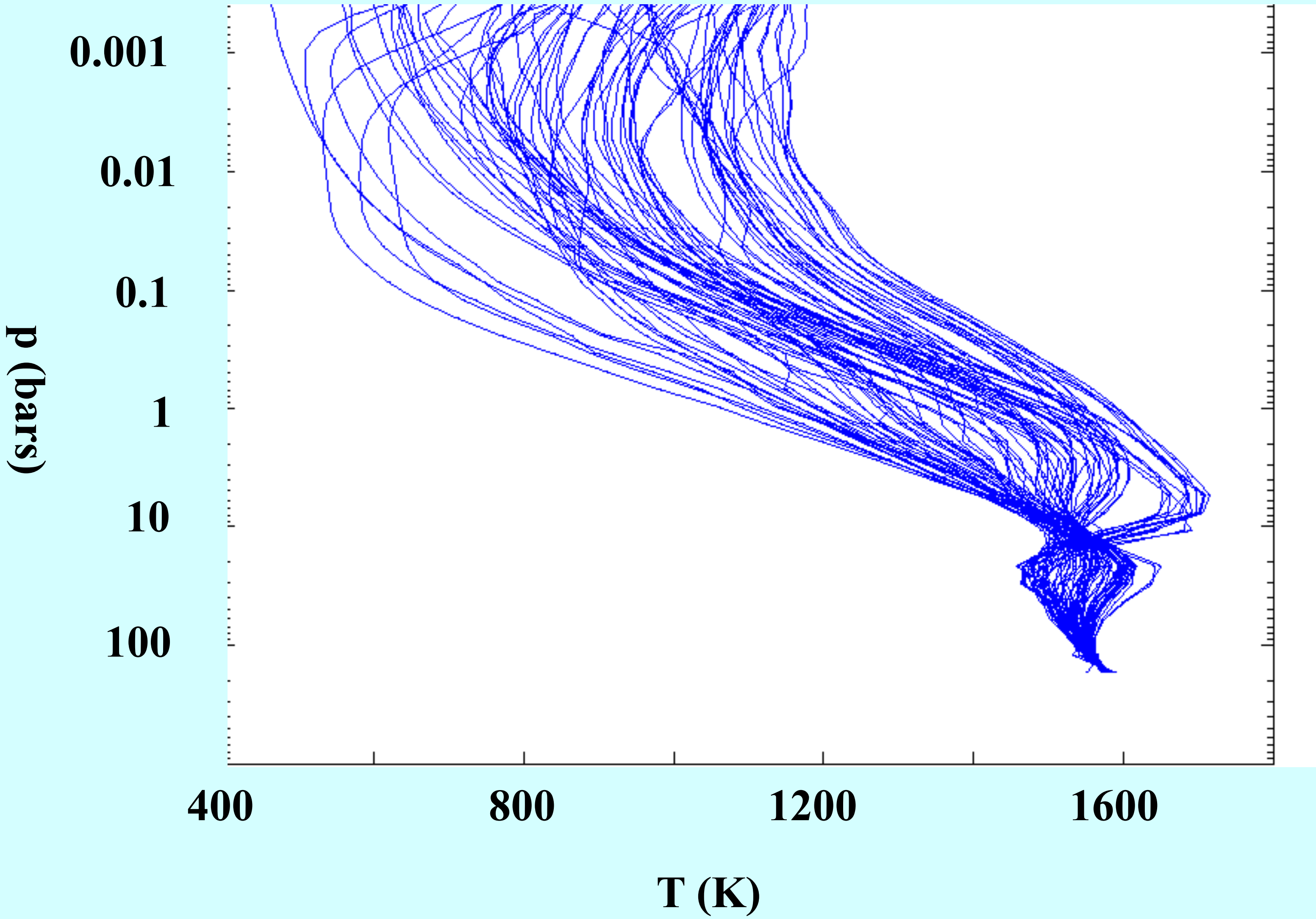
Showman et al. (2009)

