A simple model for understanding the day-night temperature contrast on hot Jupiters

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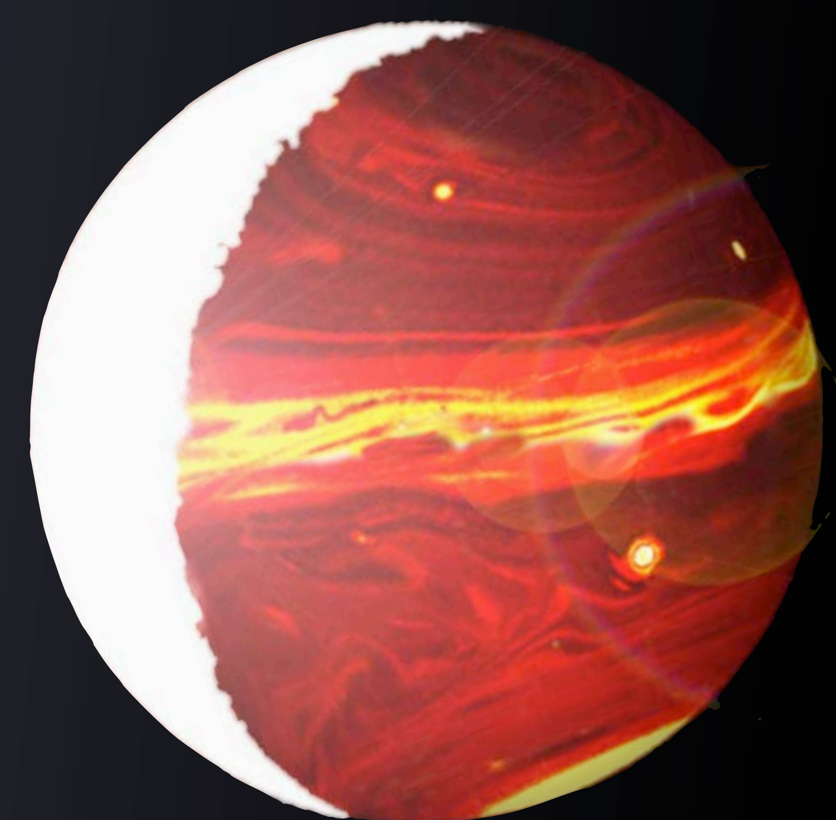


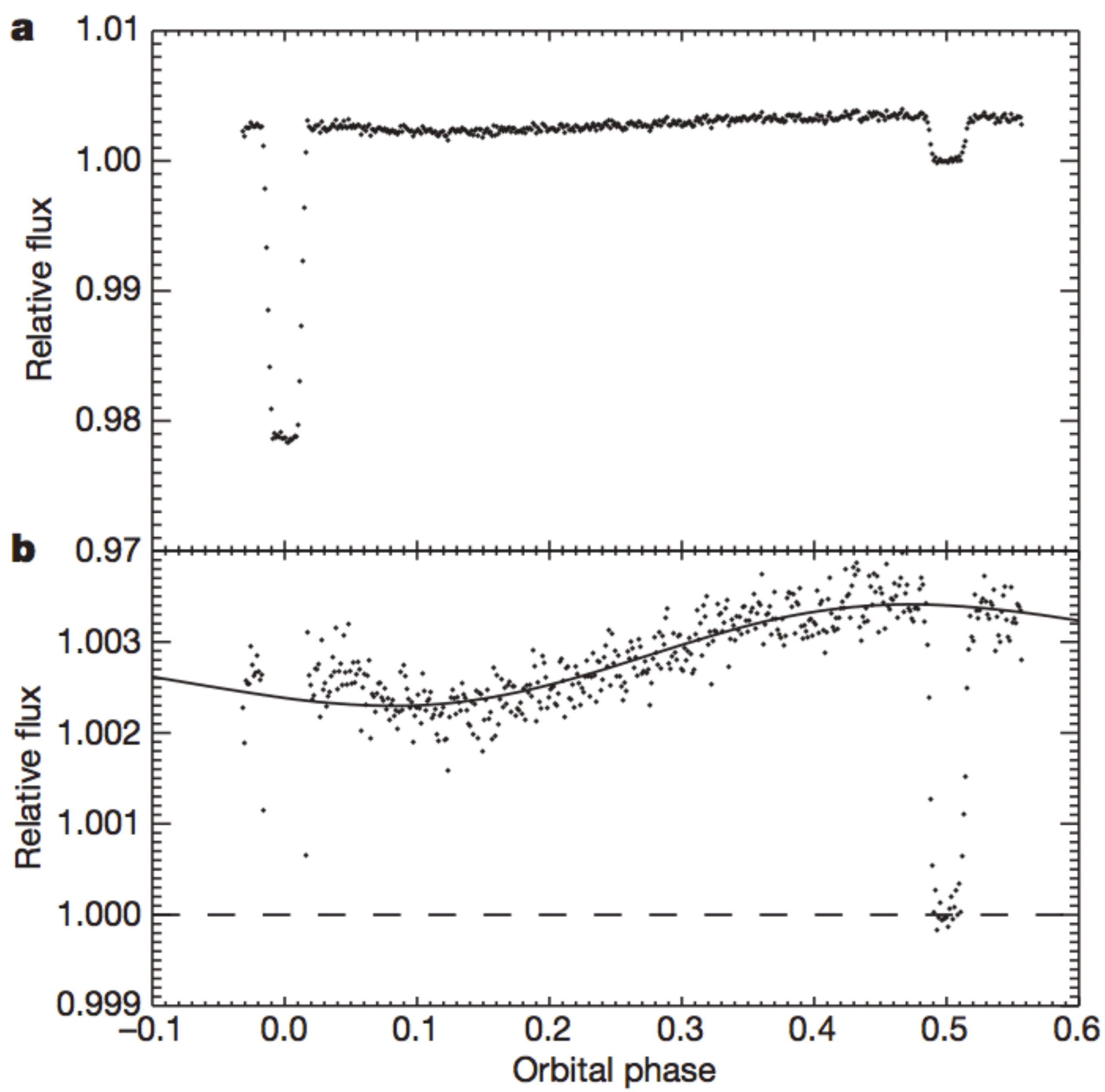
Background

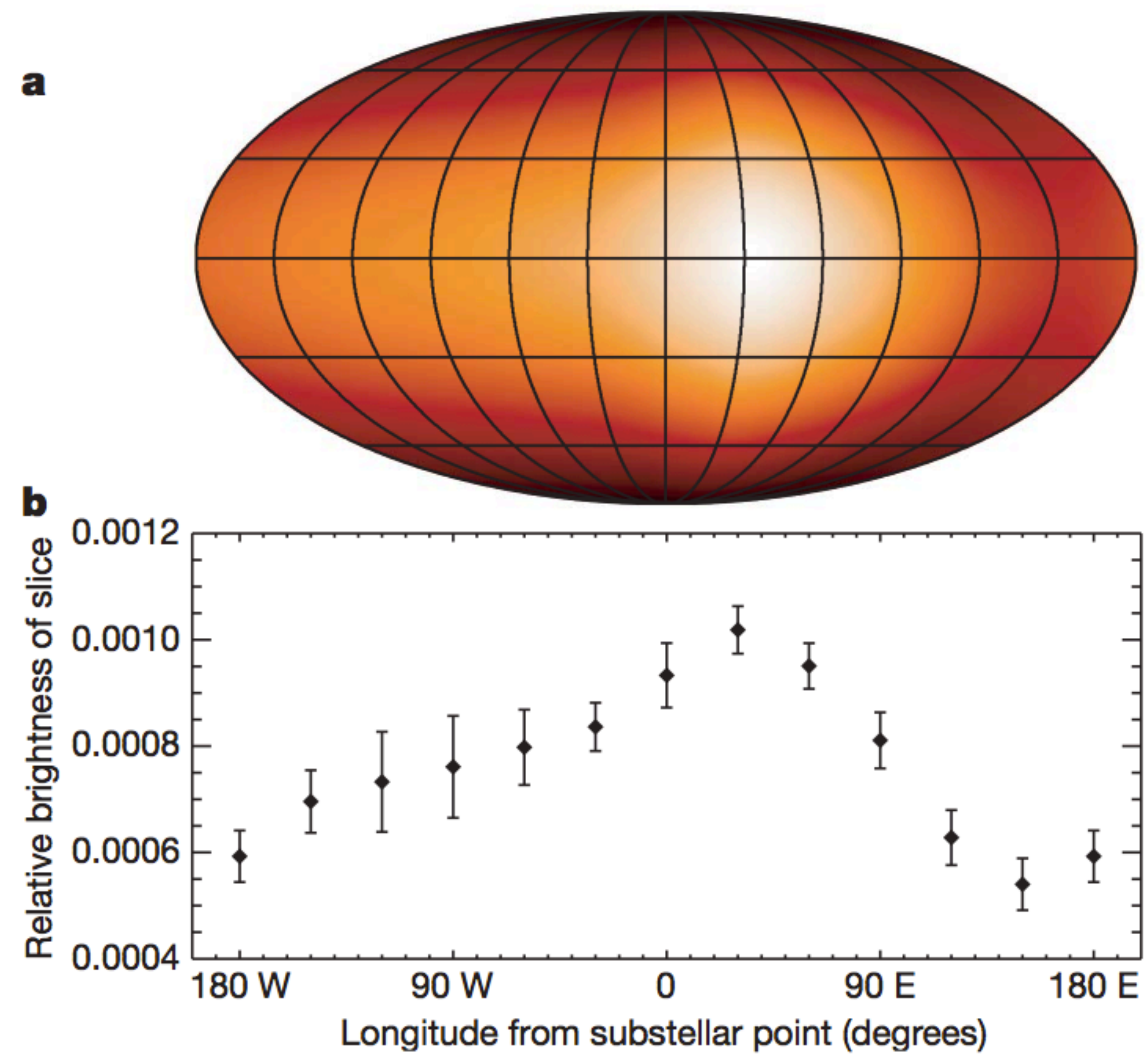
Hot Jupiters are tidally locked and therefore have a permanent dayside and nightside.

Synchronous rotation with the 1- 10 day orbital periods means that Coriolis forces are important but do not dominate the flow.

Global wind circulation is driven by the intense heating contrast. About 10^5 W/m^2 of stellar heating on dayside and IR-cooling on nightside

Spitzer observations of stellar+planet lightcurves can be used to determine temperature contrast on hot Jupiters.





