# Developing General Circulation Models for Hot Jupiters

Emily Rauscher

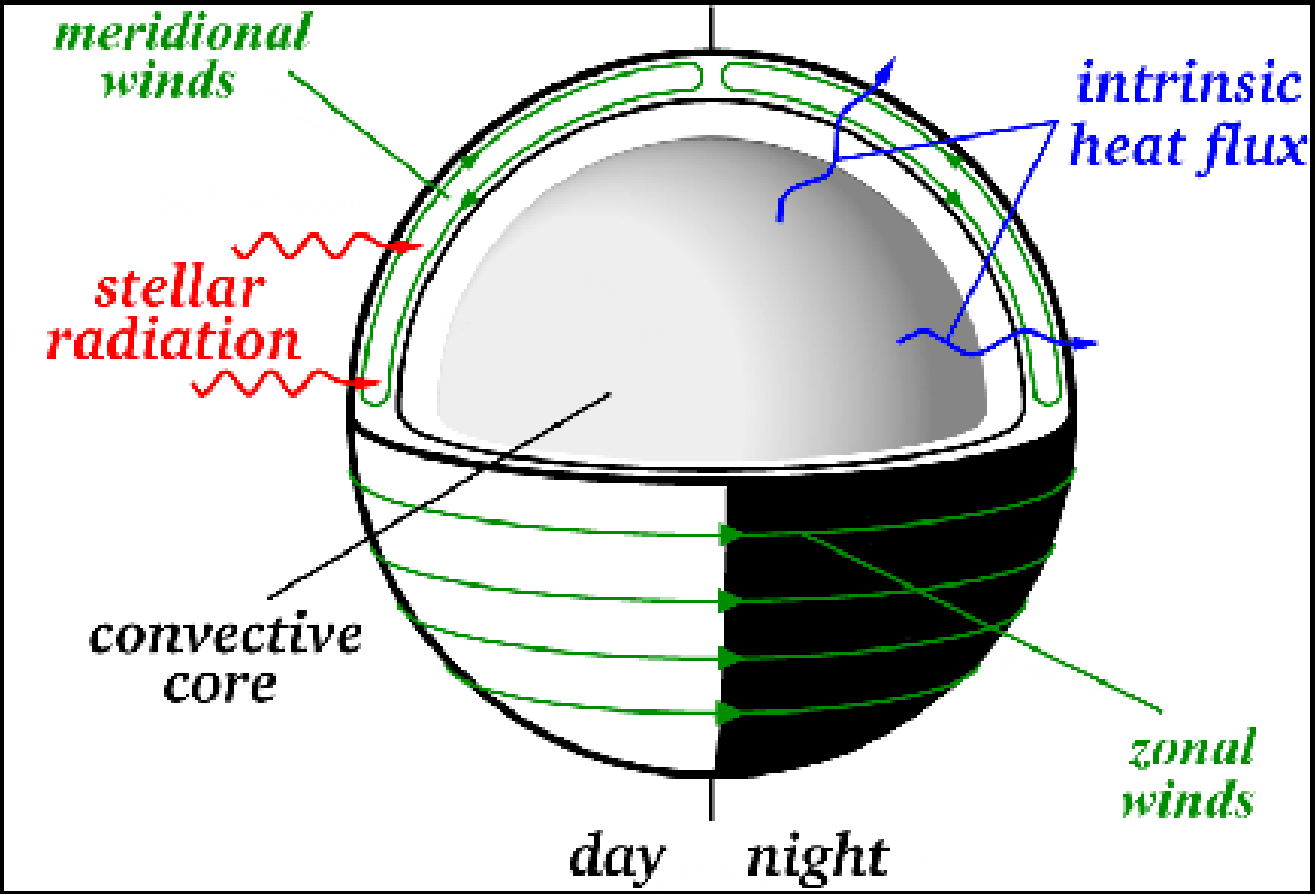
Kristen Menou

# *Planetary Science ->Exoplanetary Science*

Two main differences between close-in extrasolar giant planets and Solar System giant planets:

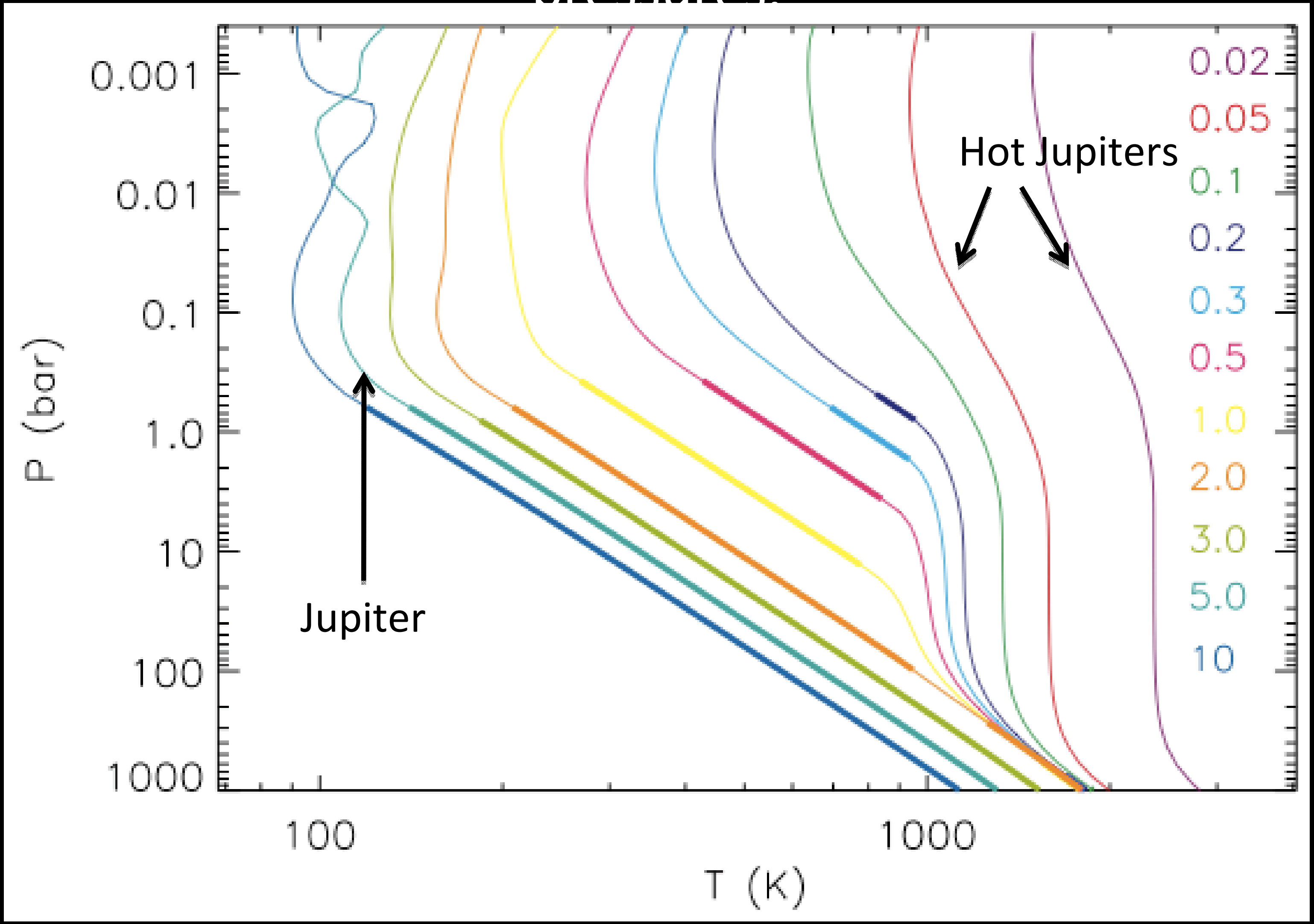
1)intense, asymmetric heating

2)slow rotation (=orbital) periods



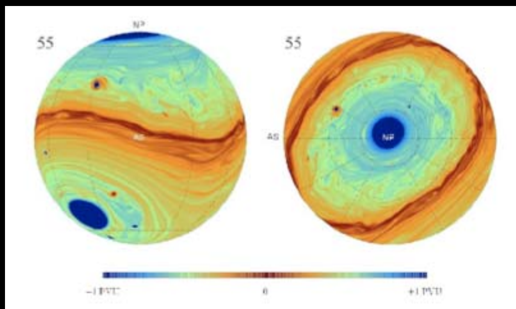

Showman &Guillot (2002)

In addition, because of the intense stellar irradiation, the internal structure of hot Jupiters differs from Solar System giant planets, with the radiative (weather) region extending to much deeper pressures.

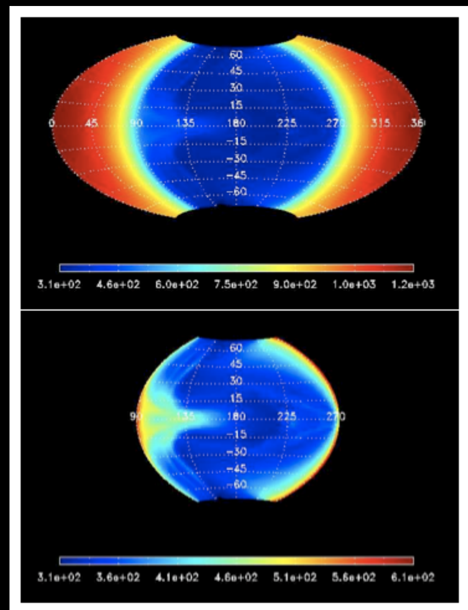



Fortney &Nettelmann (2009)

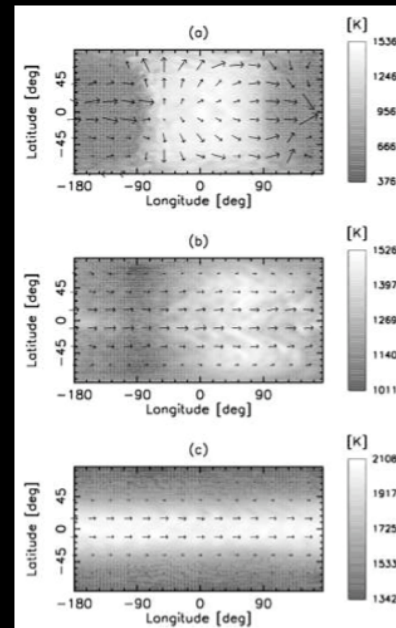
# Hierarchical Modeling of Atmospheric Dynamics



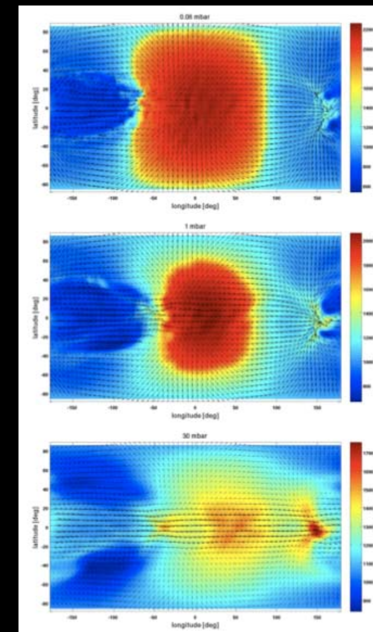

Cho et al. (2003,2008)



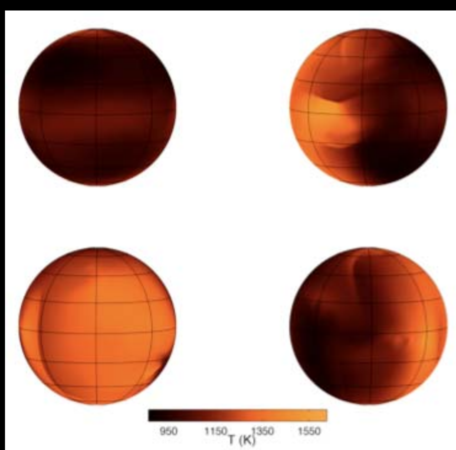

Dobbs-Dixon & Lin (2008)




Cooper & Showman (2005)



Showman et al. (2009)




Langton & Laughlin (2008)

A variety of modeling approaches have been used: quasi-2D turbulent models, models using the full Navier-Stokes equations, and models with the standard meteorological equations with simplified radiative forcing or coupled radiation and dynamics.

# Our 3-D Model

We employ the Reading Intermediate General Circulation Model (Hoskins & Simmons 1975), a pseudo-spectral solver of the "primitive equations of meteorology": the standard fluid equations applied to an inviscid, shallow atmosphere in hydrostatic equilibrium, given in its frame of rotation. We assume ideal gas and apply hyperdissipation to the divergence, relative vorticity, and temperature fields.