Lightcurves: HD 189733b, solar



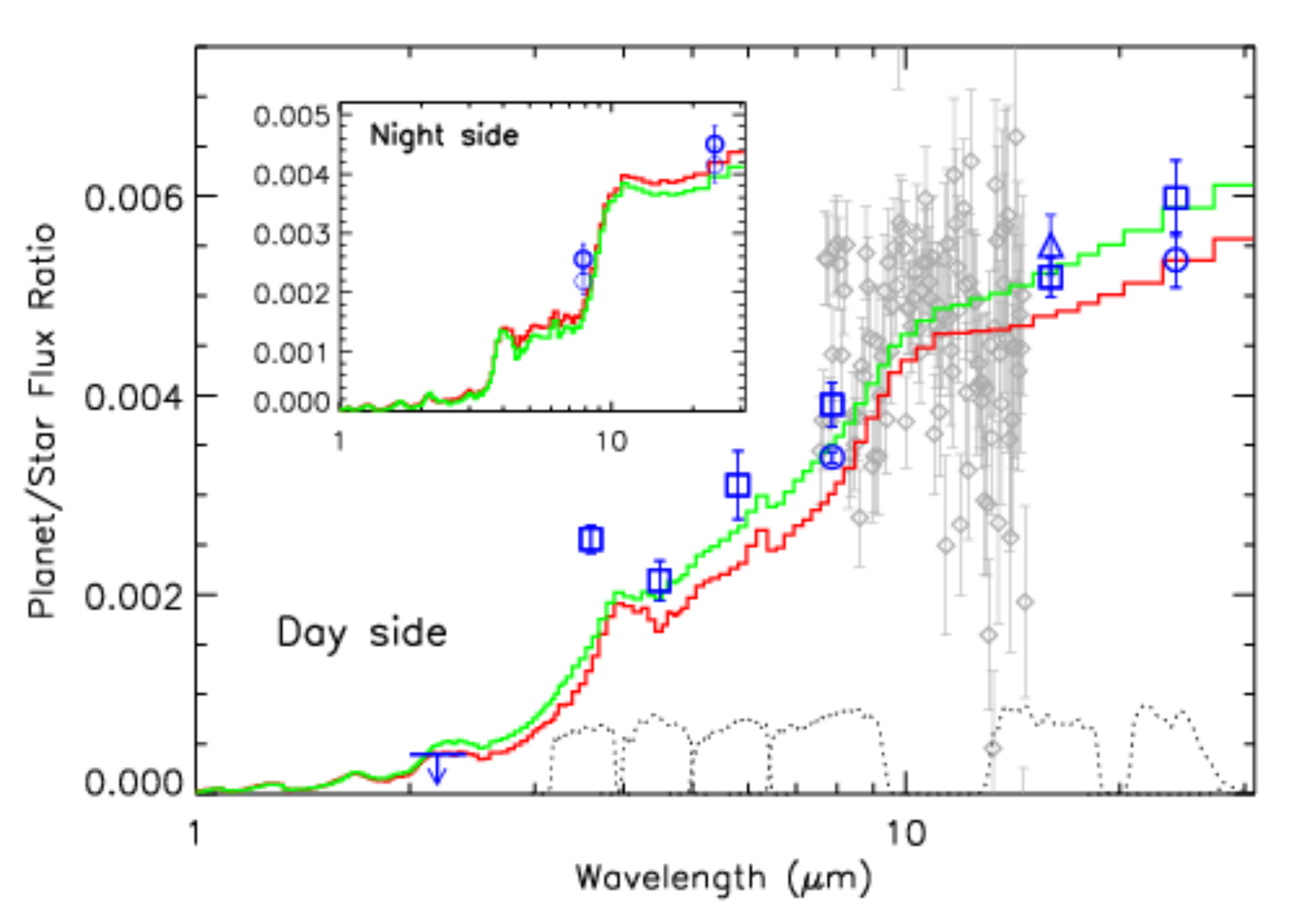
Showman et al. (2009)

Temperature profiles: HD 189733b



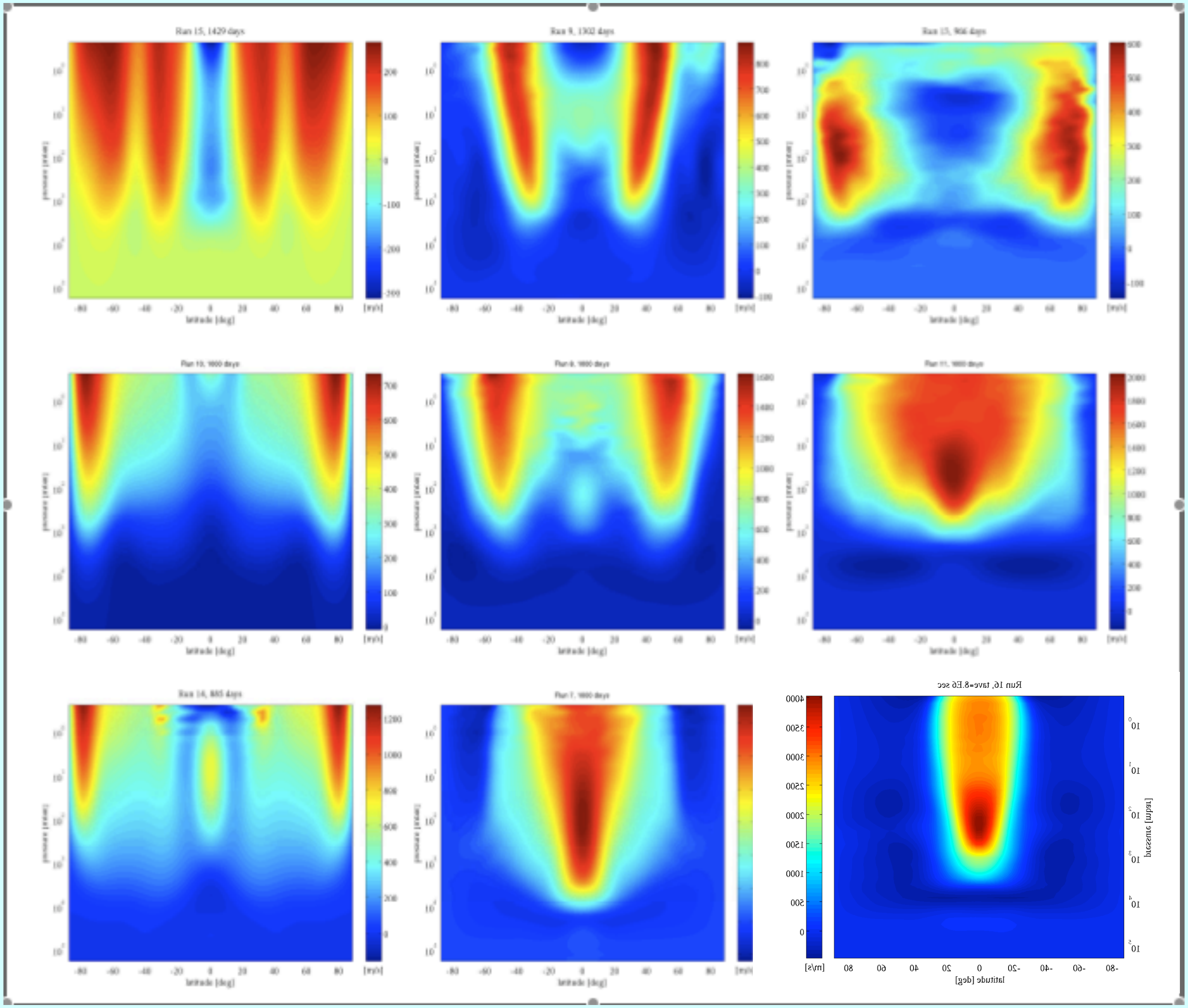
Showman et al. (2009)

