Transitions in Efficiency of Heat Redistribution in Hot Jupiter Atmospheres

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THE UNIVERSITY OF ARIZONA

31st International Colloquium of the Paris Institute of Astrophysics

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Department of Planetary Sciences
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Transitions of Day-Night Temperature Differences in Hot Jupiter Atmospheres

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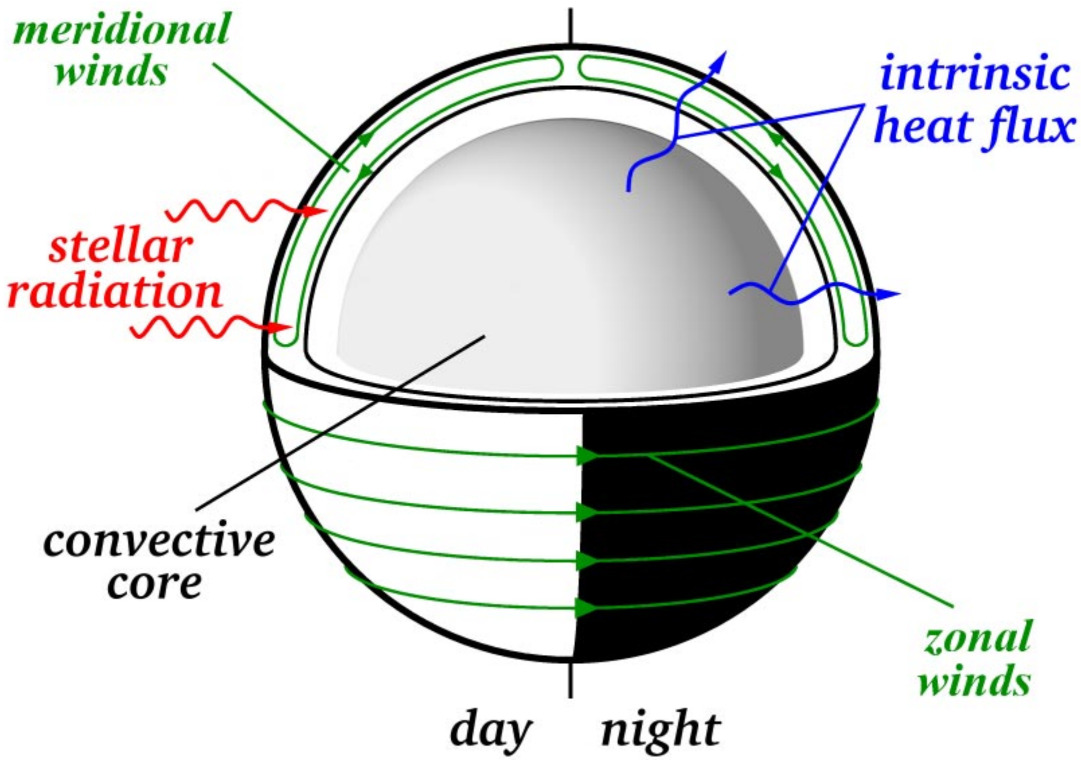
Hot Jupiters

Short spin-down timescale:

$$\tau \sim 1 \times 10^6 \left(\frac{Q}{10^5}\right)\left(\frac{a_{\rm orb}}{0.05\mathrm{AU}}\right)^6 \mathrm{yr}$$

→ **Tidally locked**

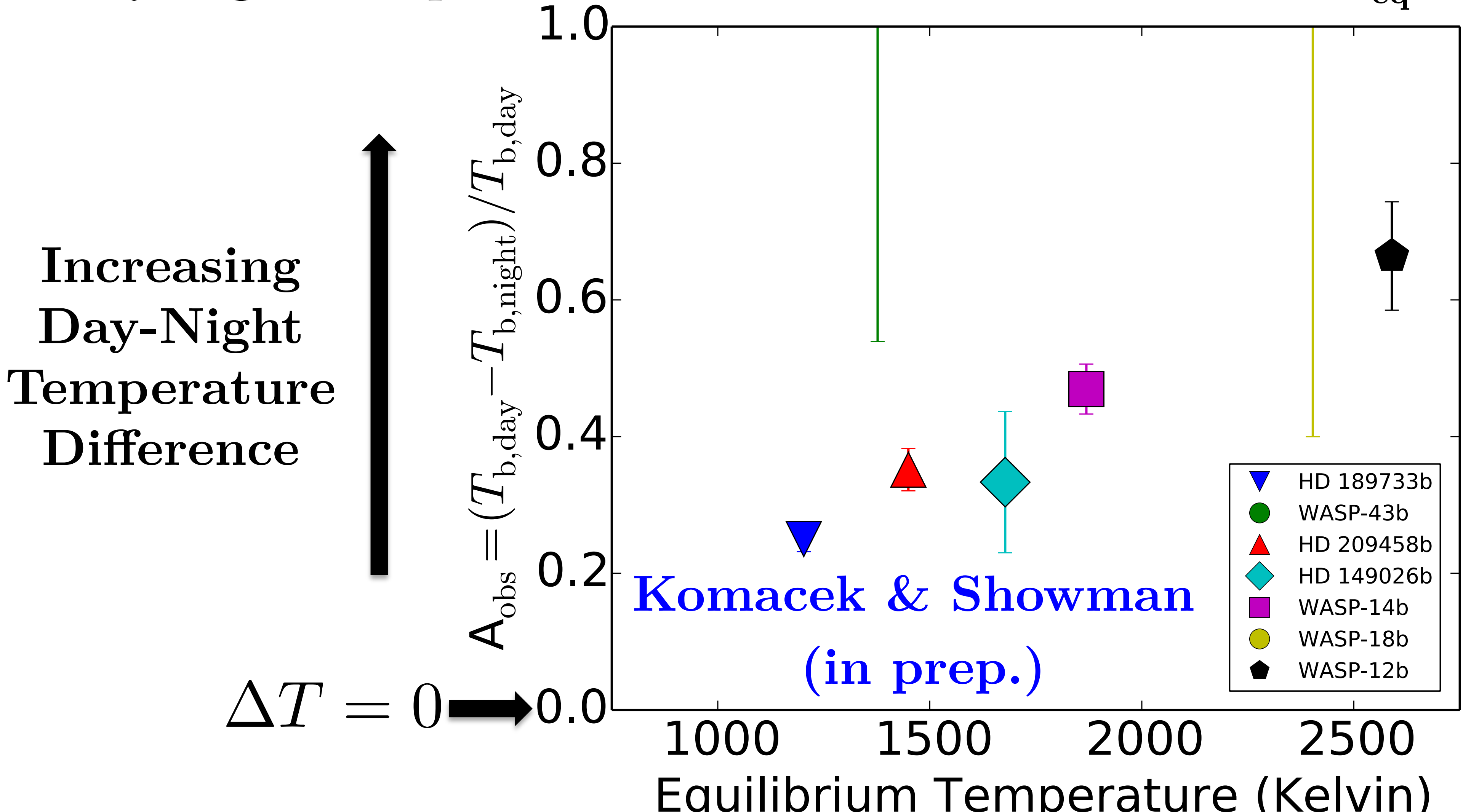


Dayside-nightside temperature differences are *forcing amplitude* of atmospheric circulation