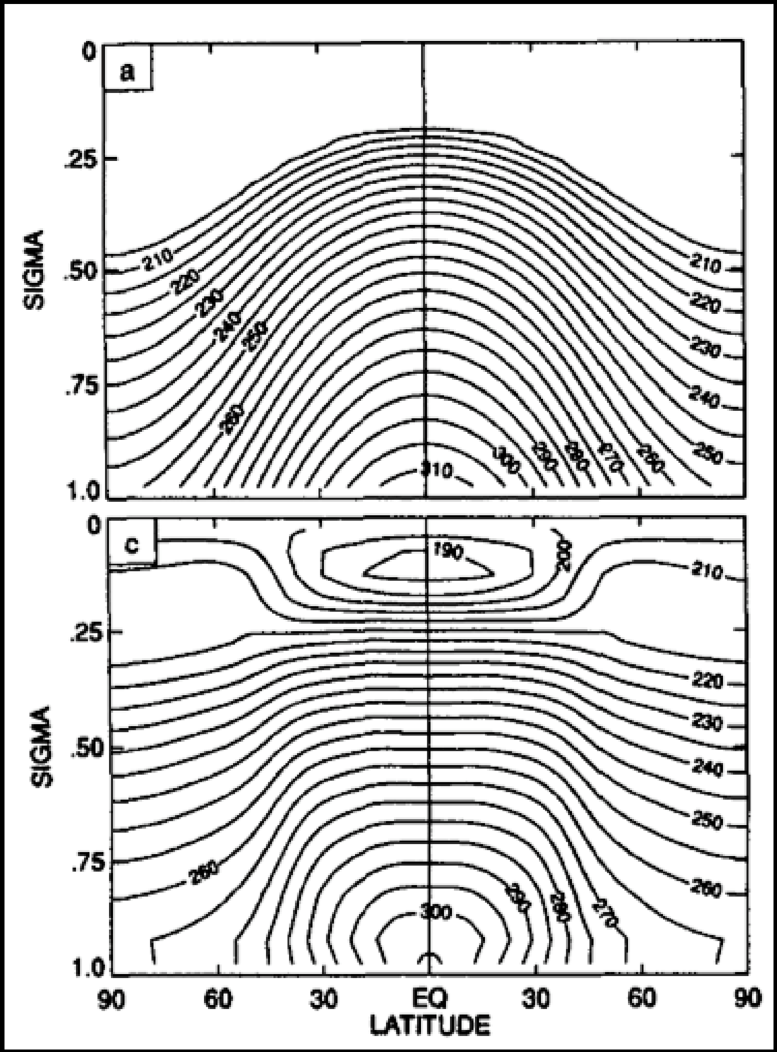
Conservation equations with pressure as the vertical coordinate:

$$\begin{aligned}
\frac{d\mathbf{v}}{dt} + \frac{u\tan\phi}{R_p}\mathbf{k}\times\mathbf{v} &= -\nabla_p\,\Phi - f\mathbf{k}\times\mathbf{v}, \\
\frac{\partial\Phi}{\partial p} &= -\frac{1}{\rho} \\
\frac{\partial\omega}{\partial p} &= -\nabla_p\cdot\mathbf{v}\ , \\
c_p\frac{dT}{dt} &= \frac{\omega}{\rho}\ + Q\ ,
\end{aligned}$$

We use a standard, Newtonian relaxation scheme for the heating:

$$Q_T = \frac{T_{\rm eq}(\sigma,\lambda,\phi) - T}{\tau_{\rm rad}(\sigma)}$$

# Newtonian Relaxation

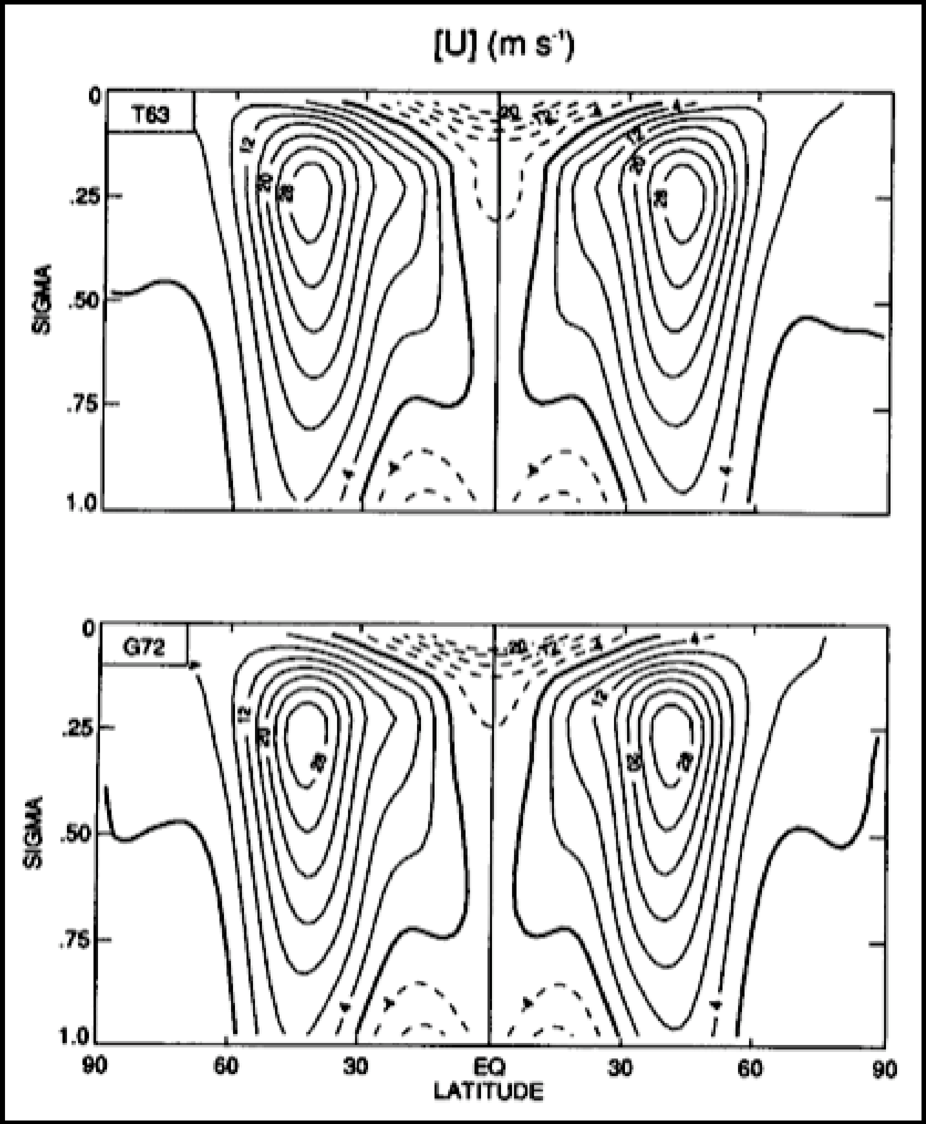



Held & Suarez (1994)