Secondary eclipse spectra: HD 189733b



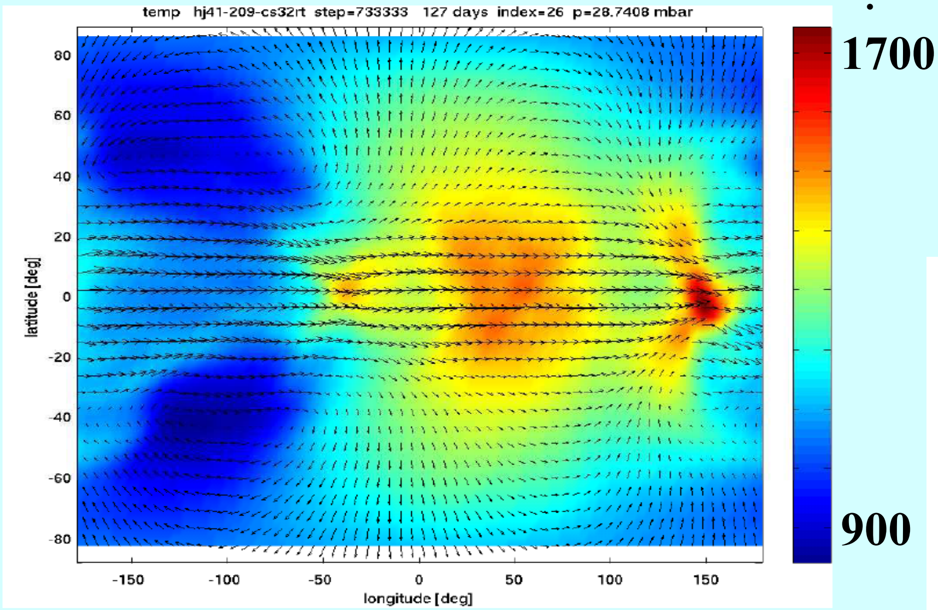
Showman et al. (2009)

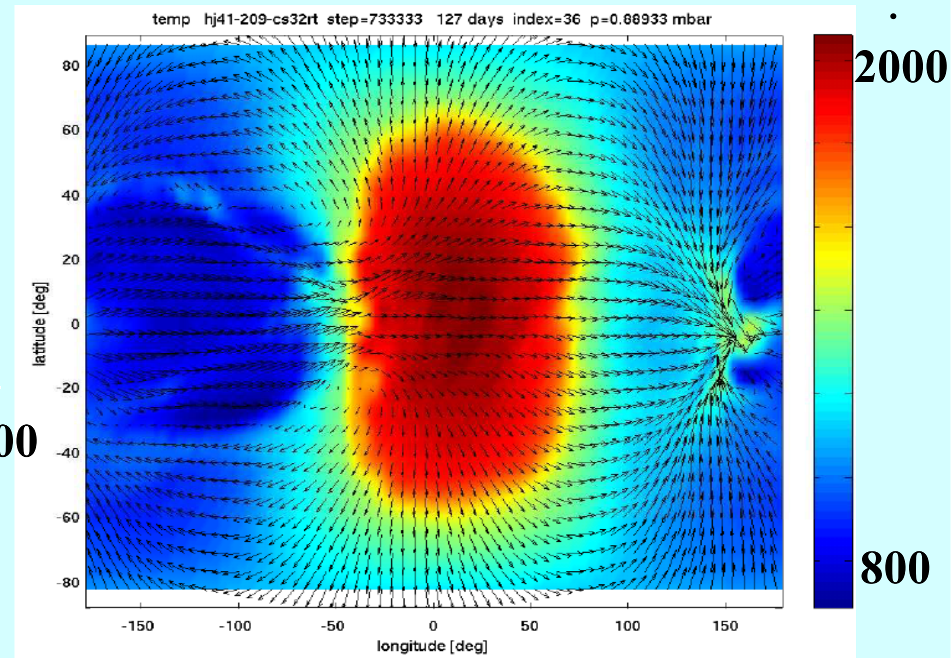
Dependence of wind pattern on rotation rate and distance from star