Showman & Guillot (2002), Showman et al. (2015)

Phase Curves: Dayside-Nightside Temperature Differences

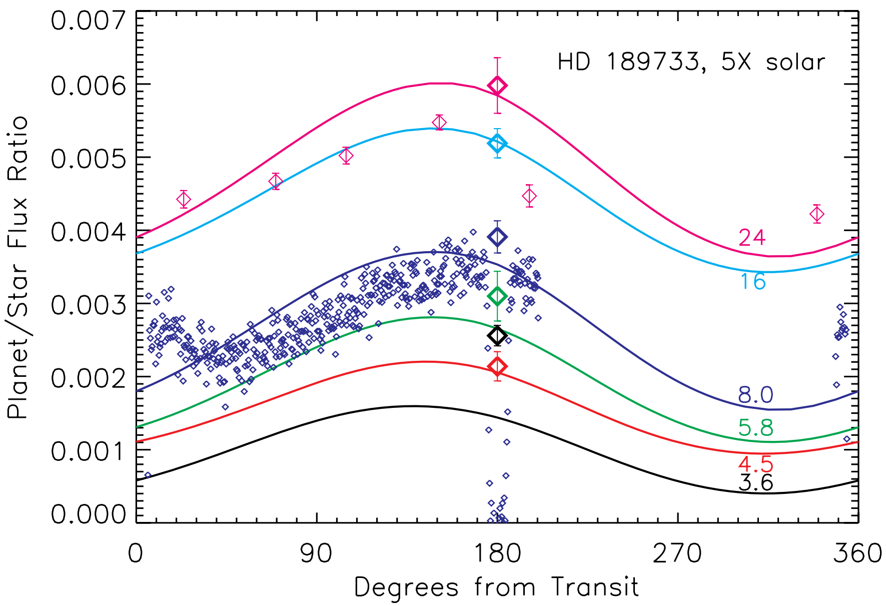
Day-night temperature differences correlate with T_{eq}



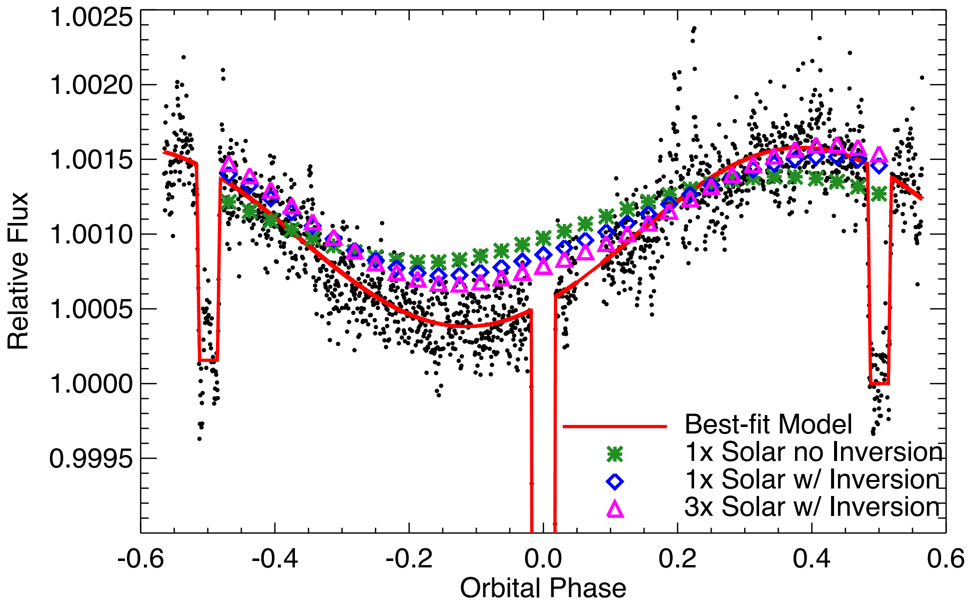
See also: Cowan and Agol (2011), Perez-Becker & Showman (2013)

Phase Curves: Fast Zonal Winds

HD 189733b



HD 209458b



Models and observations show peak flux *before* secondary eclipse

-Strong (~km/s) winds advect hottest point eastward of substellar point

Showman et al. (2009) Zellem et al. (2014)

What controls day-night temperature differences?

Initial idea: competition between advection by winds and radiation:

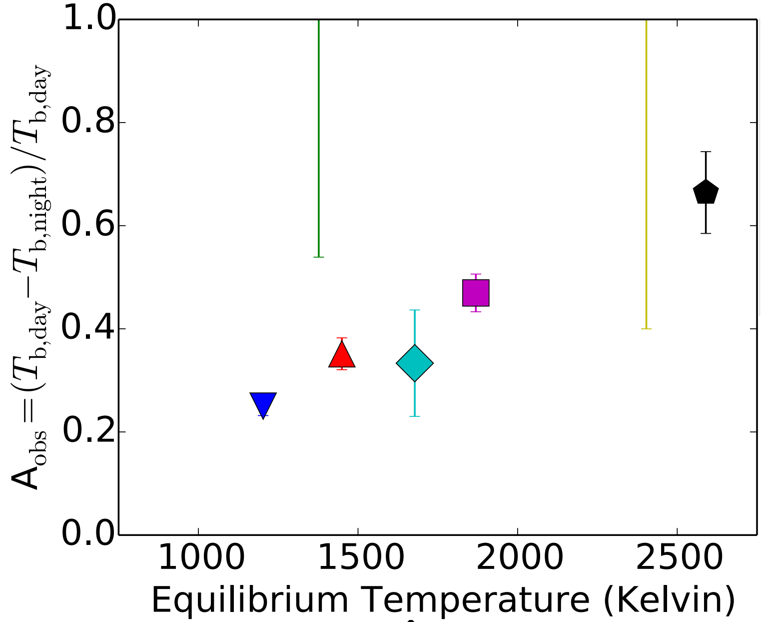
$$\tau_{\mathrm{adv}} \sim \frac{a}{\mathcal{U}}$$