HD 189733b, Knutson et al. (2007)

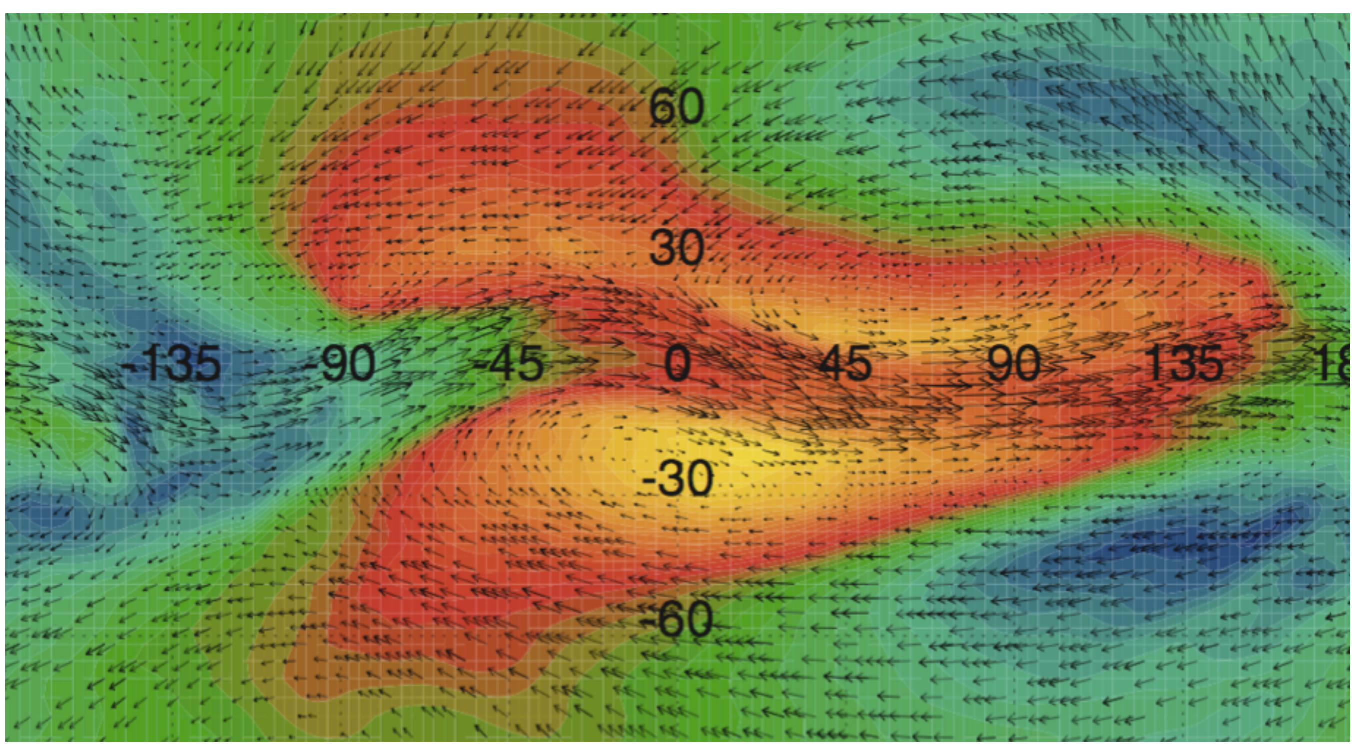
Heat advection

People traditionally assumed that heat is transported by the advection of hot gas from the dayside to the nightside

This has lead to the somewhat unjustified assumption that the day-night temperature contrast can be estimated by comparing:

$\tau_{rad} << \tau_{adv}$: large contrast in day-night temperature

$\tau_{rad} >> \tau_{adv}$: uniform global temperature



Menou & Rauscher (2009)

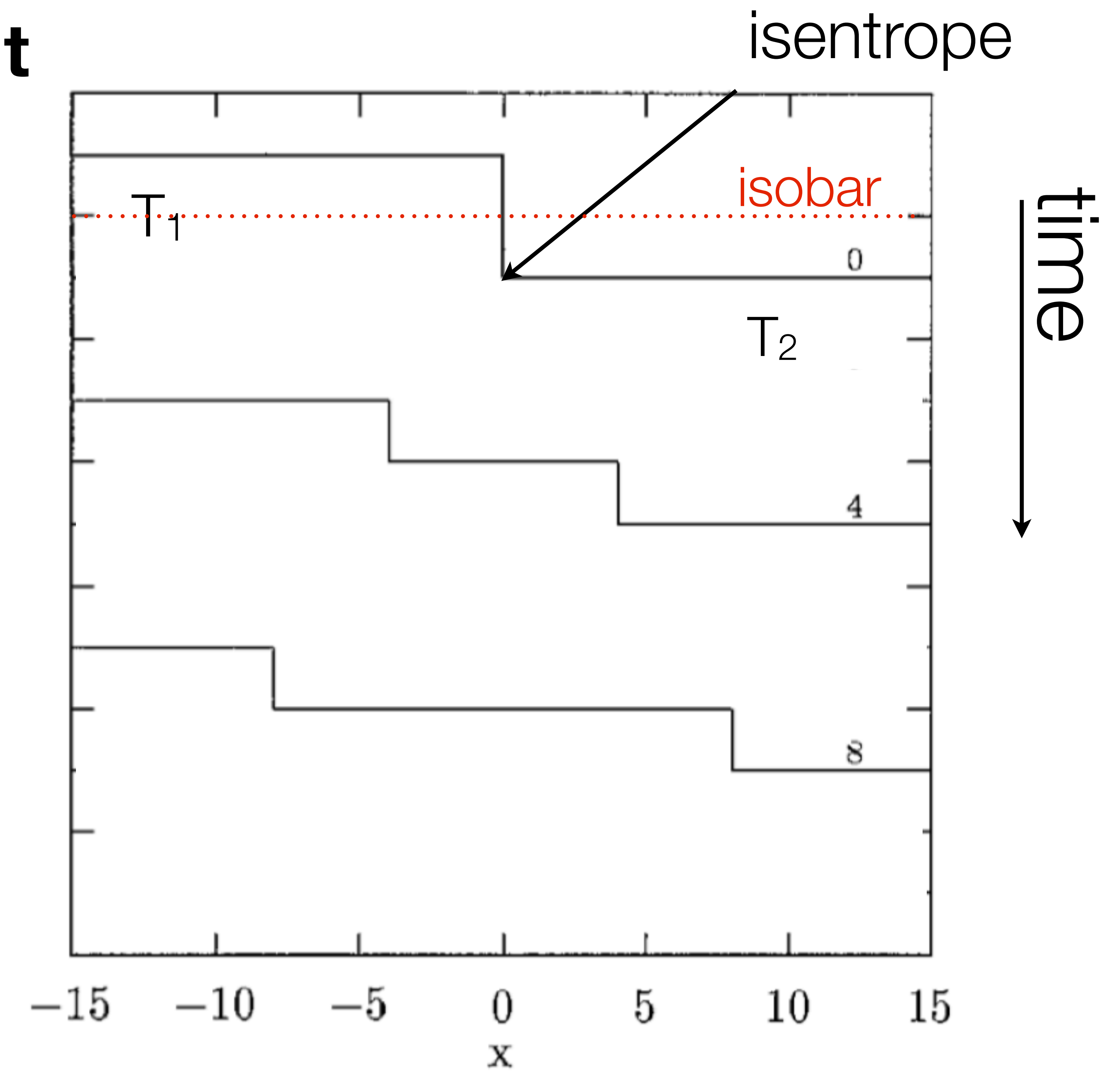
Simulations of hot Jupiter atmospheres develop superrotating equatorial jets (u_{jet} ~1km/s) that can advect heat from the dayside to the nightside.

However that is not the only mechanism for regulating the temperature on a planet...

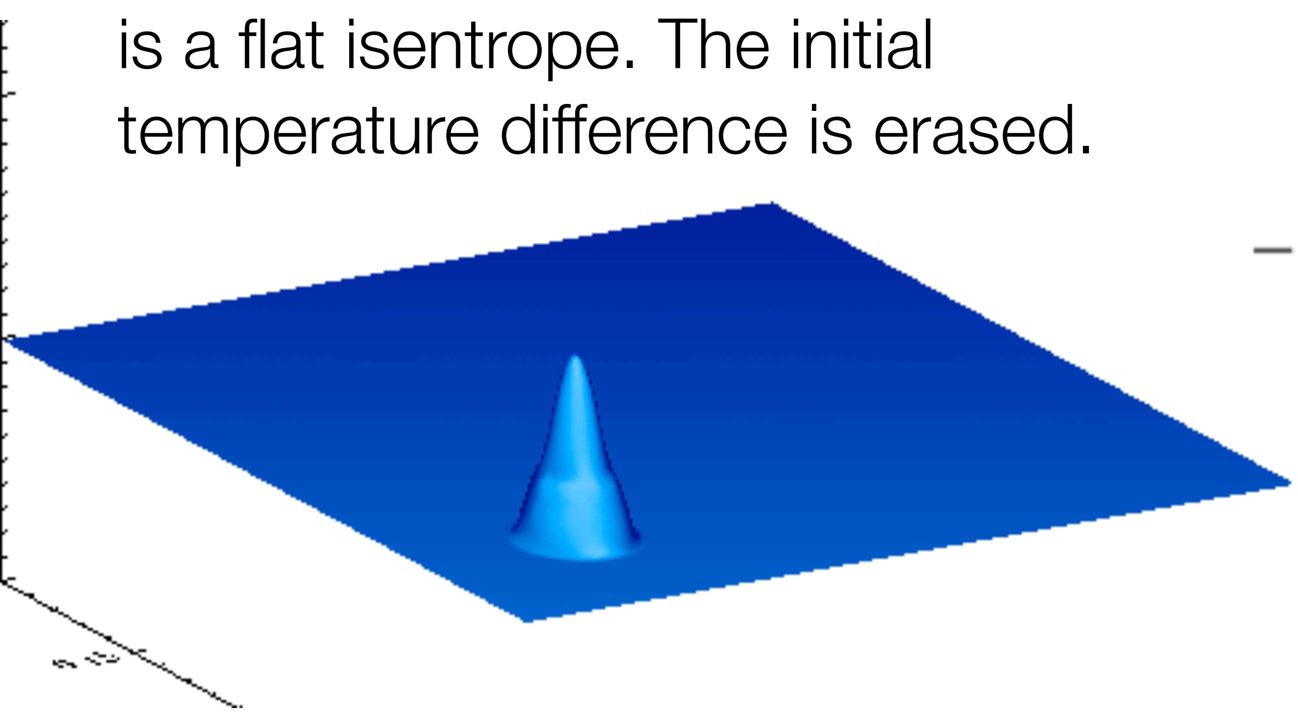
Gravity wave adjustment

Atmosphere can also adjust via gravity waves to buoyancy forces caused by lateral variations in heating and cooling rates.