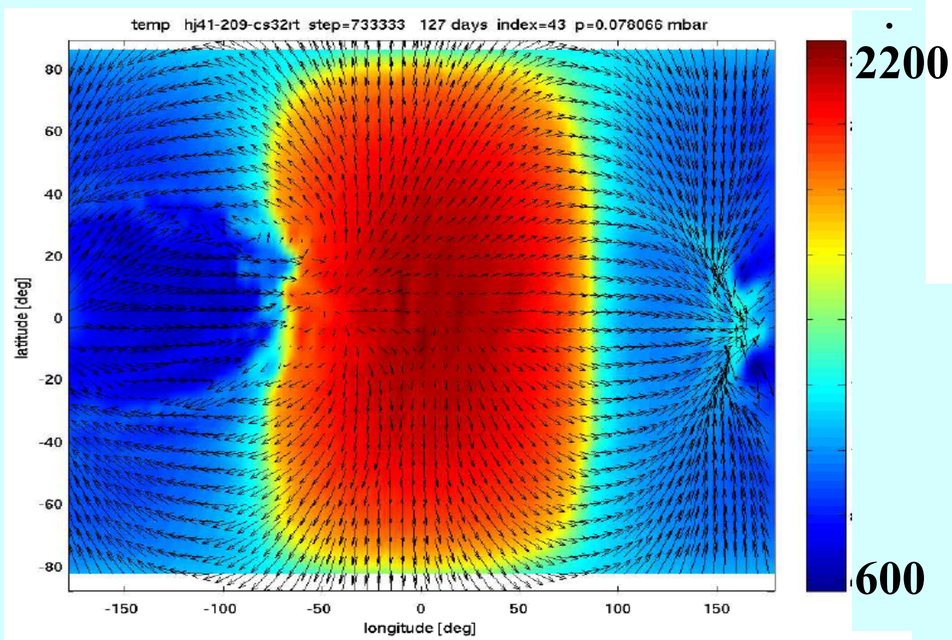


N. Lewis

Development of a stratosphere: HD 209458b with TiO/VO

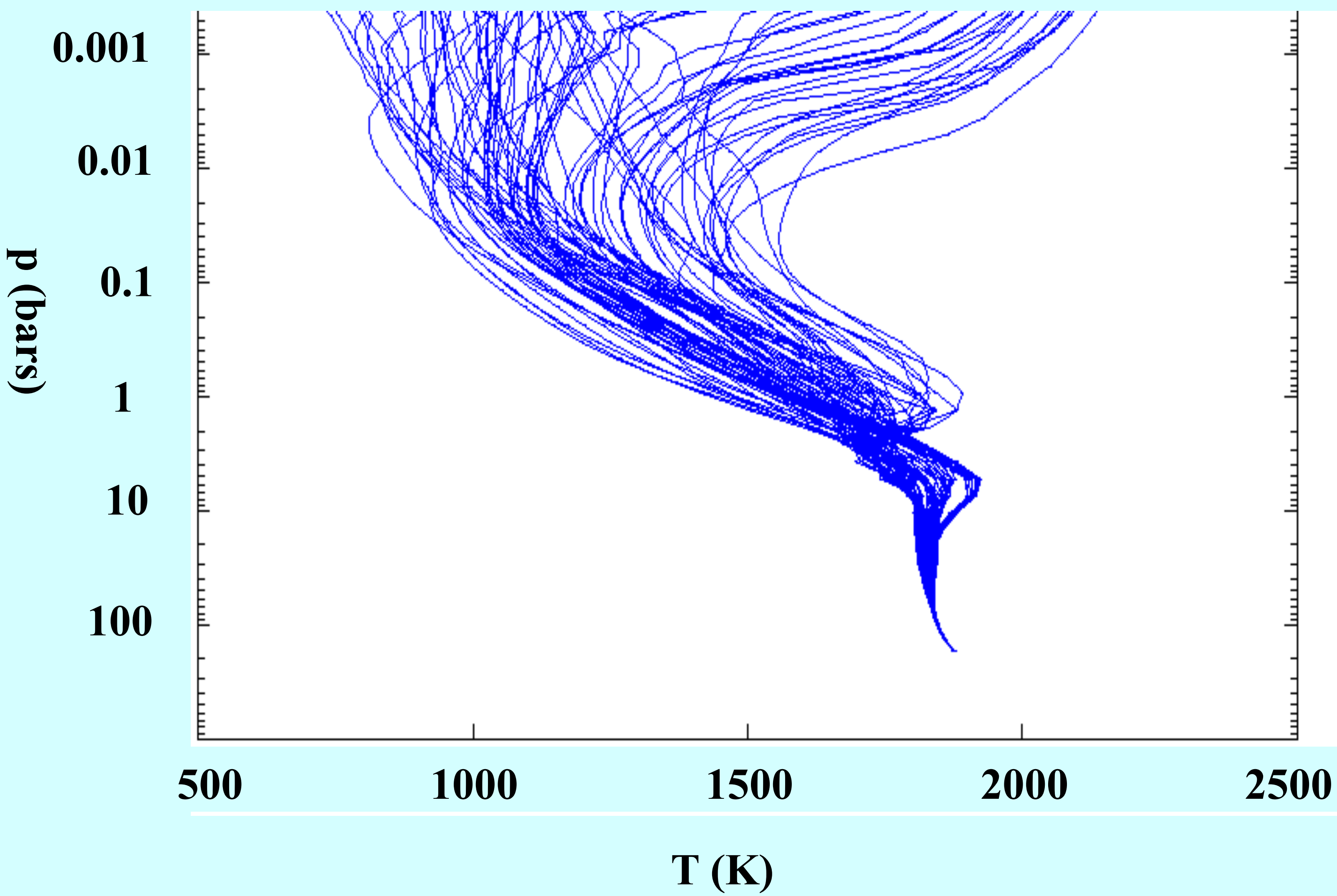






Showman et al. (2009)

Stratosphere on HD 209458b



Showman et al. (2009)

Conclusions

Atmospheric circulation is a challenging coupled radiation/hydrodynamics problem controlled especially by the atmospheric mass/composition, planetary rotation rate, and stellar heating.

Solar System planets span a wide range of atmospheric circulation/climate regimes. Our understanding of these regimes provides a strong foundation for understanding the circulation of exoplanets. But exoplanets span a much greater range of conditions and their circulation patterns are likewise probably diverse.

The hierarchy of models used for investigating circulation/climate include 0D and 1D energy balance models, one-layer and 3D dynamical models with simplified "physics," and full GCMs. Each type of models has strengths/weaknesses, and multiple approaches are needed.