High day-night differences when: $\tau_{\mathrm{rad}} \ll \tau_{\mathrm{adv}}$

Low day-night differences when: $\tau_{\mathrm{rad}} \gg \tau_{\mathrm{adv}}$

<u>This timescale comparison is not self-consistent or predictive</u>

Showman & Guillot (2002)



Would expect faster winds with increasing T_{eq}- <u>other timescales must matter!</u>

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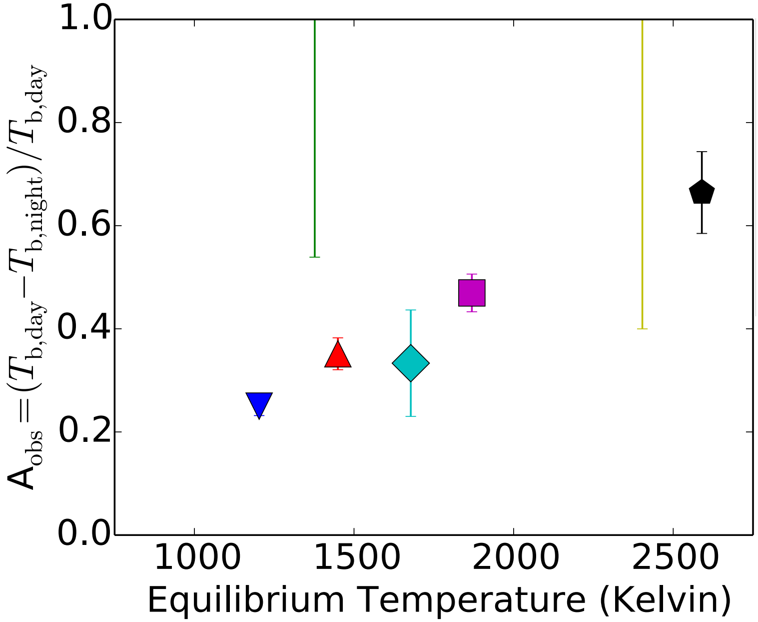
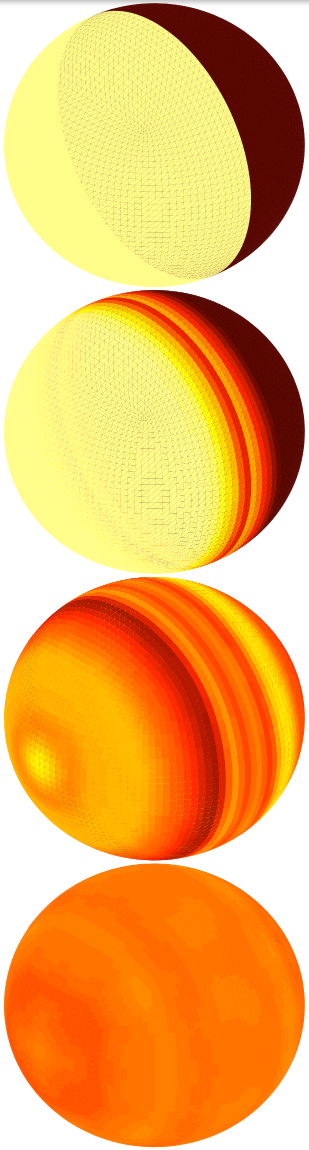


Perez-Becker & Showman (2013) showed that *wave adjustment* mediates day-night temperature differences

Wave Adjustment



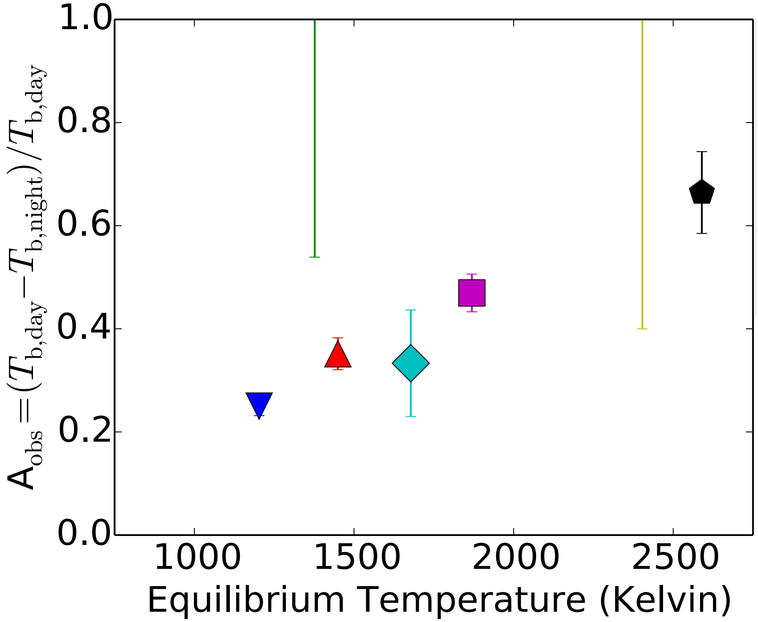
Initialize with hot dayside

↓

Waves propagate across planet

↓

Day-night temperature differences reduced

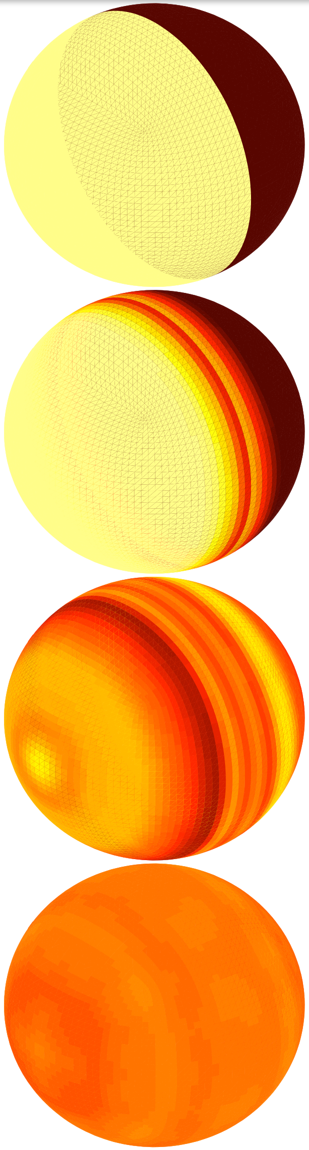


↑

Wave adjustment damped due to radiative forcing or drag, explains trend

Showman et al. (2013)