Defined temperature profile, known to give result close to actual

Realized temperature profile

# Model Intercomparisons



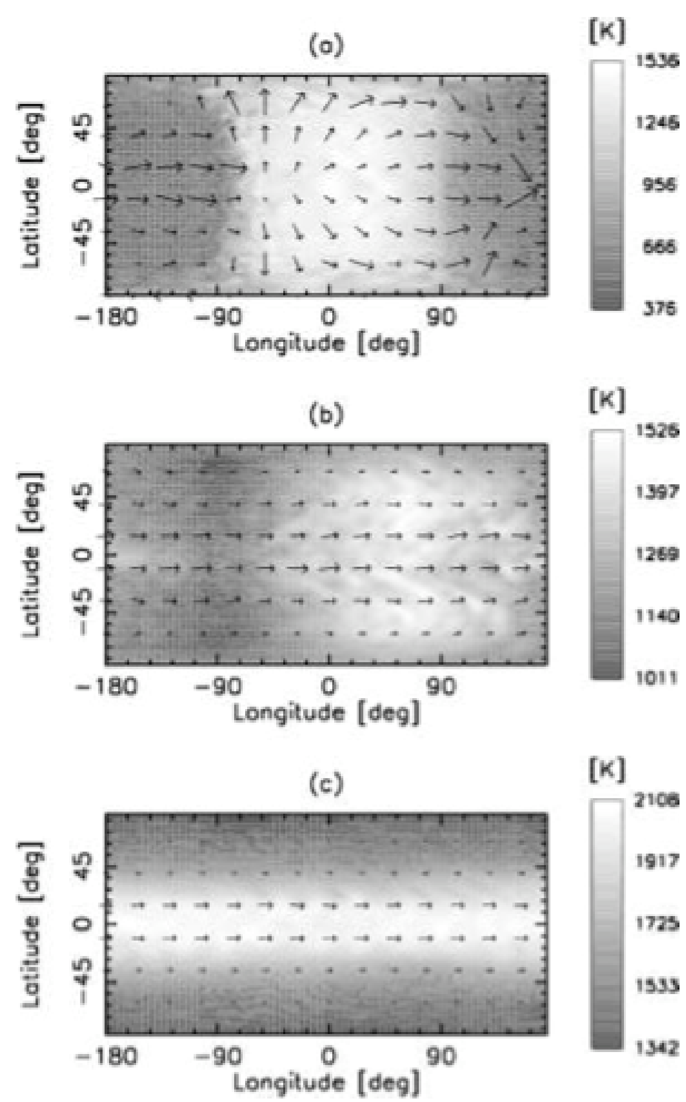

Held & Suarez (1994)

For Earth:

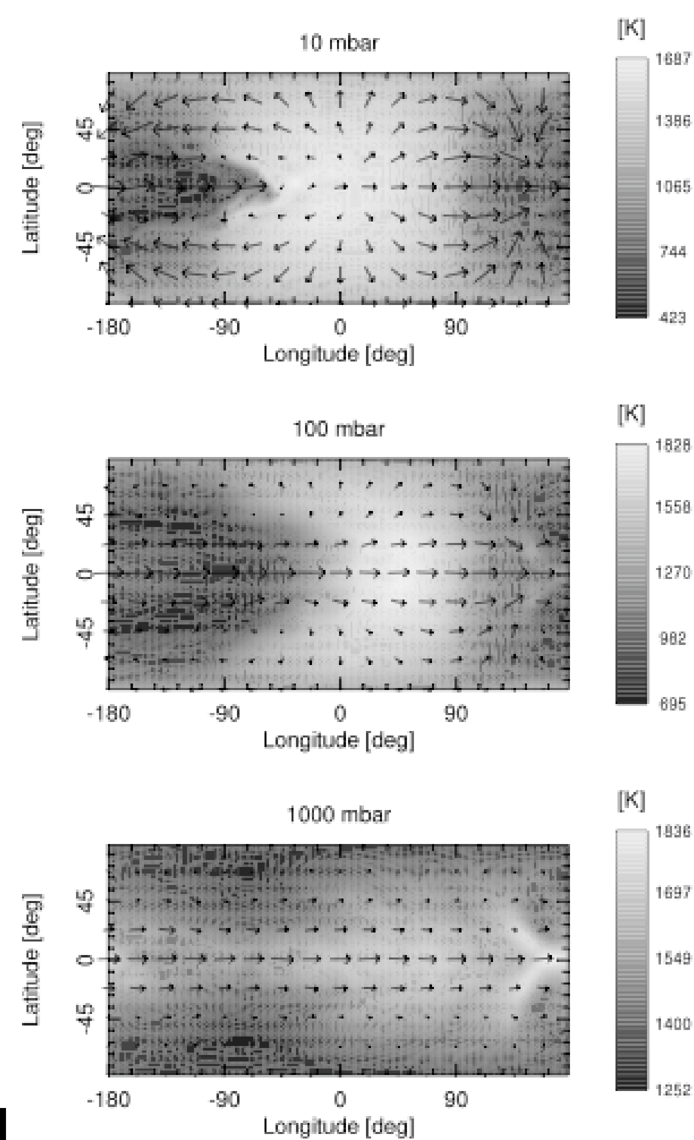
Spectral code with simplified forcing

Finite-difference code with simplified forcing

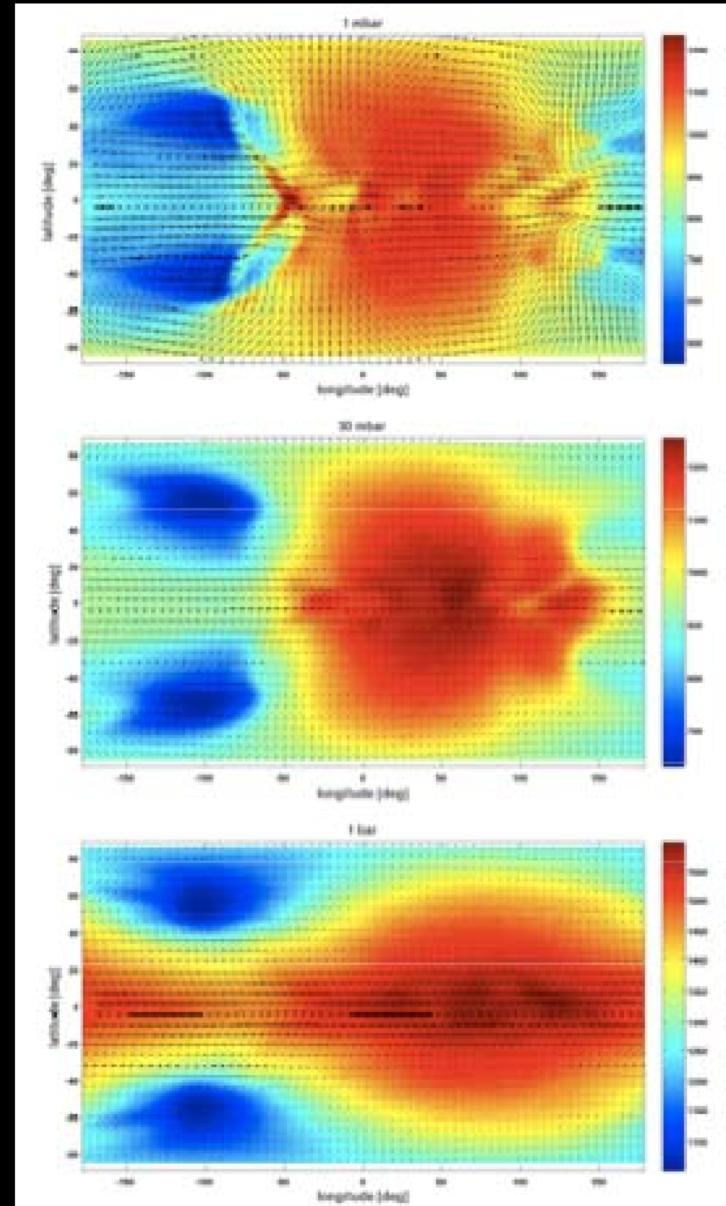
# Increasing complexity →




Cooper & Showman (2005)




Showman et al. (2008)



Showman et al. (2009)