Atmospheric circulation models of hot Jupiters suggest winds > 1 km/sec and temperature contrasts of ~200-1000 K. The winds can distort the temperature pattern in a complex manner, with implications for lightcurves/spectra. Circulation/climate models for exoterrestrial planets are in their infancy.

What sets wind speeds?

To order-of-magnitude, horizontal pressure-gradient force is $$\frac{R\,\Delta T\,\Delta \ln p}{a}$$

Suppose this is balanced by horizontal advection, $\vec{v}\cdot\nabla\vec{v}$

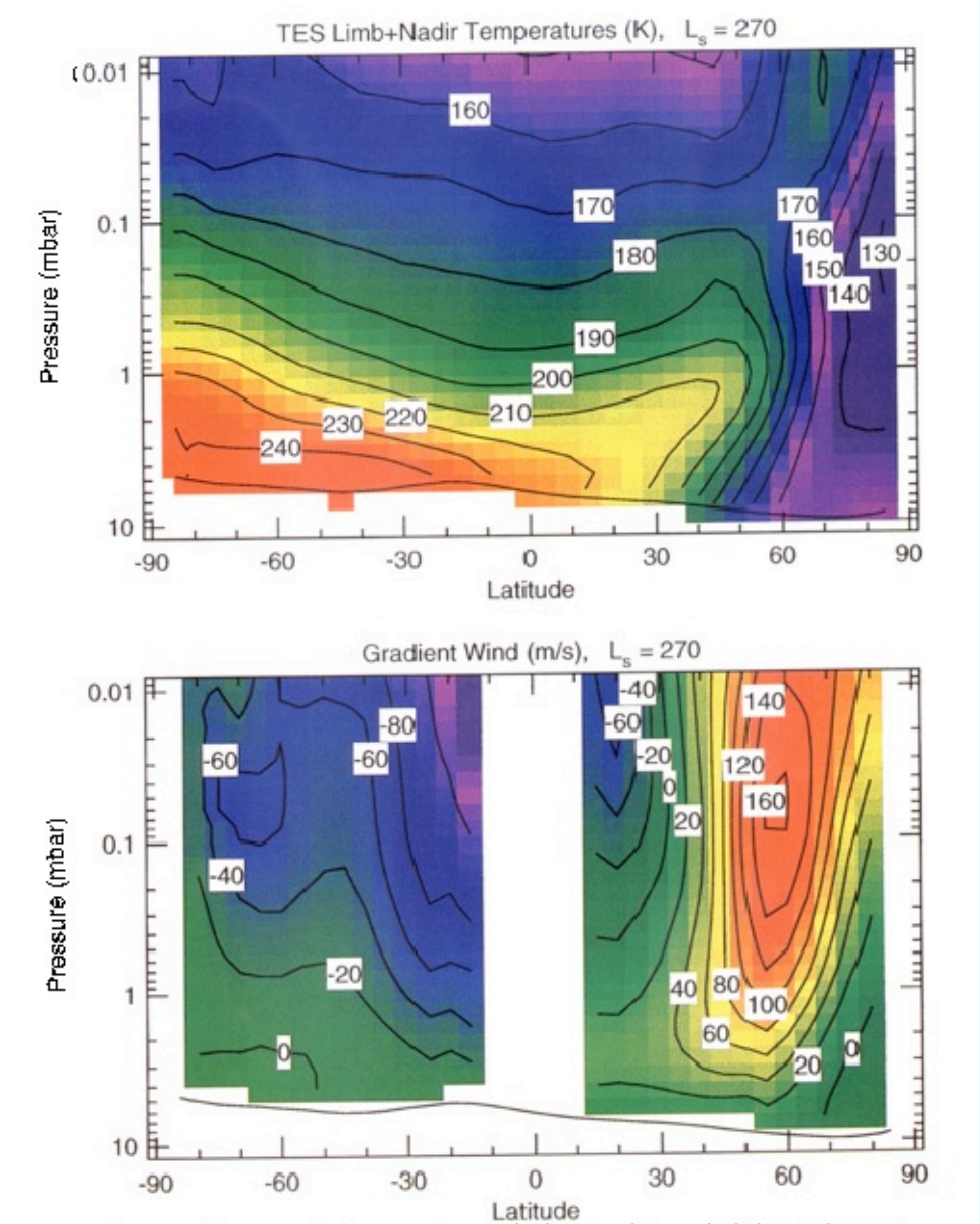
For hot Jupiters, this suggests winds of