Initial step in isentrope topography causes a strong, unbalanced horizontal pressure-gradient force, which leads to the radiation of gravity waves. Assuming the waves can radiate to infinity, the final state is a flat isentrope. The initial temperature difference is erased.



Kuo & Polvani (1997)

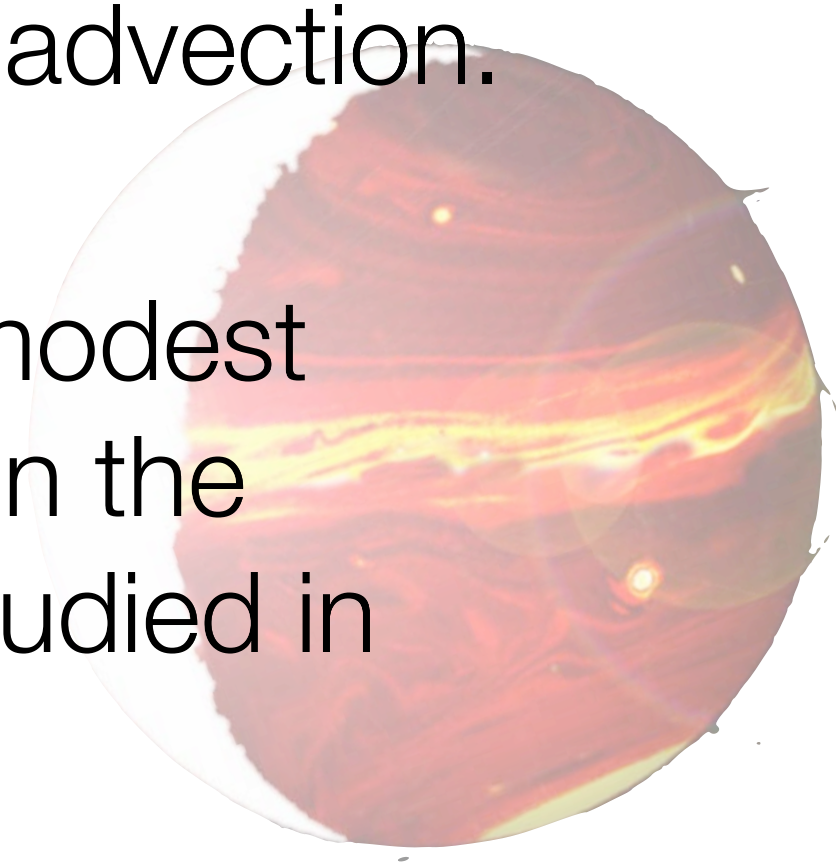


Flattening of isentropes by gravity waves erases the day-night temperature difference.

This mechanism does not involve large parcel displacements.

It acts on a different timescale than advection.

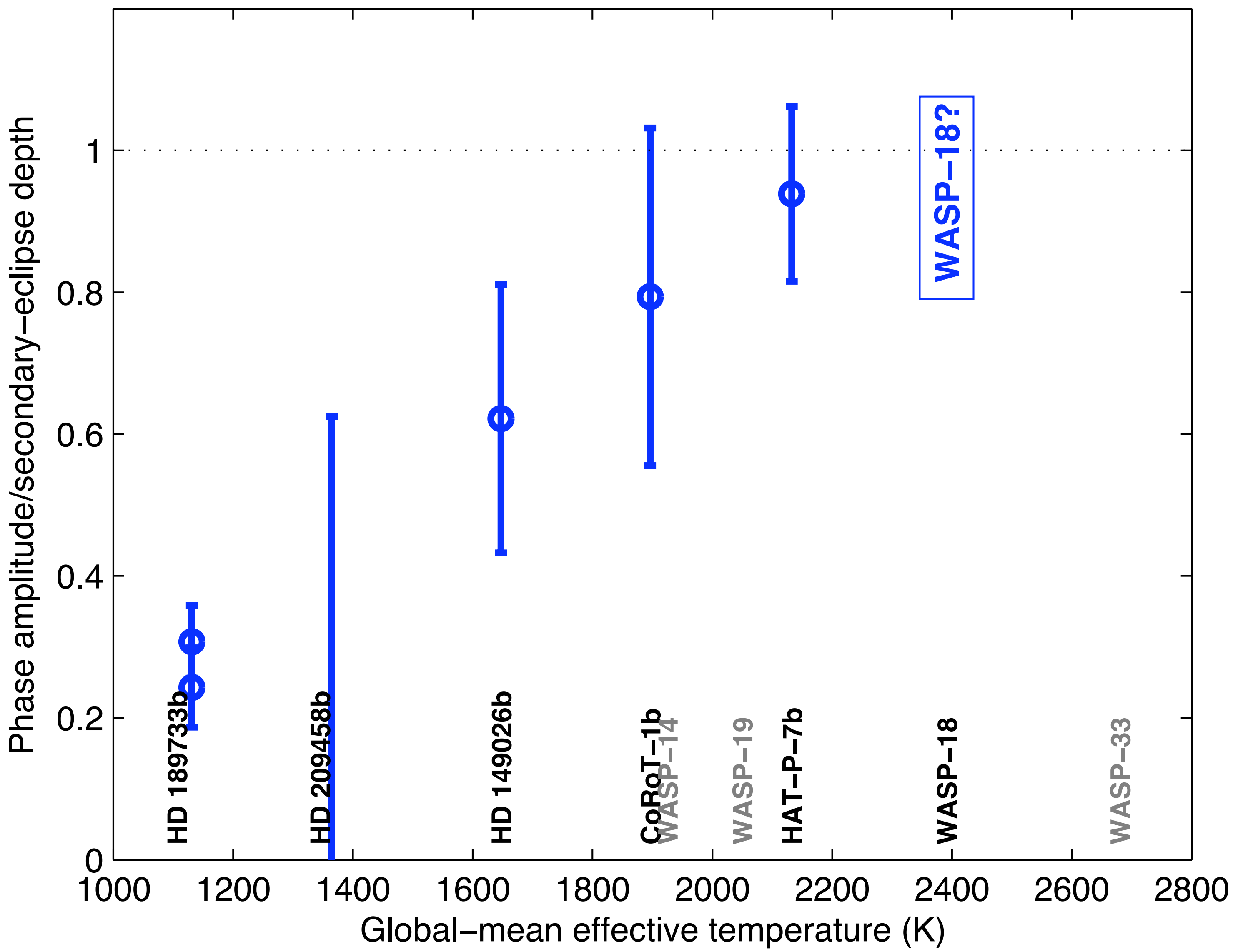
Accepted mechanism behind the modest longitudinal temperature variation on the Earth’s tropics, but has yet to be studied in the hot Jupiter context.



Which is the relevant dynamical time scale that sets the temperature contrast on hot Jupiters (advective or gravity wave)?

What should it be compared against? The radiative time constant or the frictional (drag) time constant?

What causes the transition from small to large day-night temperature contrasts on hot Jupiters?



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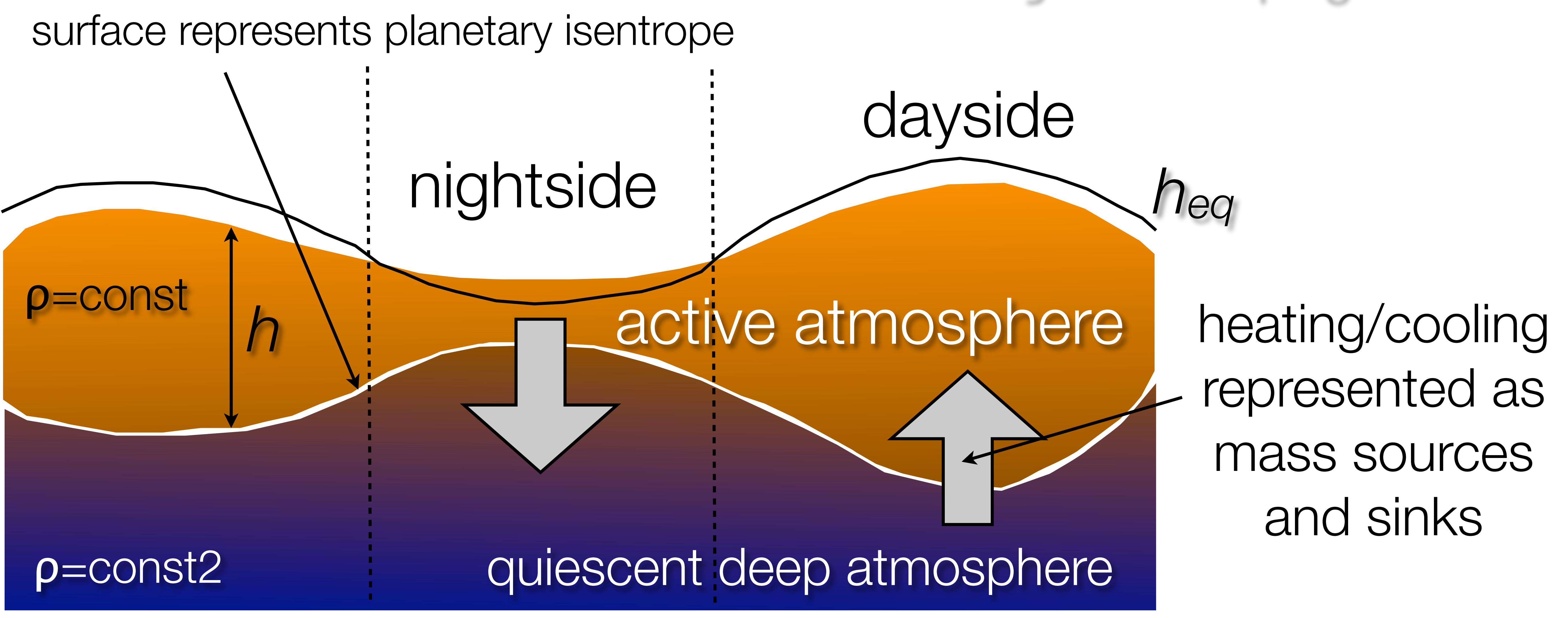
We use extremely idealized models to isolate the relevant timescales for dynamics and damping.