Wave Adjustment: Hot Jupiters



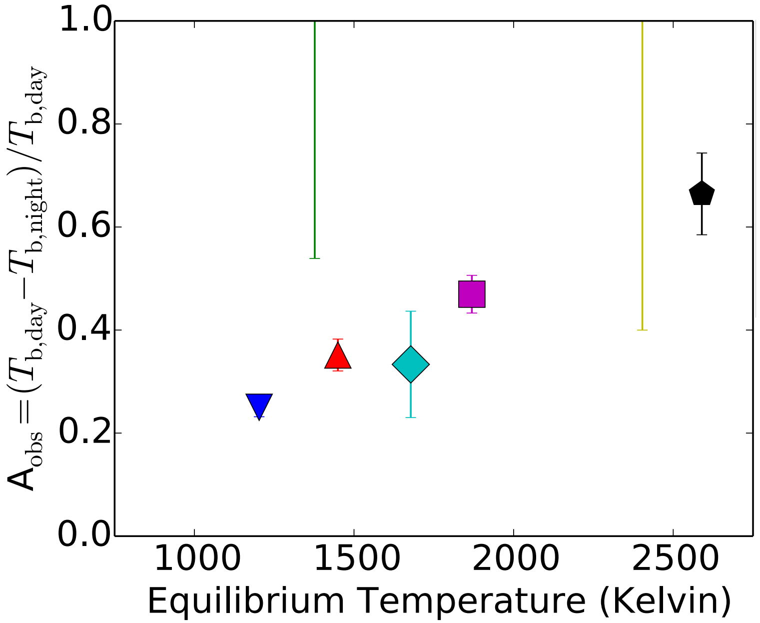
For hot Jupiters, Rossby deformation radius:

$$L_D \sim \frac{NH}{\Omega}$$

is comparable to the planetary radius.

Wave adjustment will be *global* in scale

Showman et al. (2013)



Wave adjustment damped due to radiative forcing or drag, explains trend

Model

Utilize 3D primitive equations of meteorology

-Consider varying strengths of radiative forcing and friction, both of which damp wave propagation

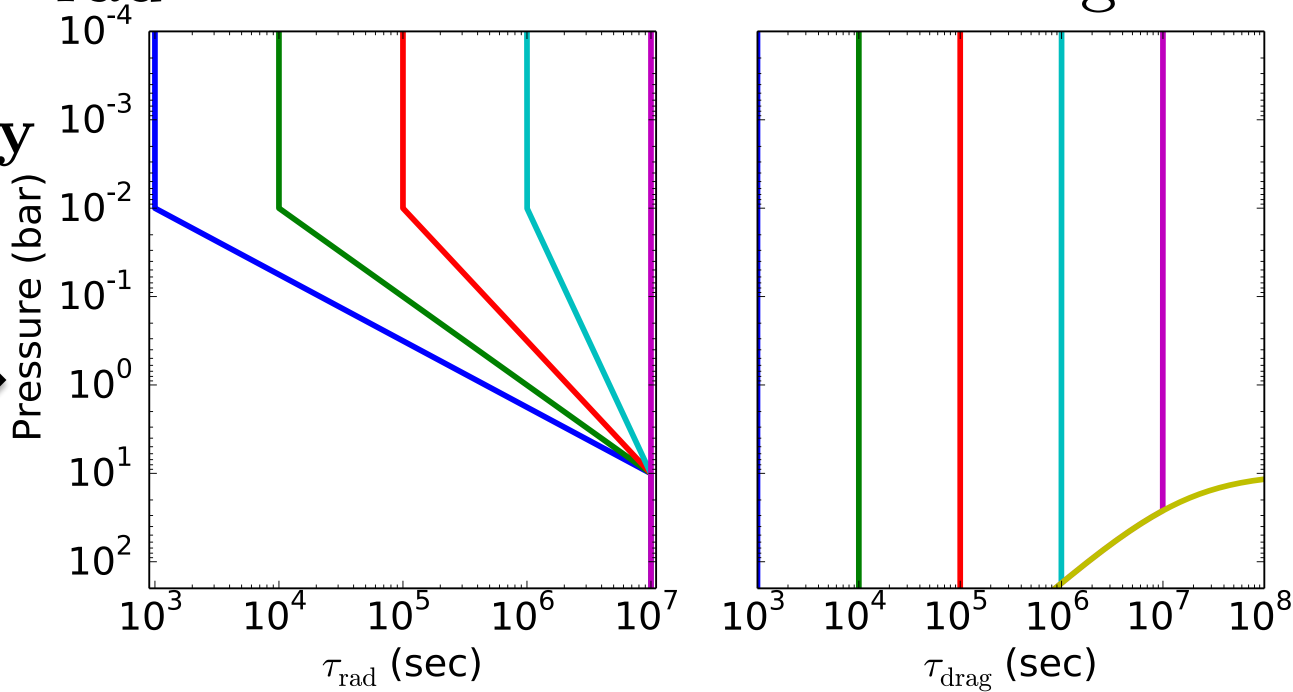
Newtonian cooling:

$$\frac{q}{c_p} = -\frac{T - T_{\mathrm{eq}}}{\tau_{\mathrm{rad}}}$$

Rayleigh Drag:

$$\mathcal{F}_{\mathrm{drag}} = -\frac{\mathbf{v}}{\tau_{\mathrm{drag}}}$$

Vary timescales by > 4 orders of magnitude in numerical simulations



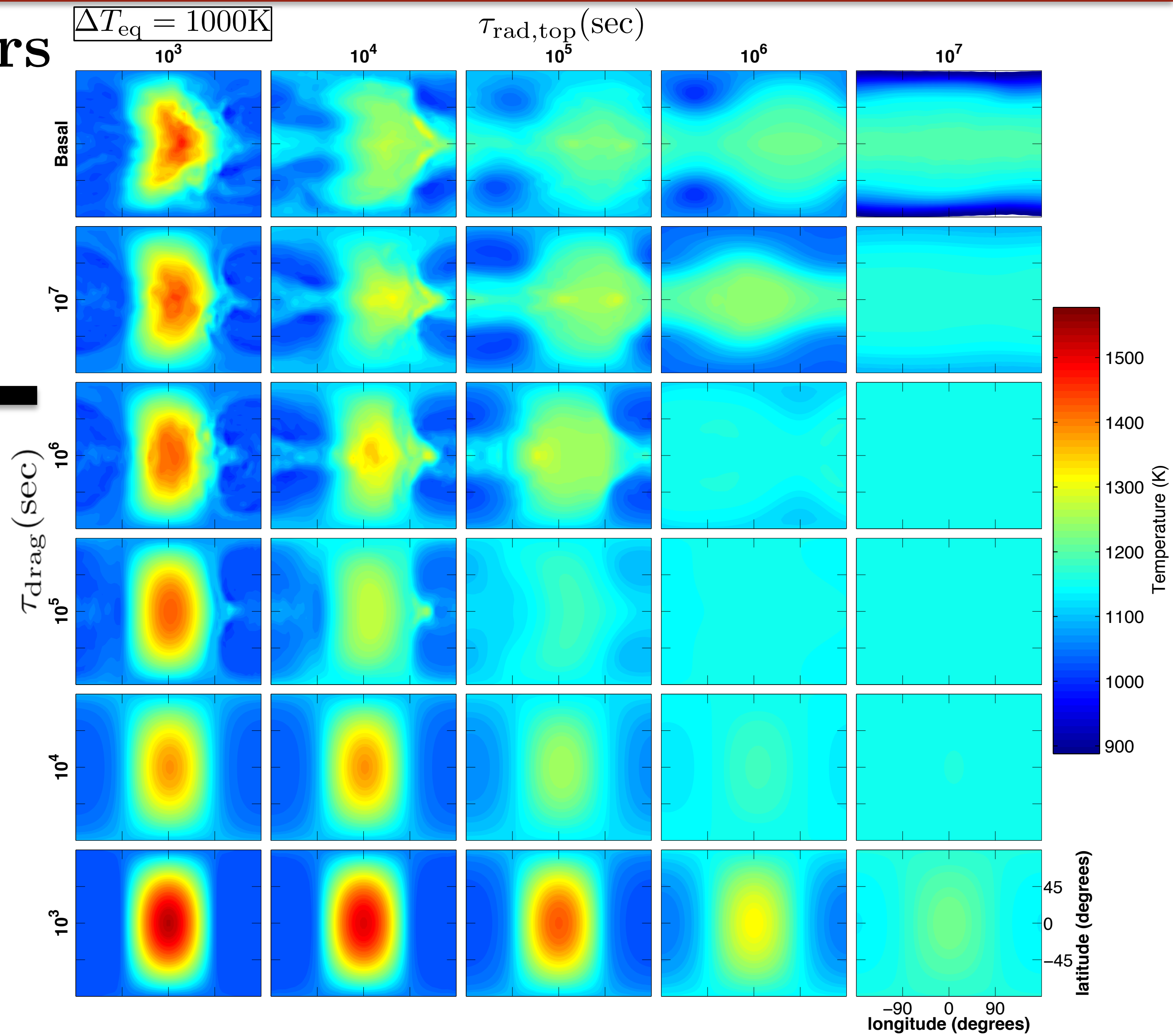
MITgcm

Numerical Results

P = 80 mbars

Increasing radiative damping

Increasing frictional drag

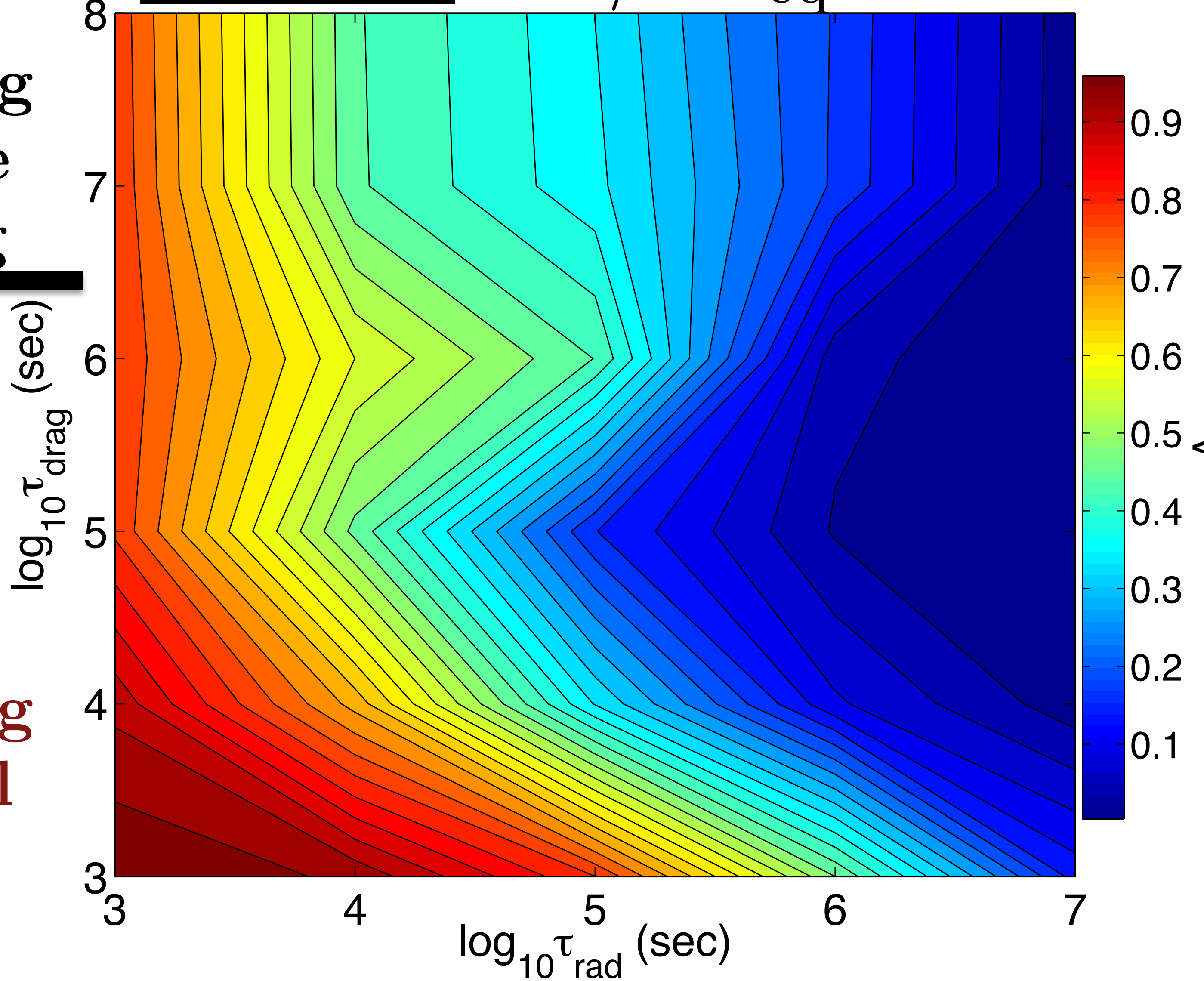


Numerical Results

P = 80 mbars **Contours:** $\Delta T/\Delta T_{eq}$

Increasing radiative damping

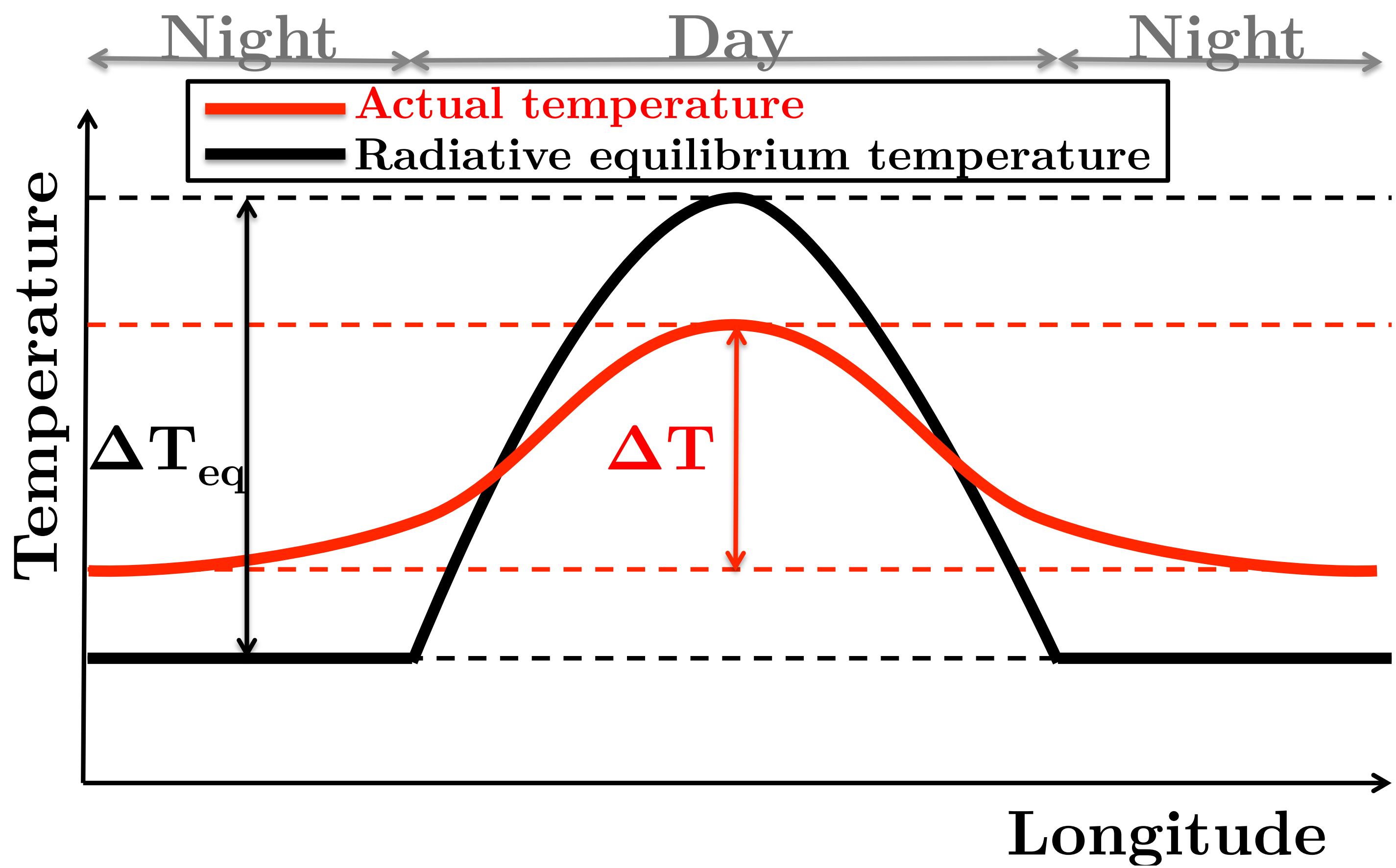
Increasing frictional drag



Analytic Theory

We have developed theory that *predicts* day-night temperature differences and wind speeds

Solve for day-night temperature differences relative to equilibrium day-night difference:



Theory: Approximate Equations

Need to assume given dominant terms in energy and momentum equations and couple them:

Which heating terms balance linear cooling?

$$\frac{dT}{dt} = \frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + \omega \frac{\partial T}{\partial p} = -\frac{T - T_{\mathrm{eq}}}{\tau_{\mathrm{rad}}} + \frac{\omega}{\rho c_p}$$

What balances day-night pressure gradients?

-Advection, Coriolis force, or drag

$$-\nabla \Phi = \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \omega \frac{\partial \mathbf{v}}{\partial p} + f\hat{\mathbf{k}} \times \mathbf{v} - \frac{\mathbf{v}}{\tau_{\mathrm{drag}}}$$

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-Run models to equilibration (steady-state)

<u>What balances day-night pressure gradients?</u>

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-Weak temperature gradient regime

-Tied closely to wave adjustment in Earth's tropics (Sobel et al. 2001)

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Theory: Approximate Equations

Need to assume given dominant terms in energy and momentum equations and couple them:

Which heating terms balance linear cooling?

$$\frac{\Delta T_{\mathrm{eq}} - \Delta T}{\tau_{\mathrm{rad}}} \sim \frac{\mathcal{W} N^2 H}{R}$$

-Weak temperature gradient regime

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What balances day-night pressure gradients?

-Advection, Coriolis force, or drag

$$\frac{R \Delta T}{a} \sim \max\left[\frac{\mathcal{U}^2}{a}, \frac{\mathcal{U}\mathcal{W}}{H}, \mathcal{U}\Omega, \frac{\mathcal{U}}{\tau_{\mathrm{drag}}}\right]$$

Theory: Approximate Equations

Need to assume given dominant terms in energy and momentum equations and couple them:

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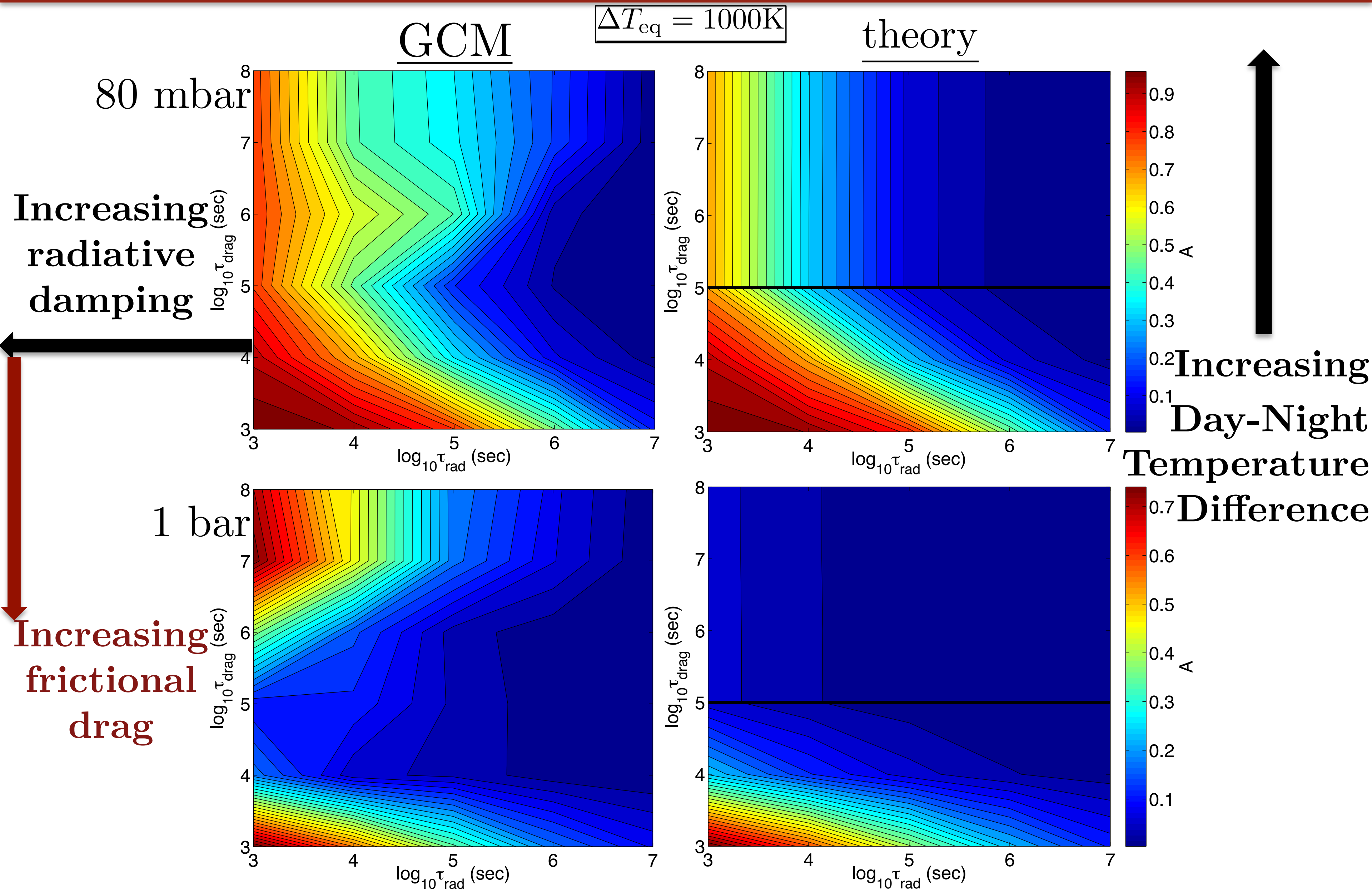
Test of the Theory: Day-Night Temperature Differences