$$u \approx (R\,\Delta T\,\Delta \ln p)^{1/2}$$

Inserting Δ*T*~400 K and Δ ln *p*~3, we have

$$u \approx 2\ \mathrm{km/sec}$$

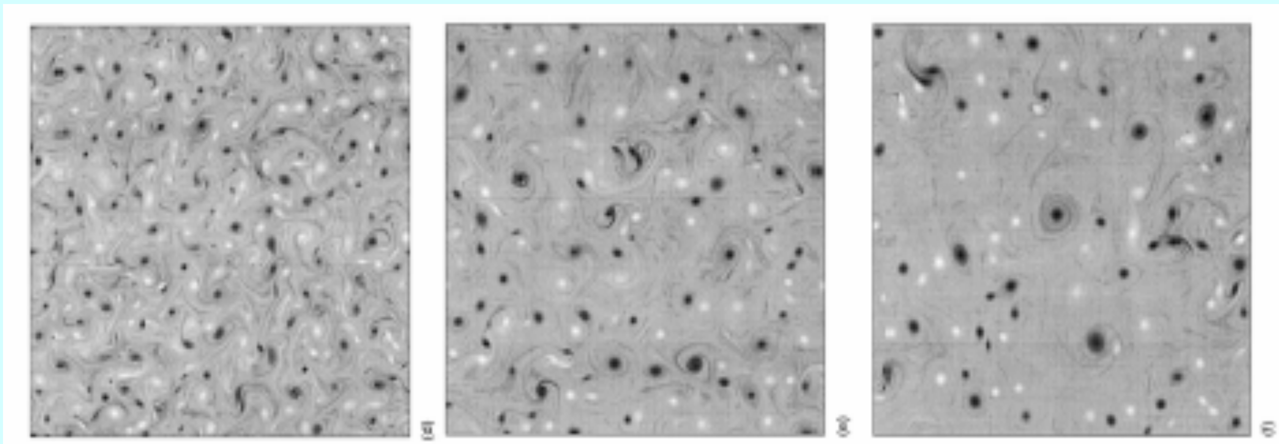
Mars



TES Limb+Nadir Temperatures (K), L_s = 270
Pressure (mbar)
Latitude
160
170
180
190
200
210
220
230
240
170
160
150
140
130
Gradient Wind (m/s), L_s = 270
-80
-60
-60
-40
-20
0
-40
-60
-20
0
20
140
120
160
40
80
100
60
20
0

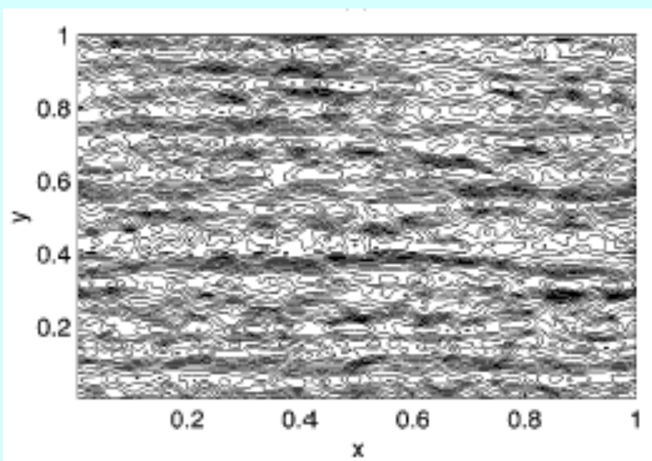
Banded structure results from modification of an inverse cascade by planetary rotation:

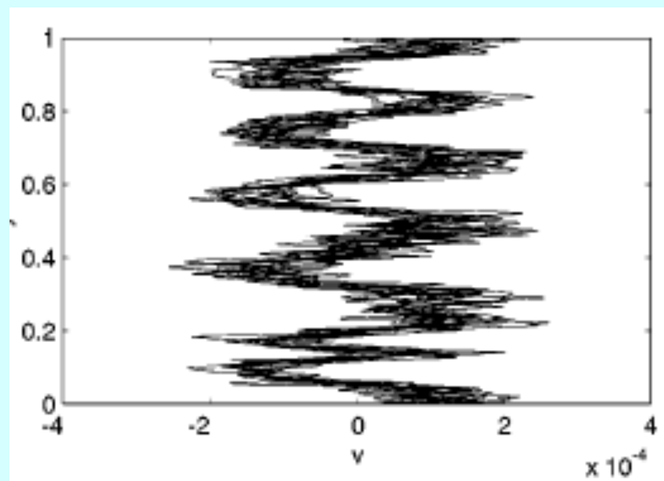
- **Small-scale 2D turbulence undergoes an inverse cascade that transfers the energy to large-scale structures:**



Bracco et al. (2000)

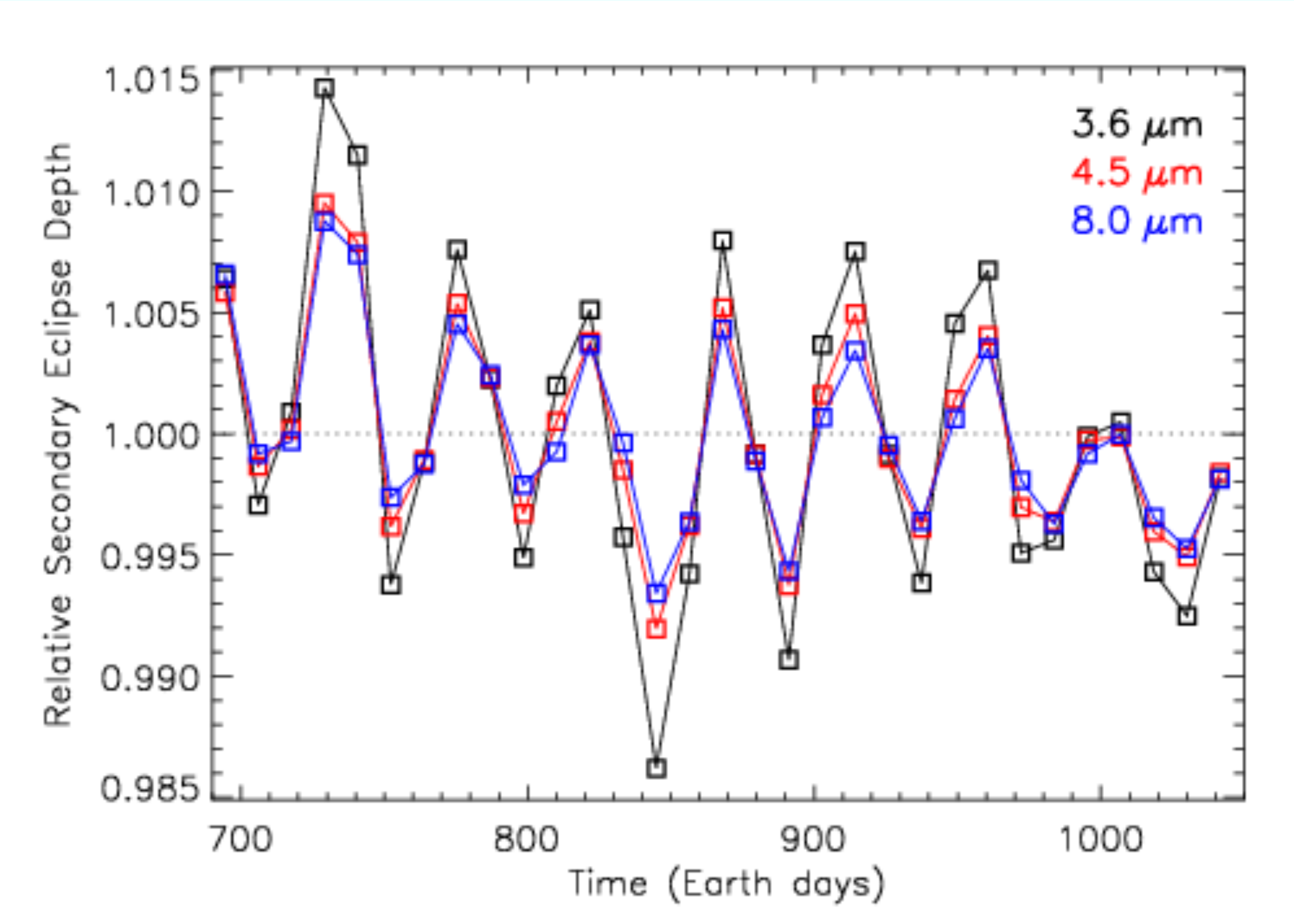
- **Gradient of planetary rotation causes anisotropy, leading to east-west elongation (jets):**