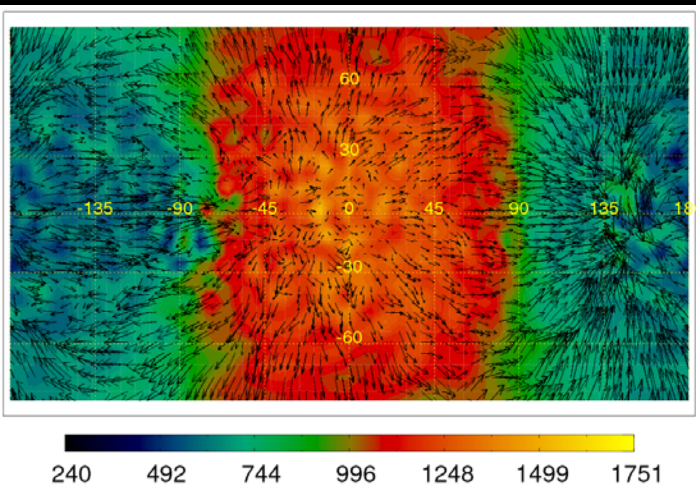
# Deep Hot Jupiter Model

- We use a set-up nearly identical to Cooper & Showman (2005) to facilitate code comparison. HD 209458b
- There are 33 logarithmically spaced vertical pressure levels, from 1 mbar to 200 bar.
- The horizontal resolution is T31, equivalent to a grid of 48 x 96, or about 4 degree resolution.
- The day side relaxation temperature profile goes as (cos $\alpha)^{1/4}$, where $\alpha$ is the angle from the substellar point. The day-night temperature difference is 1000 K above 10 mbar, and then decreases to 530 K at 10 bar. The night side relaxation profile is horizontally constant and decreases with pressure.
- The atmosphere is not heated below 10 bar.

Rauscher &Menou (2009)

# Atmospheric Structure

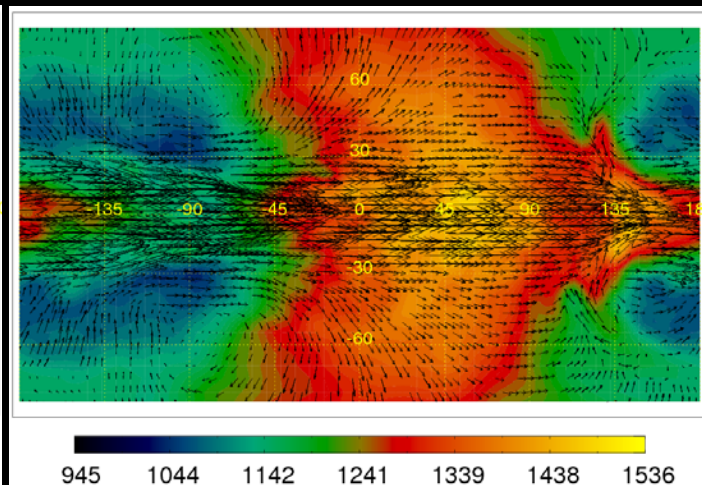
Upper atmosphere: 2.5 mbar




Temperature [K]

Max wind speed: 10 km/s

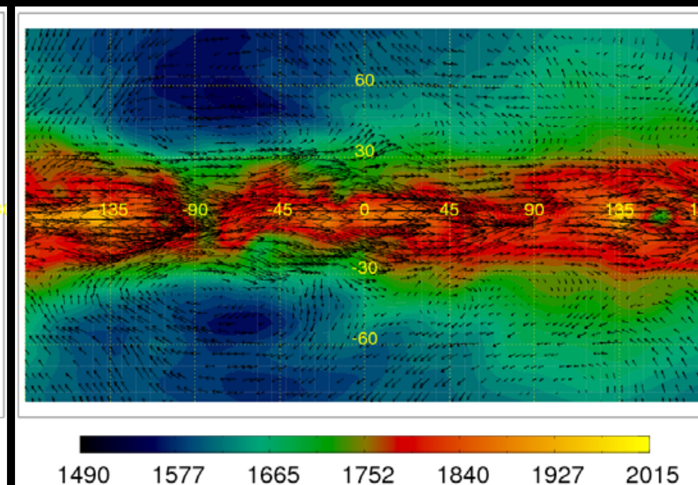
220 mbar




Temperature [K]

Max wind speed: 4 km/s

Lower atmosphere: 4.4 bar




Temperature [K]