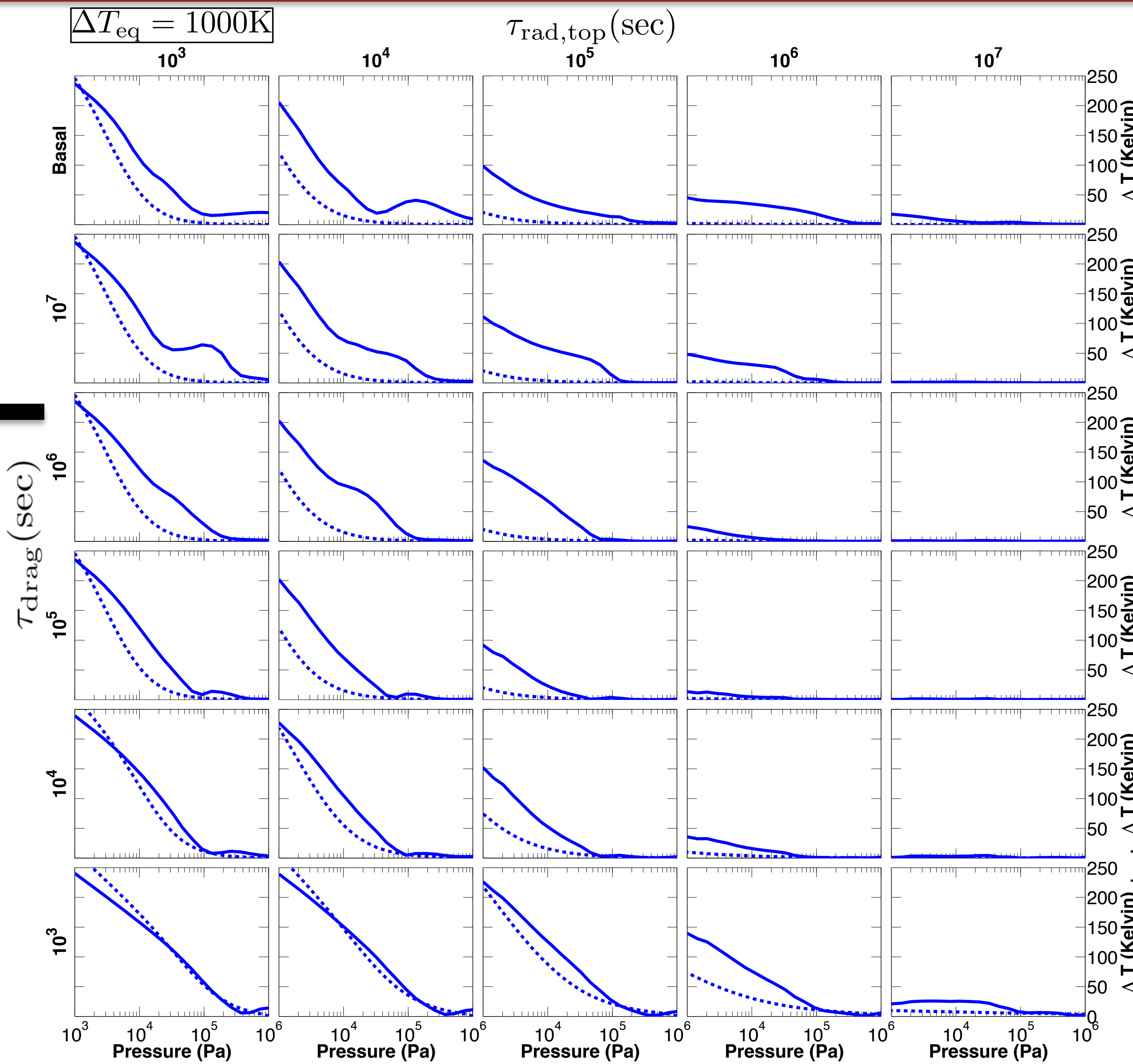


Test of the Theory: Pressure-Dependent Day-Night Temperature Differences

P = 80 mbars

Increasing radiative damping

Increasing frictional drag



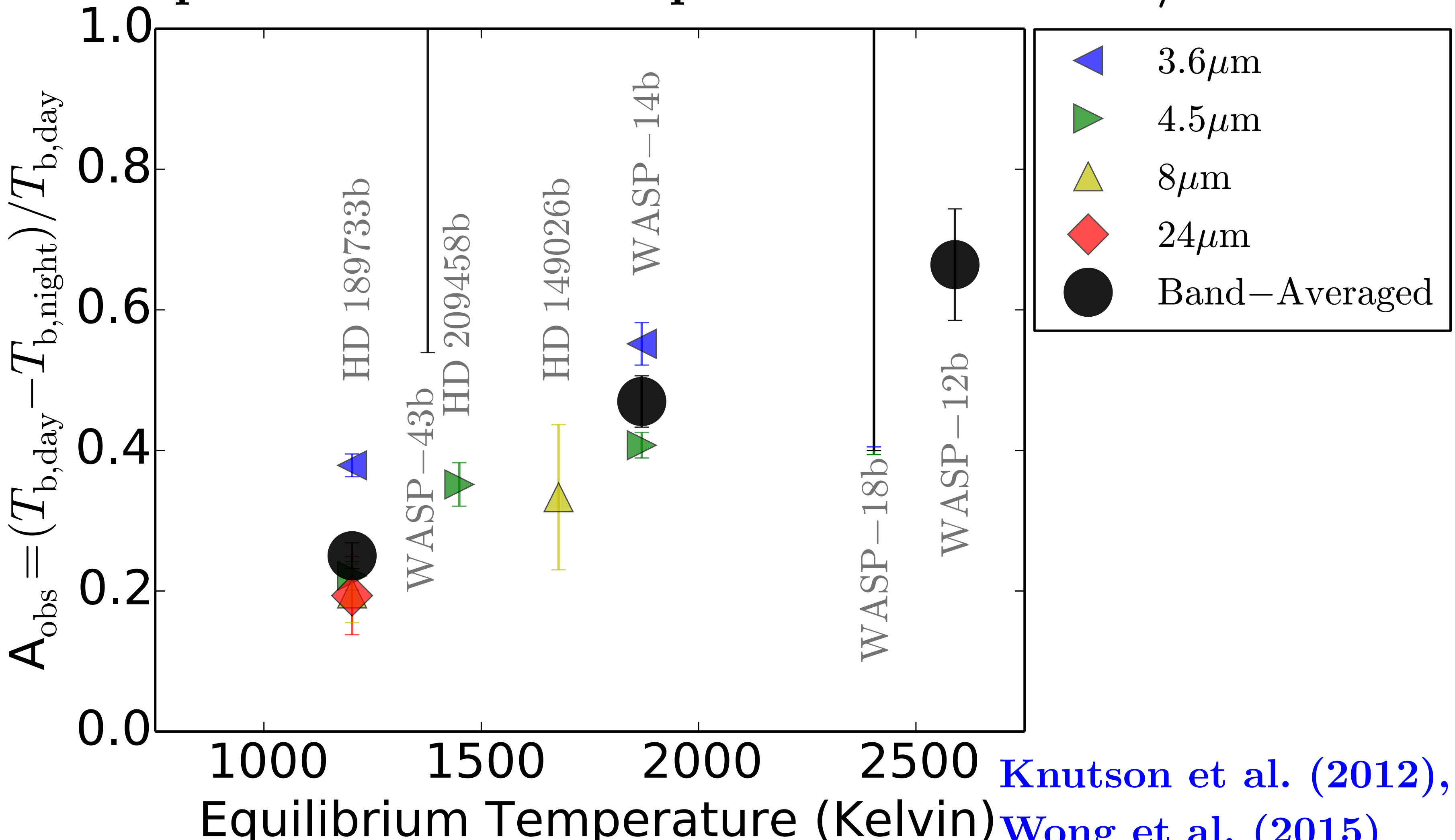
Dashed: Theory

Solid: GCM

Increasing Day-Night Temp Difference

Phase Curves: Non-Grey Effects

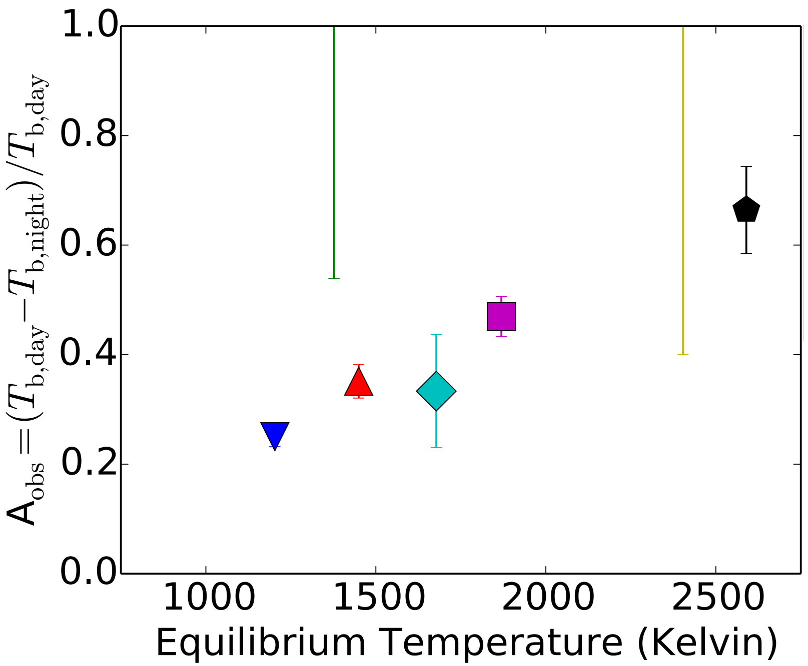
Day-night temperature differences depend on waveband: Photospheres at different pressure levels – C/O ratio?



Knutson et al. (2012), Wong et al. (2015)

Conclusions

1) **Heat Redistribution in hot Jupiter atmospheres is mediated by *wave adjustment***



2) **Simple analytic theory explains day-night temperature differences**

-Transitions in day-night temperature differences controlled by radiative forcing, with $\tau_{rad} \propto T_{eq}^{-3}$

3) **Non-grey effects play a large role in observed phase curve amplitudes**

-Next step: construct a band-grey model to enable comparison with multi-wavelength observations