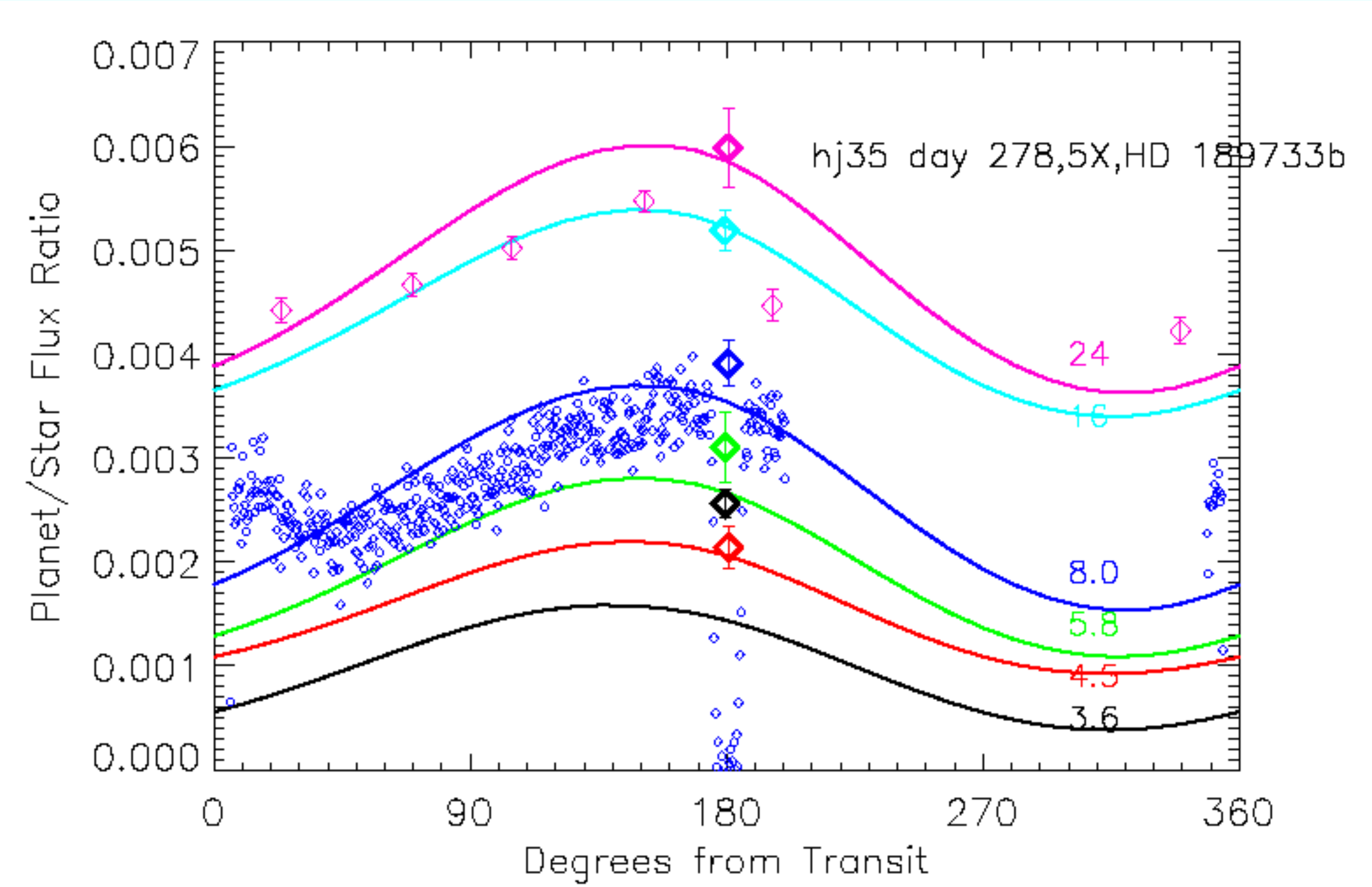


Marcus et al. (2000)