Shallow water equations for a single fluid layer

$$\frac{d\mathbf{v}}{dt} + g\nabla h + f\mathbf{k}\times\mathbf{v} = \mathbf{R} - \frac{\mathbf{v}}{\tau_{\rm drag}} \quad \text{Drag}$$

$$\frac{\partial h}{\partial t} + \nabla\cdot(\mathbf{v}h) = \frac{h_{\rm eq}(\lambda,\phi) - h}{\tau_{\rm rad}} \equiv Q \quad \text{Thermal forcing/damping}$$



Study problem with models increasing in complexity

First consider 1D linear, steady, analytic solutions
Then 2D linear, steady, analytic solutions
Finally, consider 2D nonlinear solutions on a sphere

$$\left.\begin{aligned}\frac{d\mathbf{v}}{dt}+g\nabla h+f\mathbf{k}\times\mathbf{v}&=\mathbf{R}-\frac{\mathbf{v}}{\tau_{\text{drag}}}\\ \frac{\partial h}{\partial t}+\nabla\cdot(\mathbf{v}h)&=\frac{h_{\text{eq}}(\lambda,\phi)-h}{\tau_{\text{rad}}}\equiv Q\end{aligned}\right\}\left\{\begin{aligned}u\frac{\partial u}{\partial x}+g\frac{\partial h}{\partial x}&=-\frac{u}{\tau_{\text{drag}}}\\ \frac{\partial}{\partial x}(uh)&=\frac{h_{\text{eq}}-h}{\tau_{\text{rad}}}\end{aligned}\right.$$

2D shallow water model

1D shallow water at the Equator

linearize about:
$h = H + \eta; \quad u = \bar{u} + u'$

Linearized 1D shallow water model

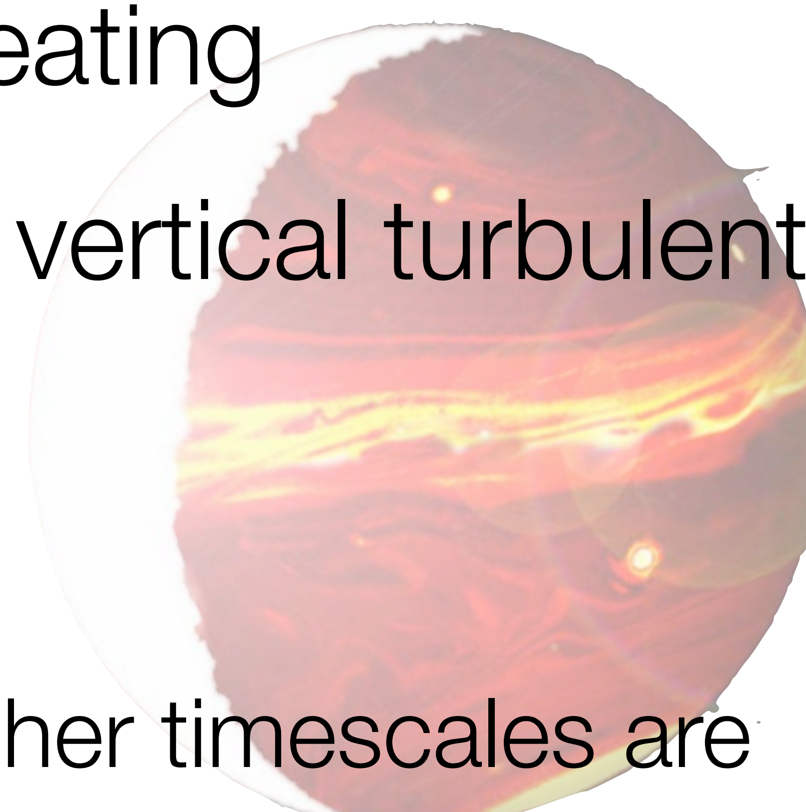
$$\bar{u}\frac{\partial u'}{\partial x} + g\frac{\partial \eta}{\partial x} = -\frac{u'}{\tau_{\mathrm{drag}}}$$

$$\bar{u}\frac{\partial \eta}{\partial x} + H\frac{\partial u'}{\partial x} = \frac{h_{\mathrm{eq}}-H}{\tau_{\mathrm{rad}}} - \frac{\eta}{\tau_{\mathrm{rad}}}$$

Relevant timescales:

τ_{rad}: radiative timescale for cooling/heating

τ_{drag}: magnetohydrodynamic friction, vertical turbulent mixing...

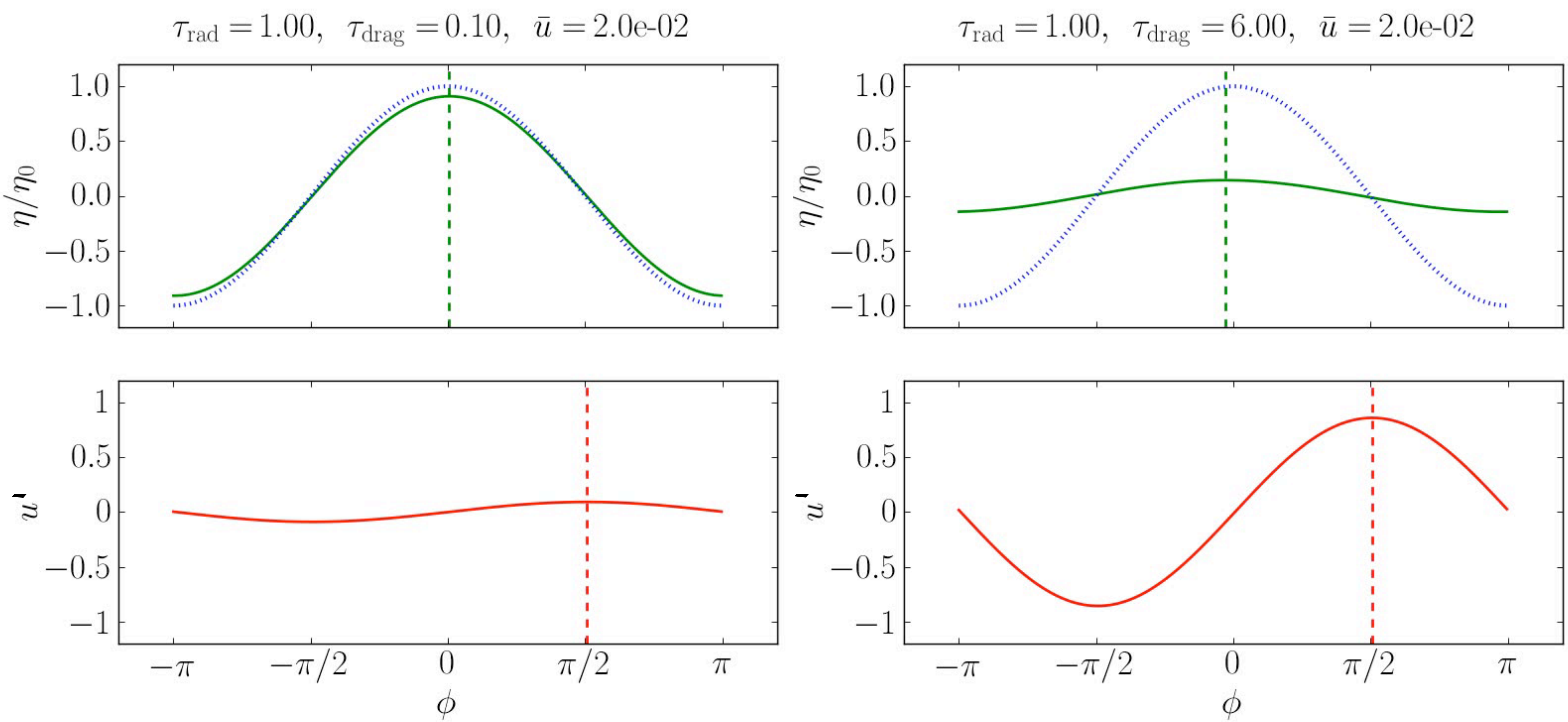


$\tau_{\mathrm{adv}} \sim a/\bar{u}$

$\tau_{\mathrm{wave}} \sim a/\sqrt{gH}$ — kept constant, all other timescales are normalized to the wave timescale

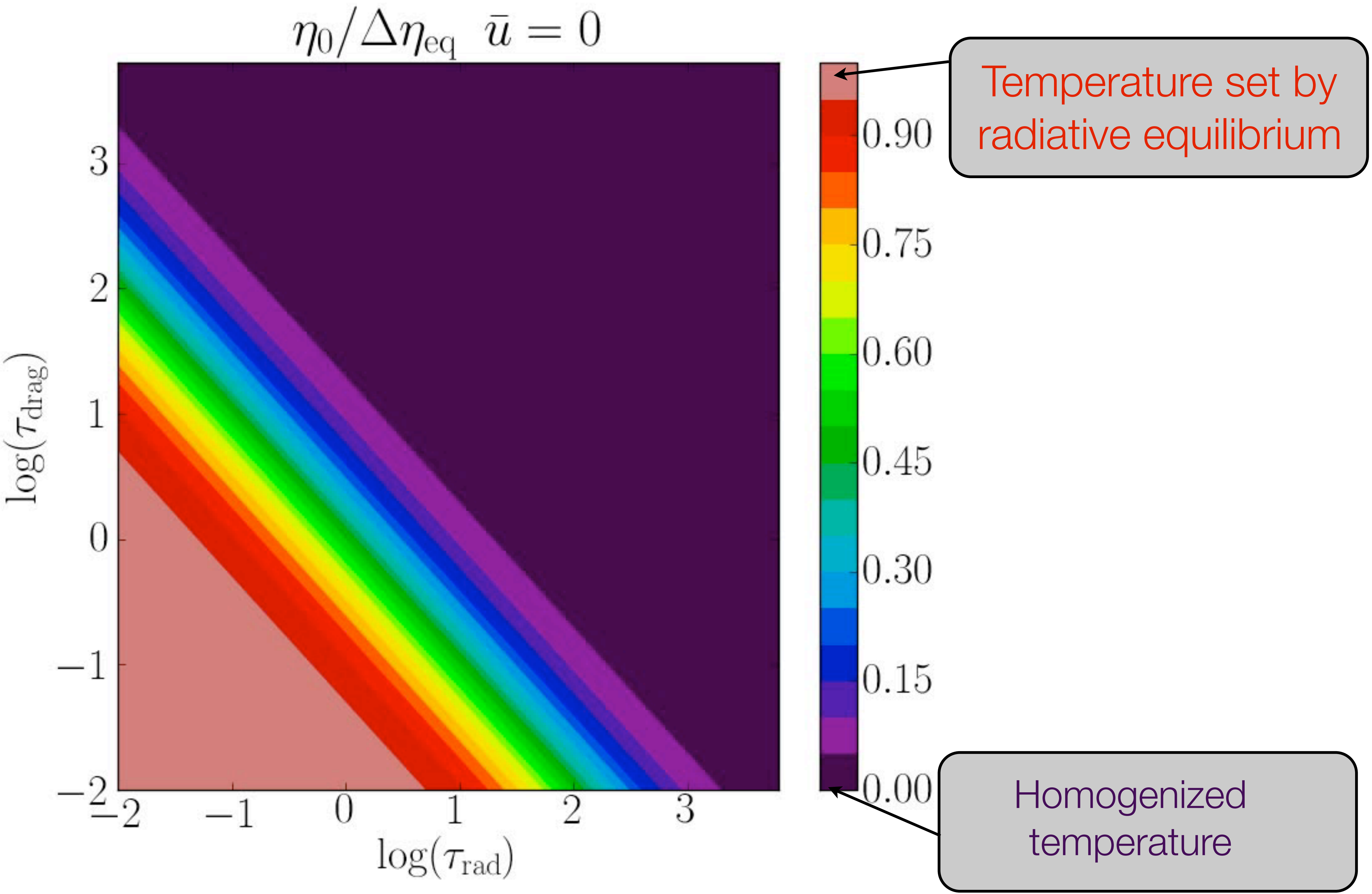
In the strong drag limit, heat is transported primarily by advection.