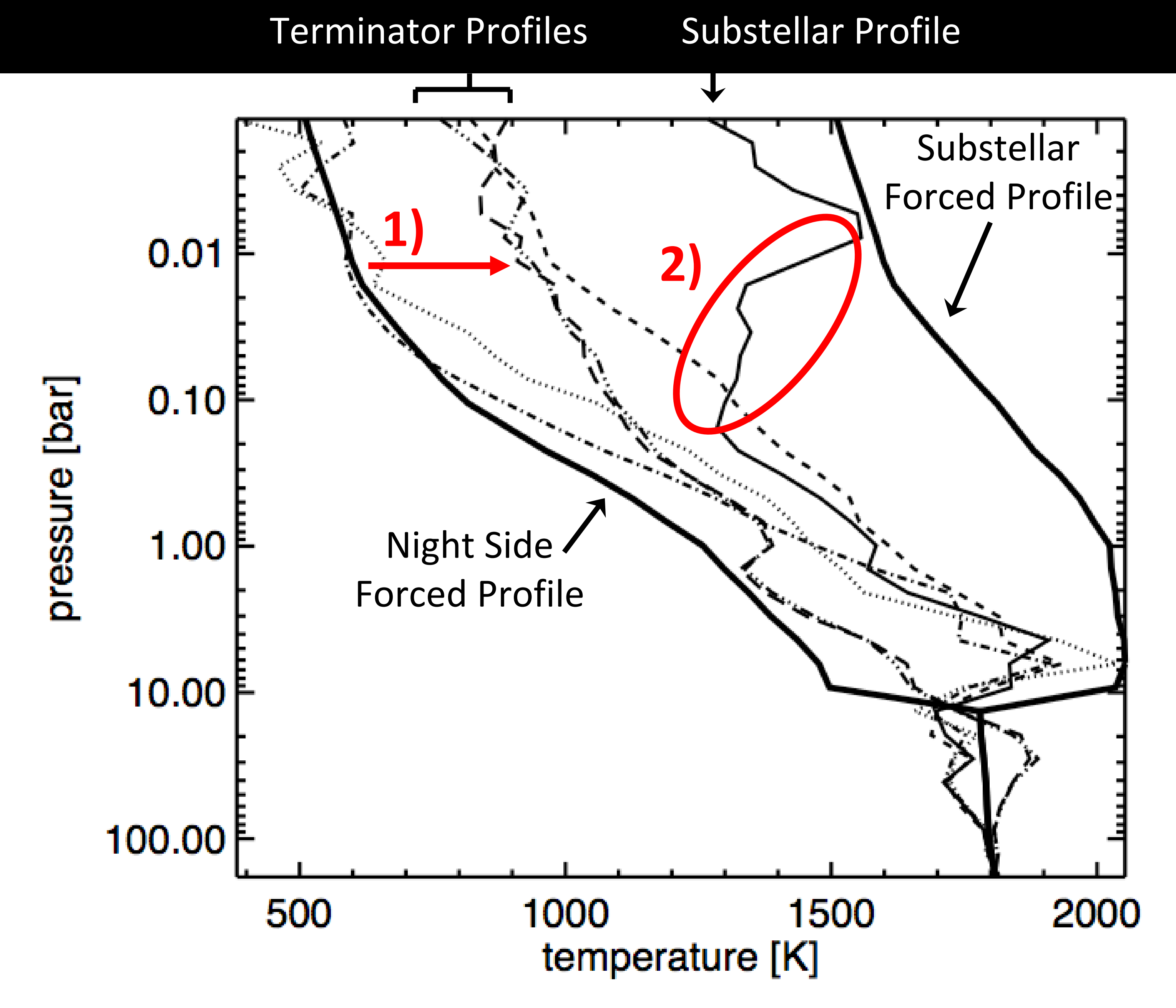
Max wind speed: 1 km/s

Radiation dominated
and
Transonic winds

↔

Advection dominated
and
Subsonic winds

# Dynamically-altered T-P Profiles

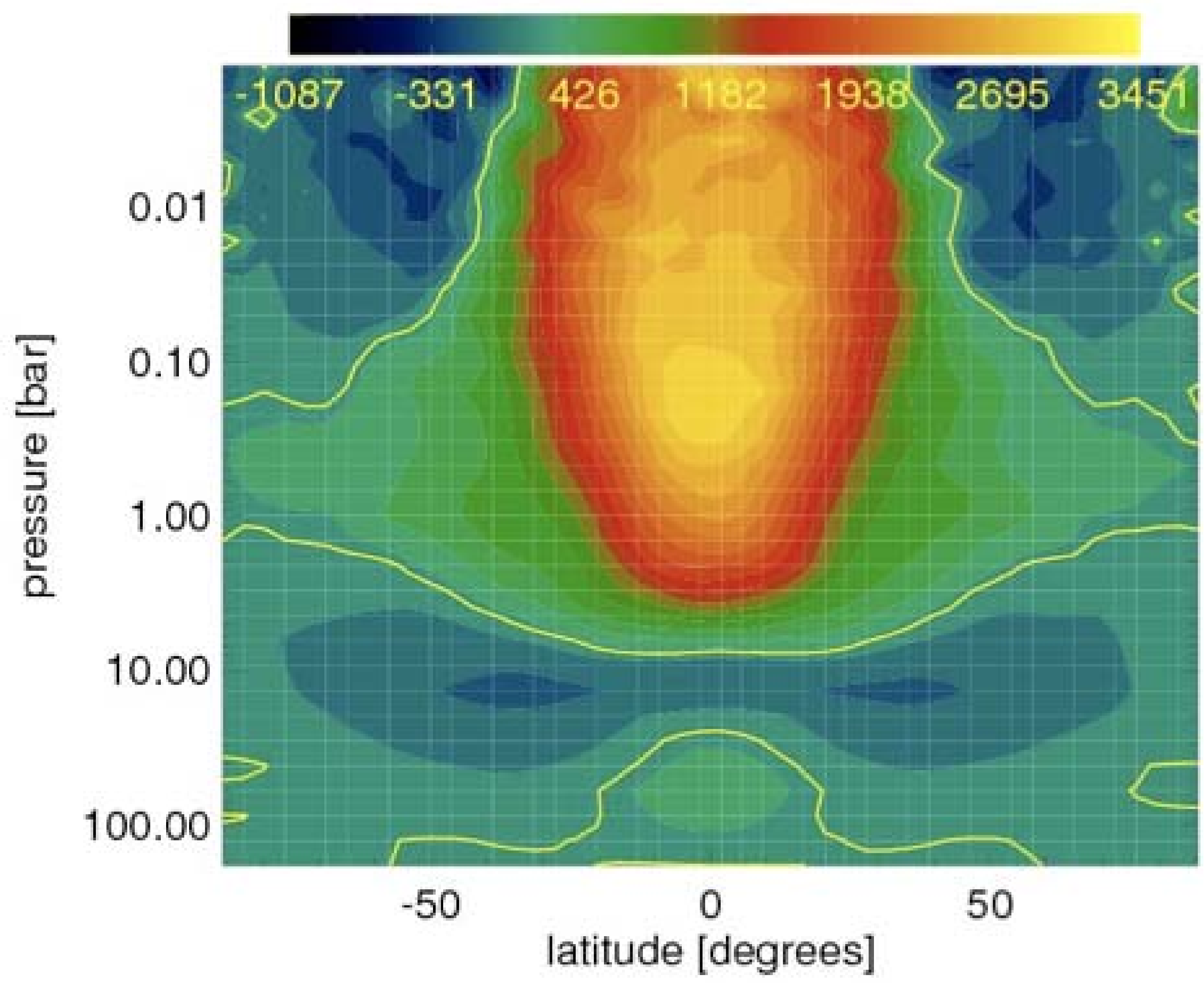



1) Bias: raised temperatures along the terminator

2) Dynamically-induced temperature inversion on the day side

# Interaction Between the Atmosphere and Interior

Zonal average of the zonal (east-west) wind [m/s]