Variability



Lightcurves: HD 189733b, 5 x solar, no TiO/VO



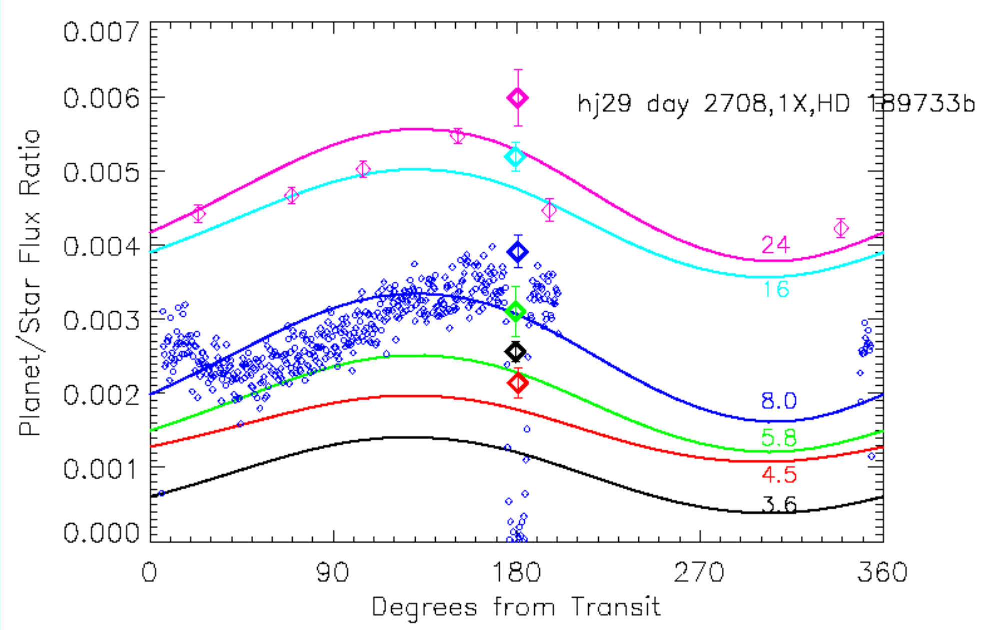
Temporal Variability?

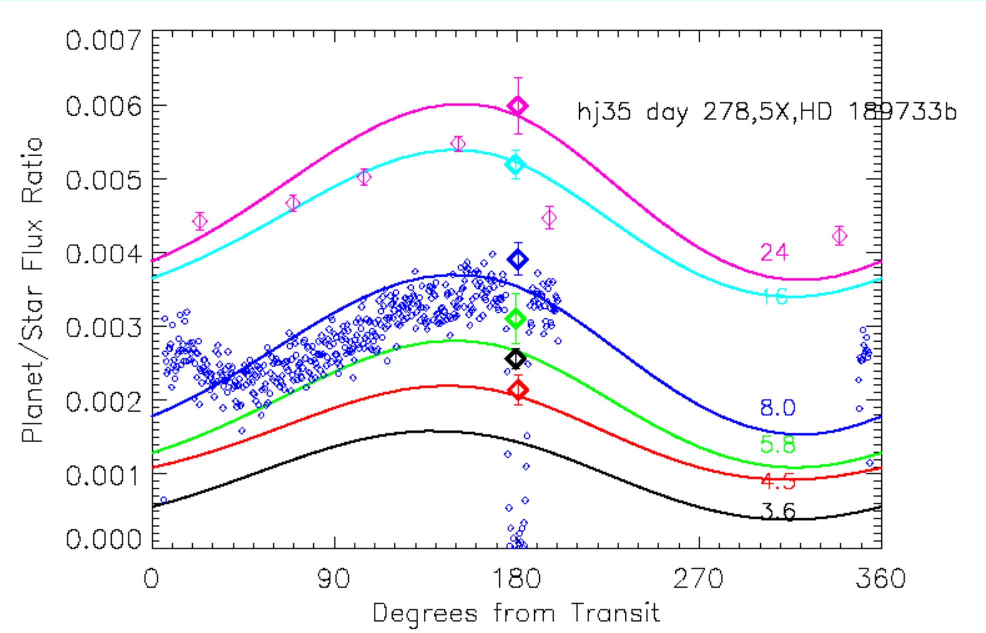
Mechanisms for producing variability:

- **Convection in the deep interior?**
- **Convection on the nightside?**
- **Shear/baroclinic instability of the jet streams?**
- **Clouds are a wild-card...**

A range of behaviors is possible. Some hot Jupiters may exhibit steady and other may exhibit time-variable lightcurves/spectra.

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





The transiting hot Jupiter Bestiary

- Semimajor axes 0.022 -- 0.15 AU
- Periods 1.2 -- 21 days
- Radii 0.39 – 1.7 $R_{Jupiter}$
- Masses 0.07 – 20.2 $M_{Jupiter}$
- Gravities ~10 – 760 m/sec^2
- Stellar fluxes of 30,000 – 4,500,000 W/m^2
- Stellar metallicities [Fe/H] -0.3 to +0.45
- Orbital eccentricities 0 – 0.67

The huge ranges in these parameters probably implies a huge range of behaviors!

What controls the size and shape of flow structures?

- **Rhines length**, $(U/\beta)^{1/2}$, is the scale at which planetary rotation causes east-west elongation (jets).
- **Deformation radius**, 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.