For low drag, there is a complex interplay between heat transport by gravity waves and jet advection.

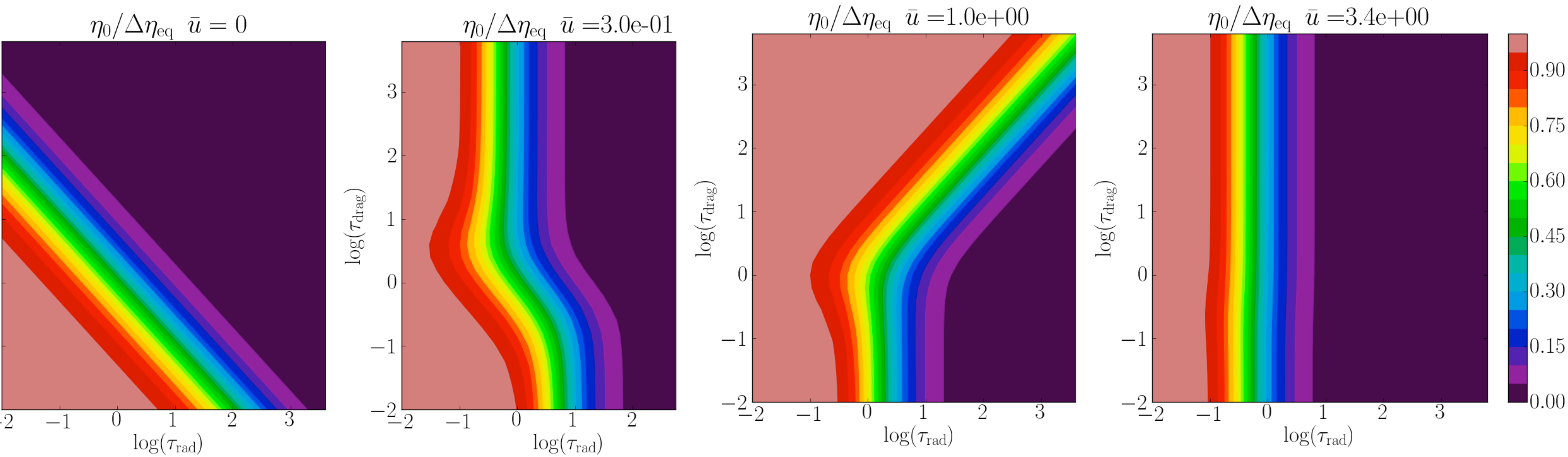


Final states are both advection dominated, drag becomes irrelevant

Day-Night temperature contrast as a function of timescales
1D Model



Day-Night temperature contrast as a function of ū

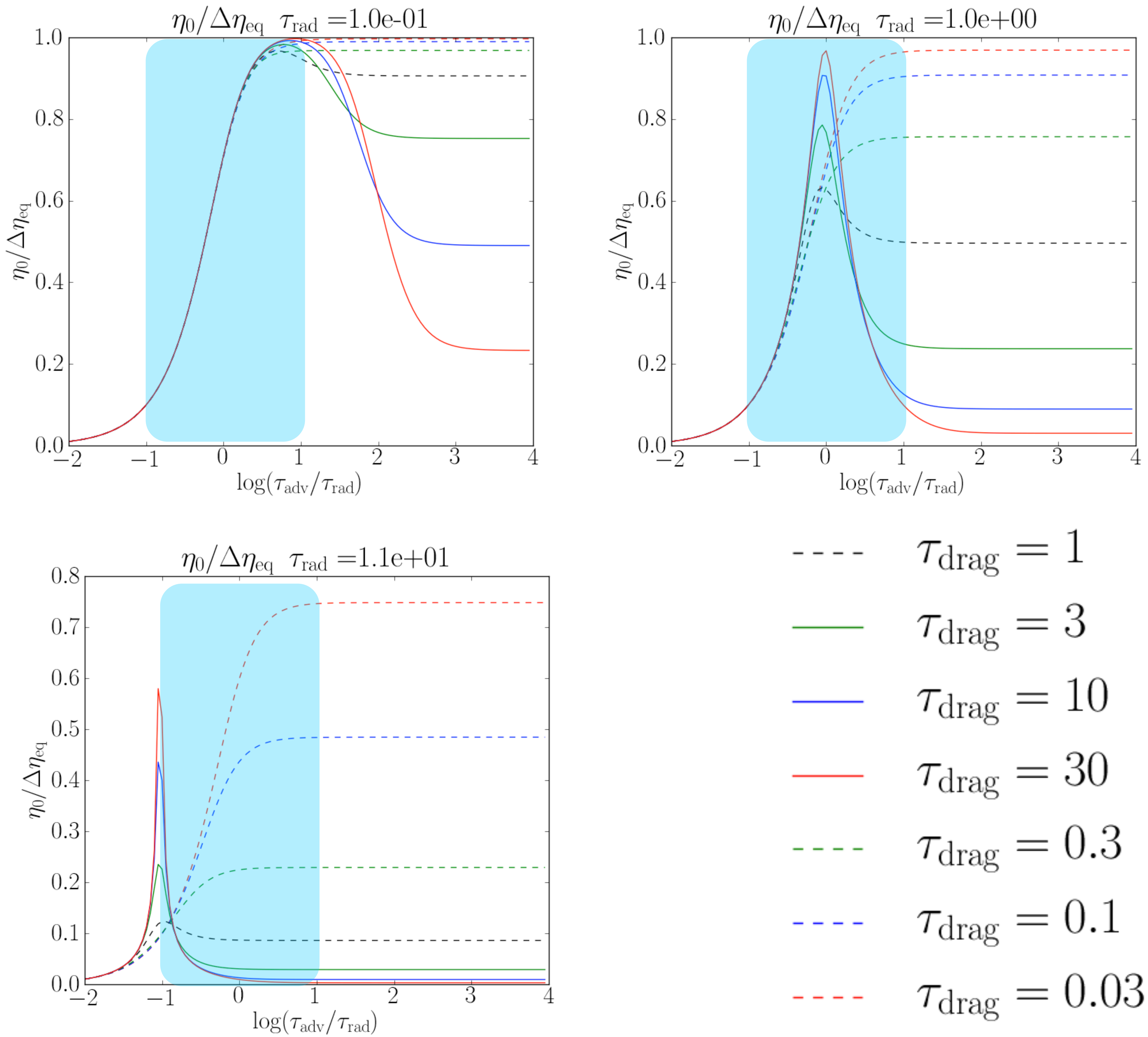


$\bar{u}_{adv} = 0$ $\bar{u}_{adv} < u_{wave}$ $\bar{u}_{adv} \sim u_{wave}$ $\bar{u}_{adv} > u_{wave}$

Typical values for hot Jupiters:

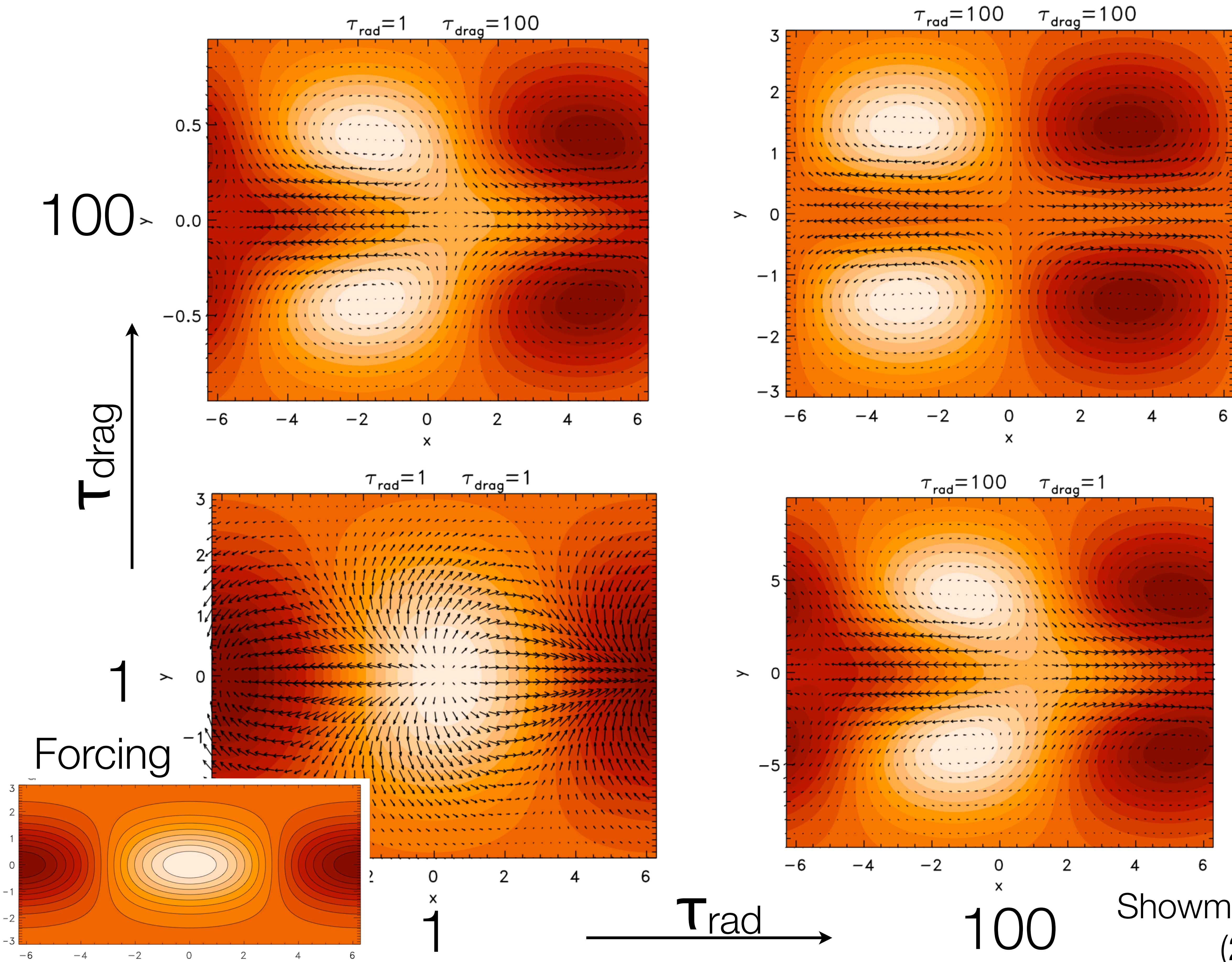
$\bar{u}_{adv} \sim u_{jet} \sim$ 1-3 km/s