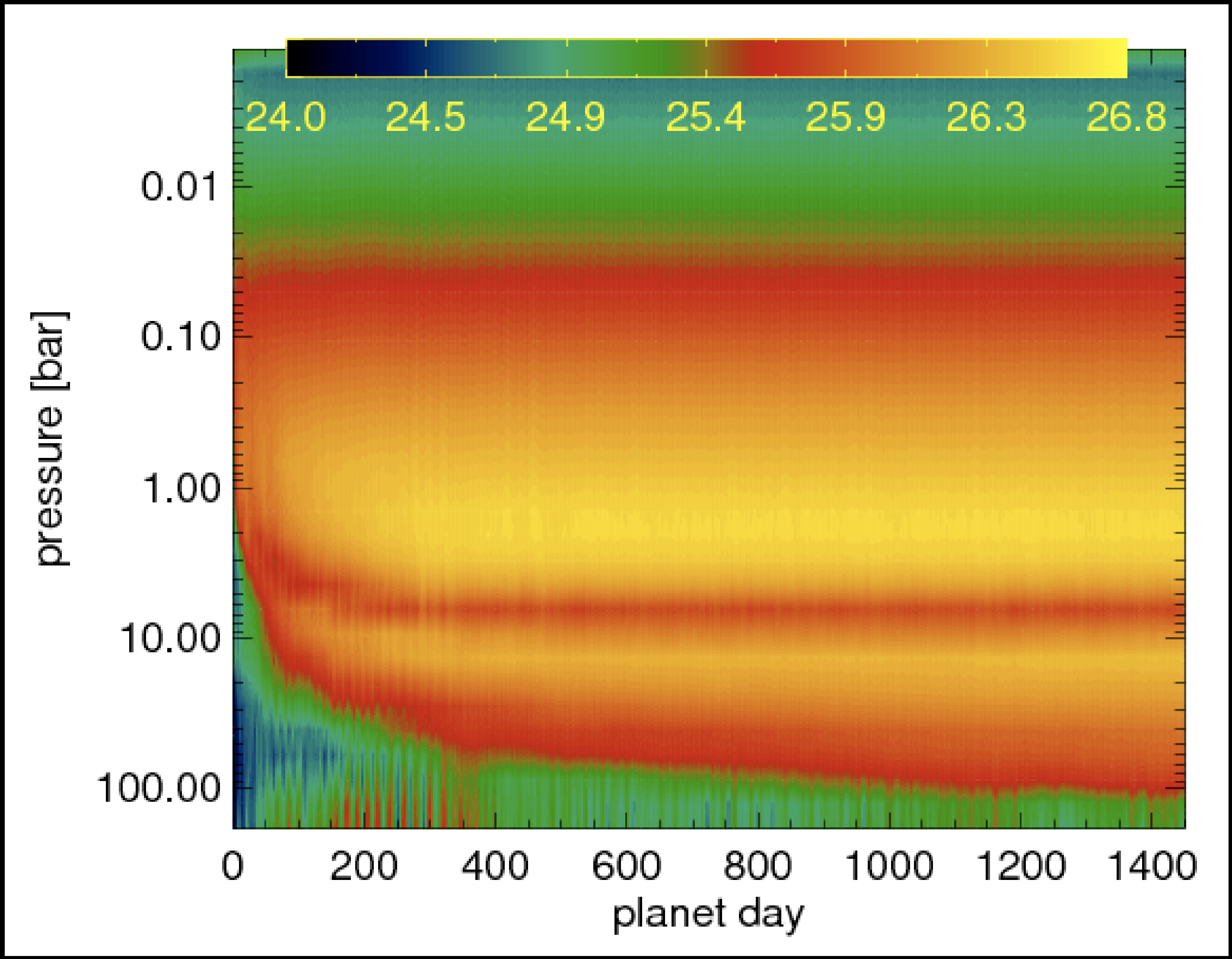



We see significant momentum transfer between:

"Active" layers: heated by stellar irradiation

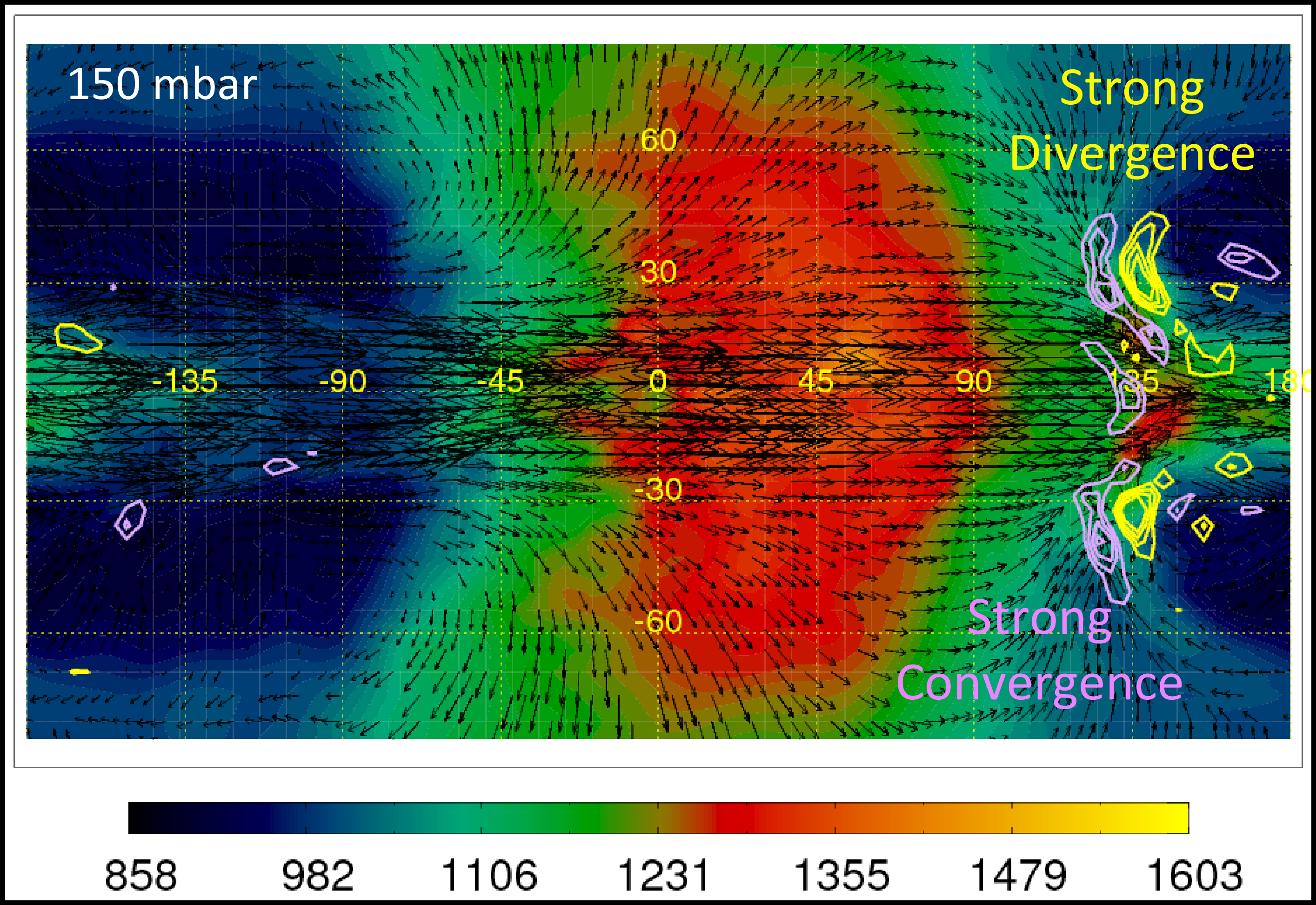
"Inert" layers: not heated

# $\text{Log}_{10}$ of the total kinetic energy at each level = $\Sigma \rho v_h^2$



# Shocks?

In our transonic flow we find narrow, strongly convergent features. Atmospheric models typically do not include shock-capturing schemes, but they may be required in hot Jupiter models.