$u_{wave} \sim$ 2 km/s



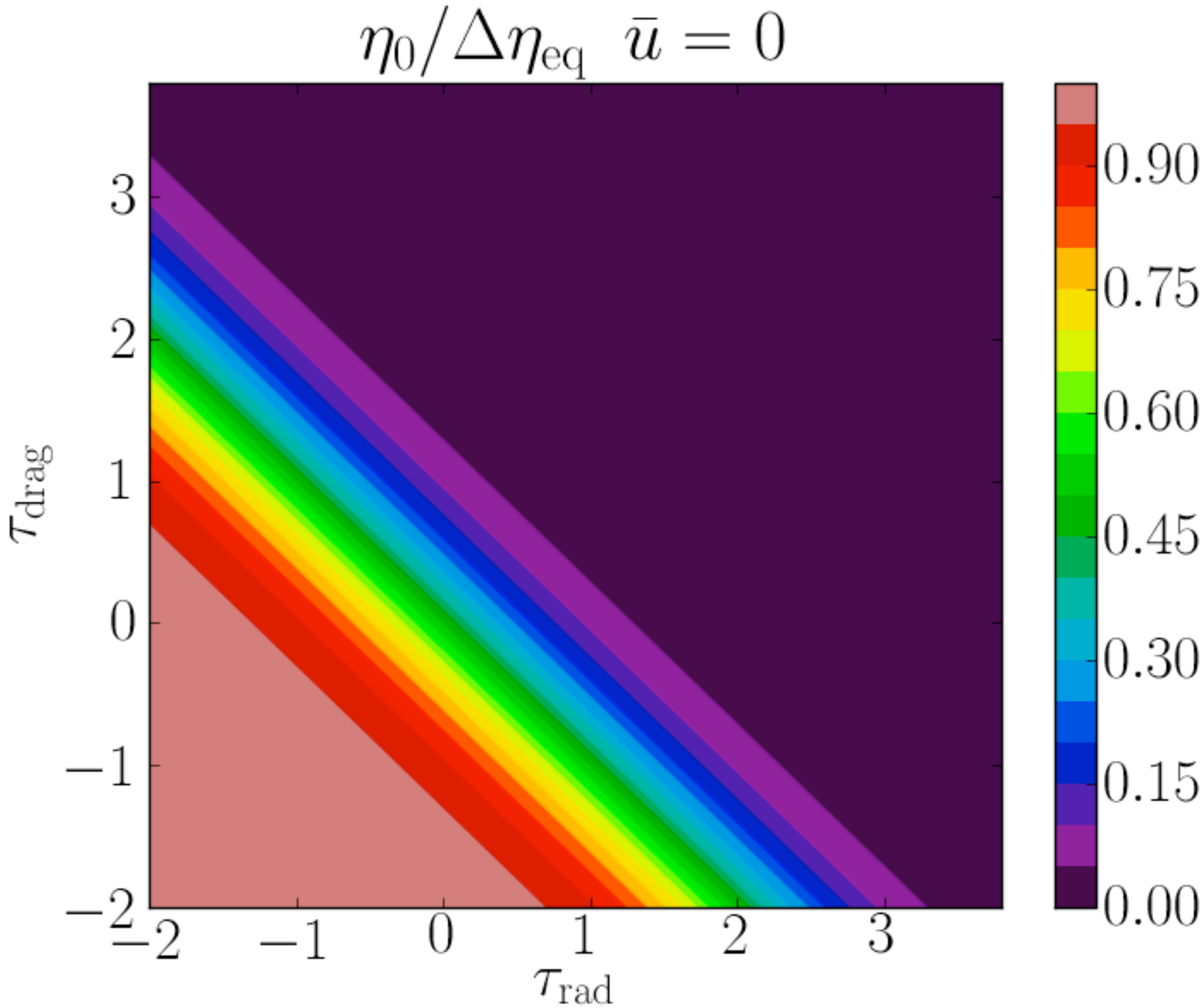
$\eta_0/\Delta\eta_{eq}$ τ_{rad} =1.0e-01
$\eta_0/\Delta\eta_{eq}$ τ_{rad} =1.0e+00
$\eta_0/\Delta\eta_{eq}$ τ_{rad} =1.1e+01
$\eta_0/\Delta\eta_{eq}$
$\log(\tau_{adv}/\tau_{rad})$
$\tau_{drag} = 1$
$\tau_{drag} = 3$
$\tau_{drag} = 10$
$\tau_{drag} = 30$
$\tau_{drag} = 0.3$
$\tau_{drag} = 0.1$
$\tau_{drag} = 0.03$

Linear 2D model with $\bar{u}=0$

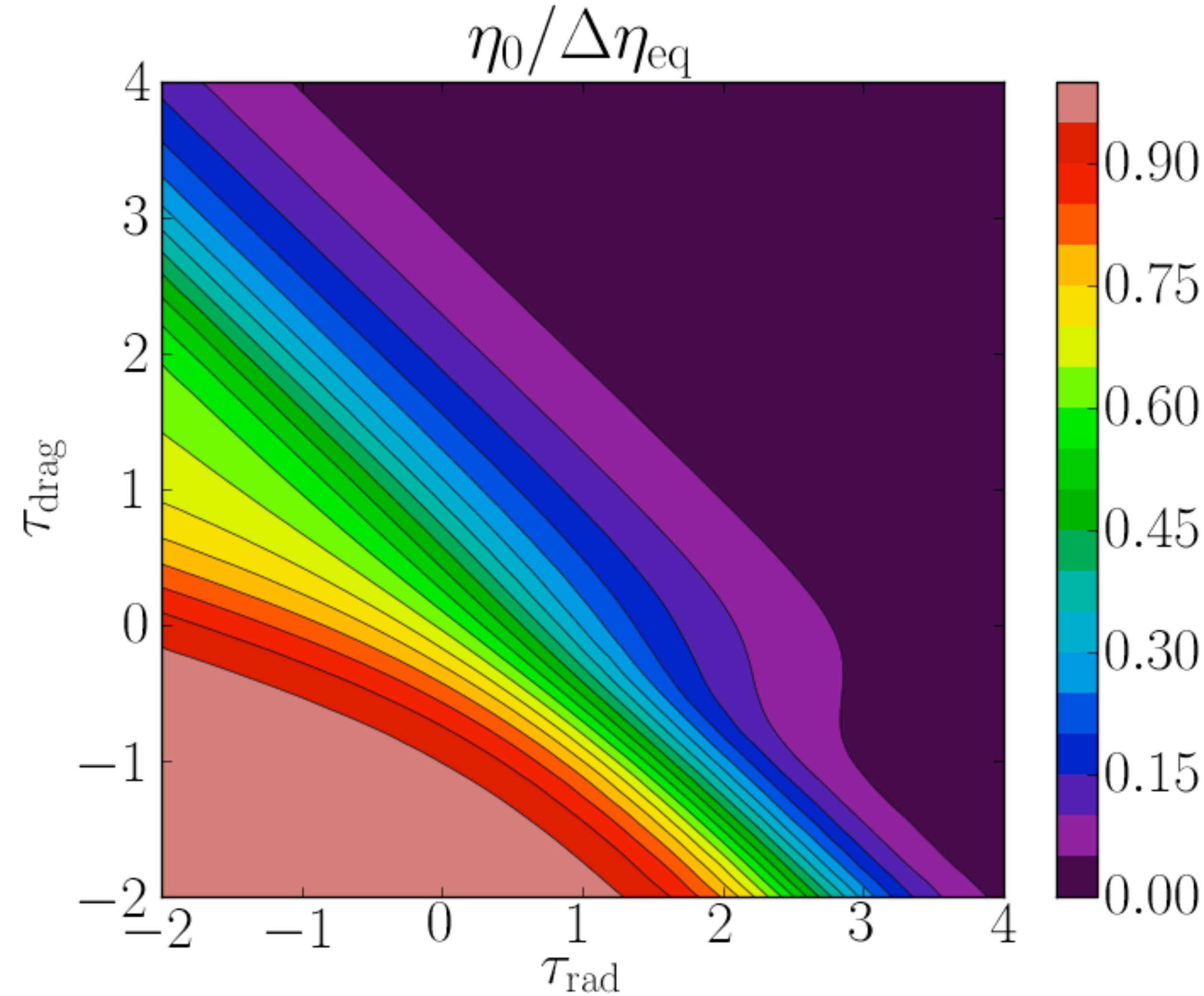


Showman & Polvani (2011)

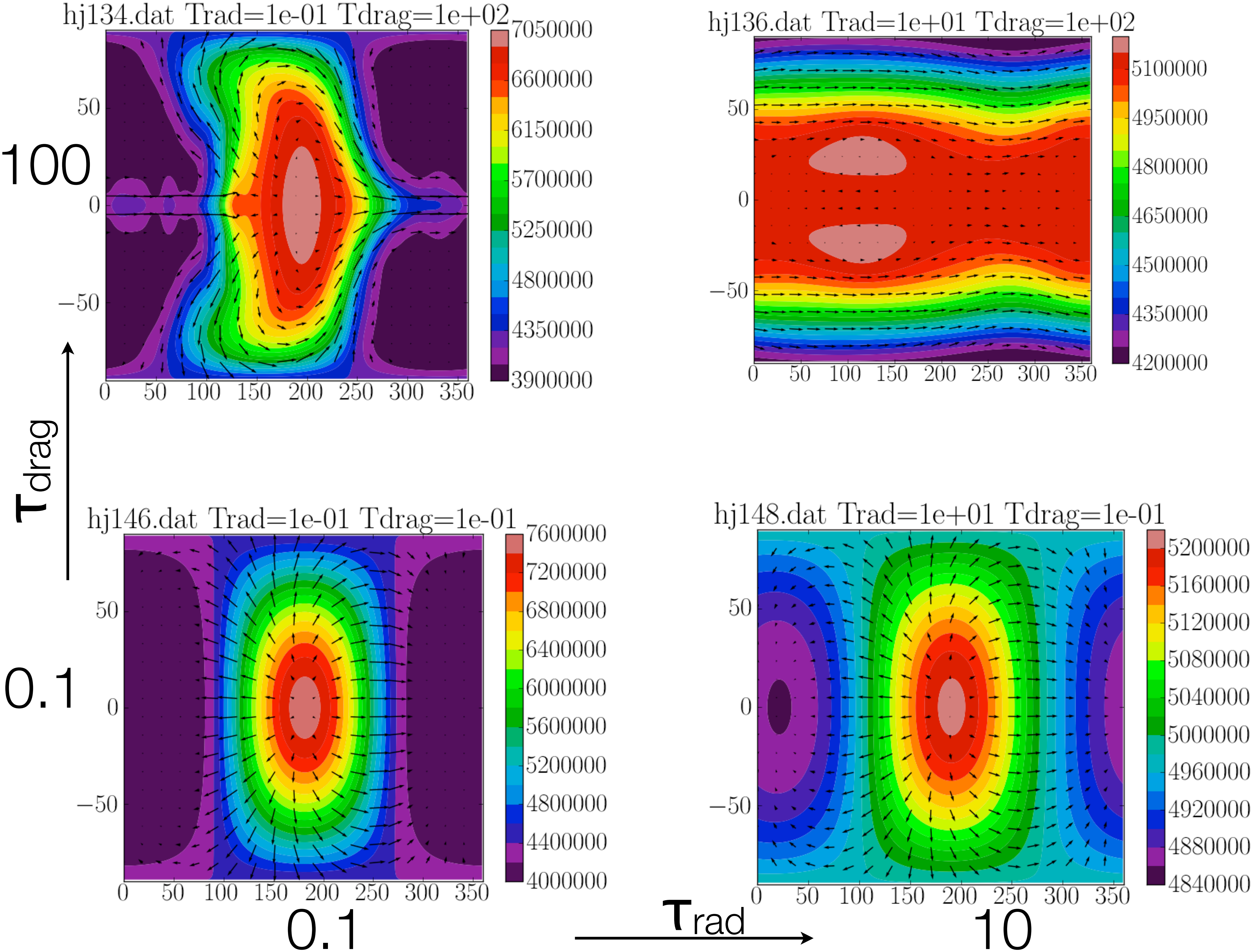
1D linear u=0 (analytical solution)

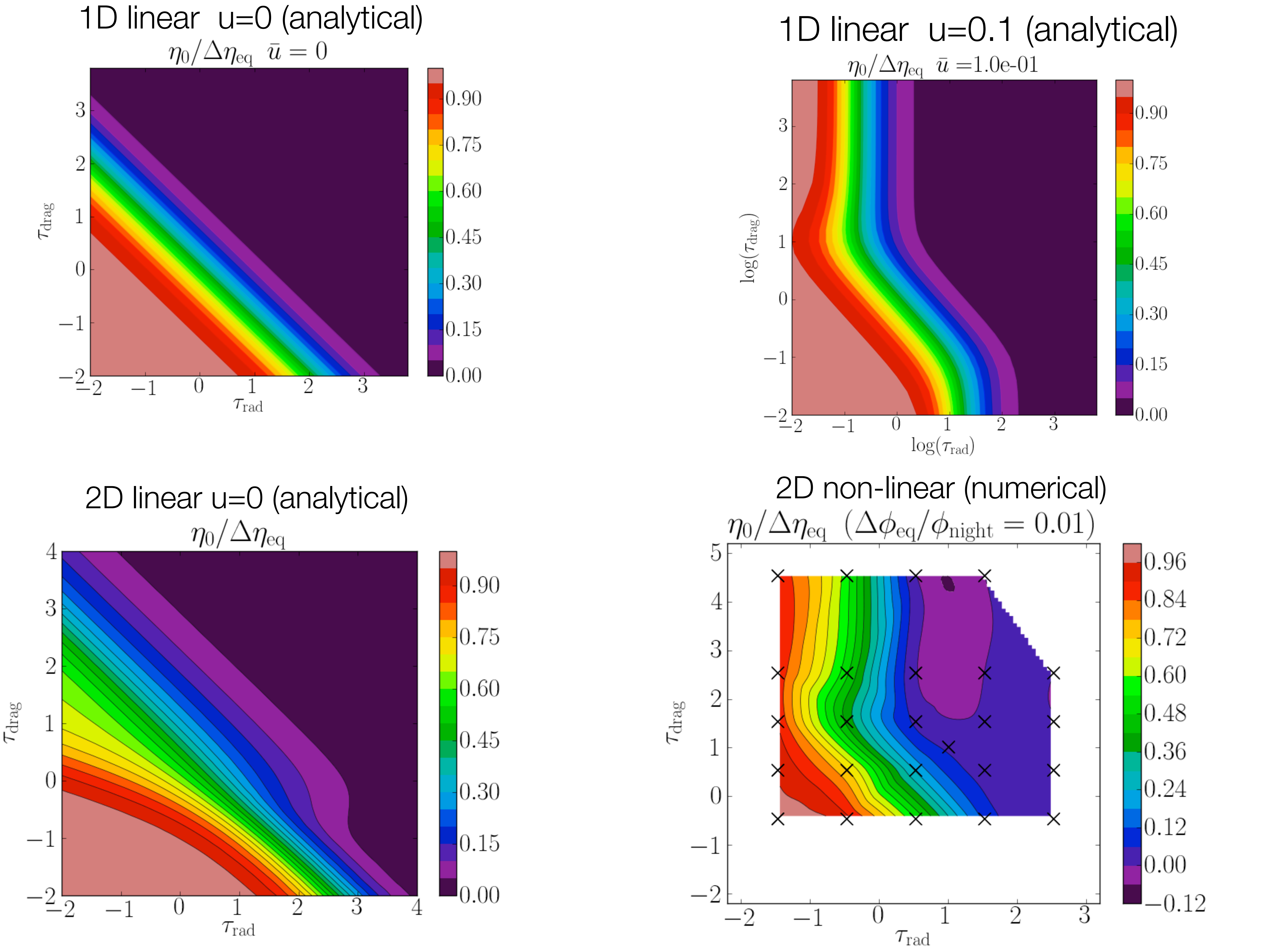


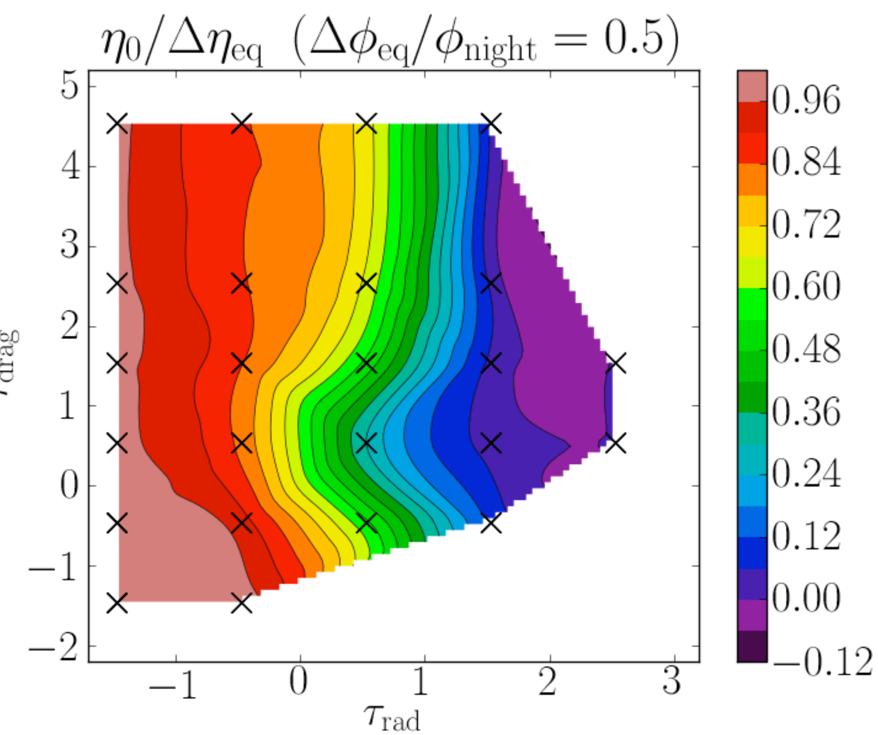
2D linear u=0 (analytical solution)