Temperature [K]

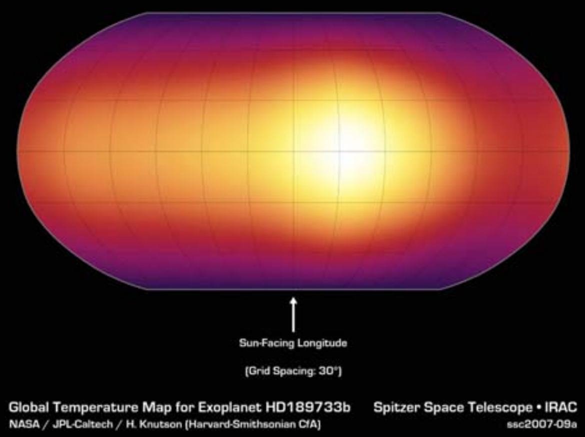
# Summary

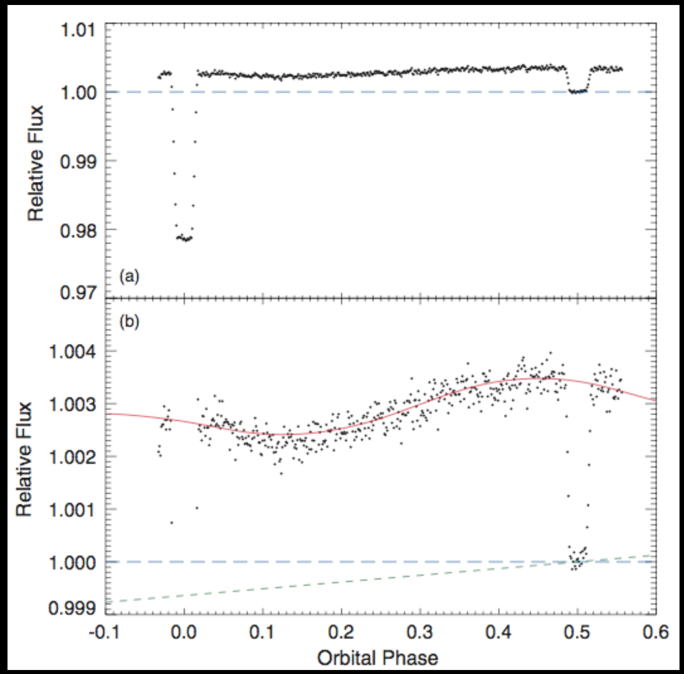
- Fairly confident: atmospheric features are large, day-night temperature contrasts are stronger higher in the atmosphere, winds are very strong
- Questions: Is the flow really transonic? Do shocks form (and how do they affect the circulation)? Are instabilities either not triggered or efficiently damped? What is the nature of any deep flow and its interaction with the weather layers? Why are different systems different?
- Observational implications: global maps, emitted spectra, transmission spectra, chemistry and mixing of species, etc.
- And more: Earth-like planets around M-dwarfs

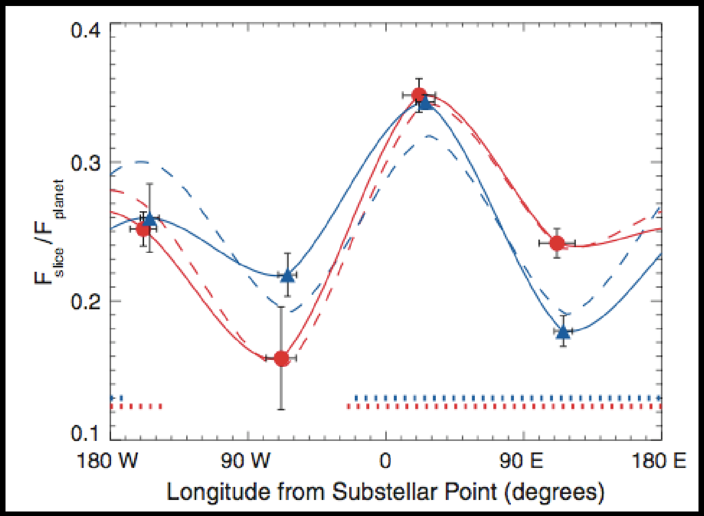
# To do:

- Simple radiation schemes
- Parameter space -> underlying physics
- Checking assumptions
- Eccentric planets
- Tidal-thermal(-atmospheric?) evolution
- Clouds???
- Matching data?

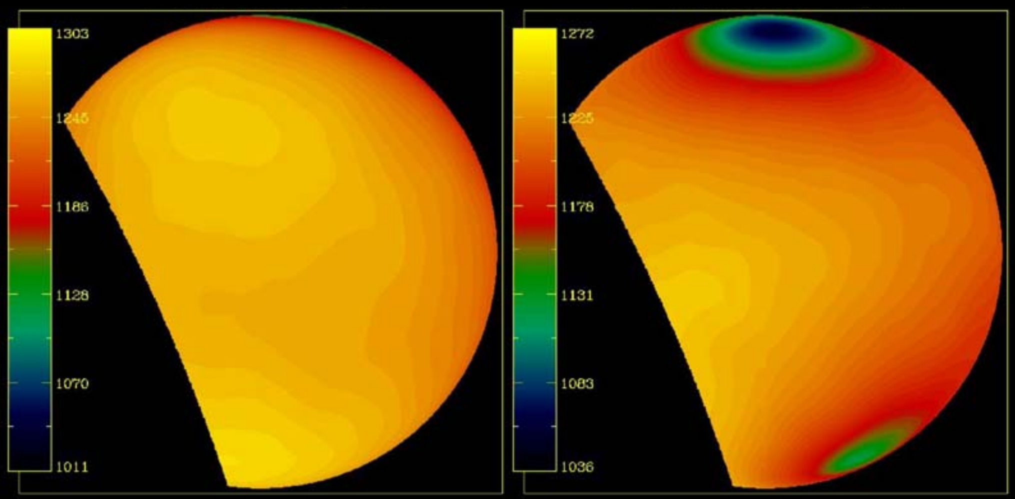
# Observational Caution: Degeneracy

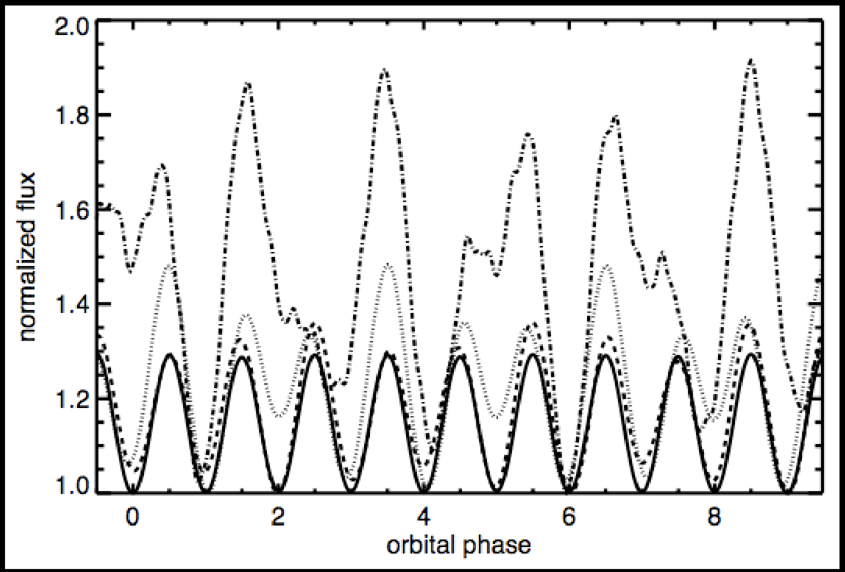



Knutson et al. (2009)






Rauscher et al. (2007a, 2008)