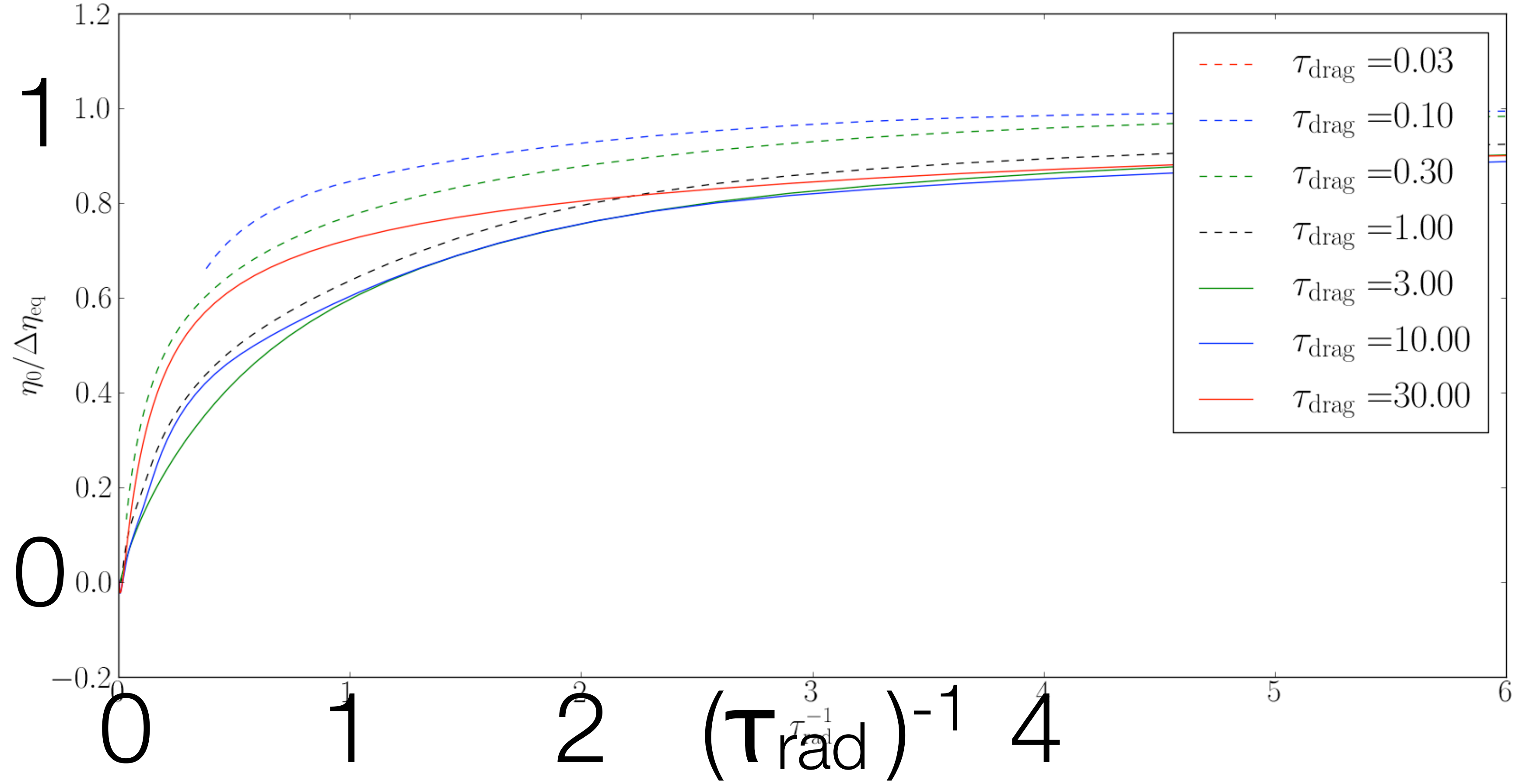


Full non-linear 2D model



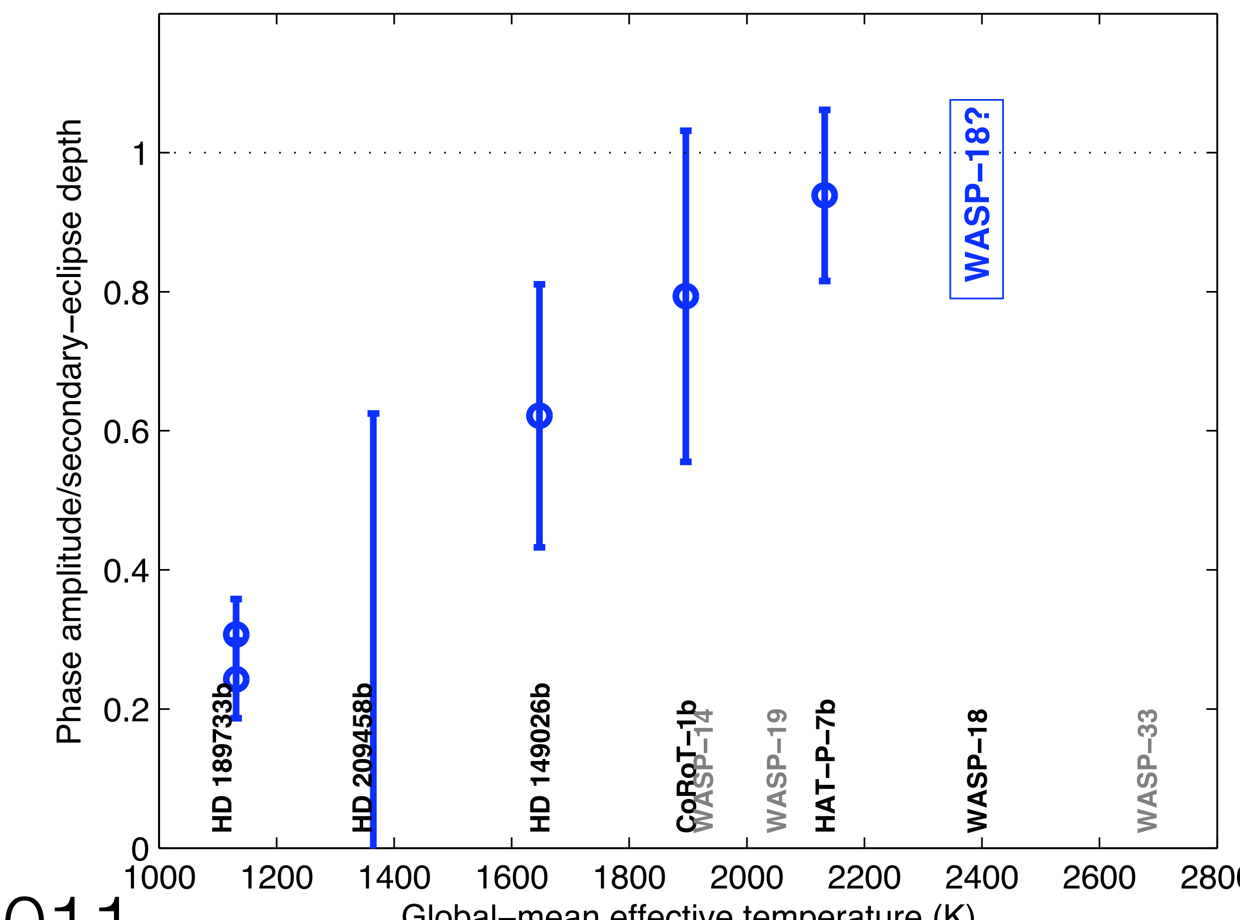

1D linear u=0 (analytical)
$\eta_0/\Delta\eta_{eq}$ $\bar{u}=0$
τ_{drag}
τ_{rad}
1D linear u=0.1 (analytical)
$\eta_0/\Delta\eta_{eq}$ $\bar{u}$ =1.0e-01
$\log(\tau_{drag})$
$\log(\tau_{rad})$
2D linear u=0 (analytical)
$\eta_0/\Delta\eta_{eq}$
τ_{drag}
τ_{rad}
2D non-linear (numerical)
$\eta_0/\Delta\eta_{eq}$ $(\Delta\phi_{eq}/\phi_{night}=0.01)$
τ_{drag}
τ_{rad}





$\tau_{rad} \sim \dfrac{\text{energy in given layer}}{\text{net radiated flux of layer}}$

$\tau_{rad} \propto T^{-3}$



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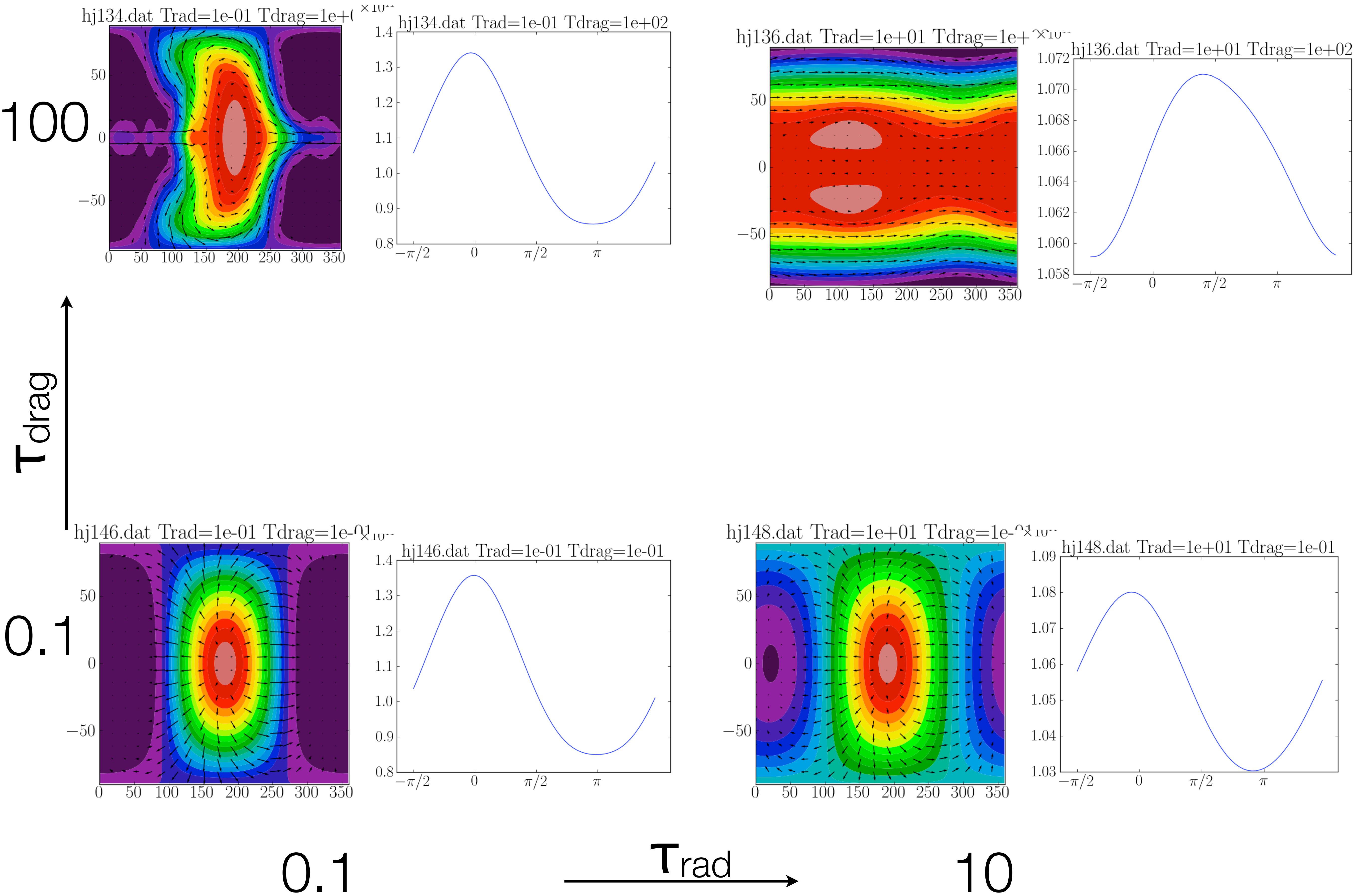
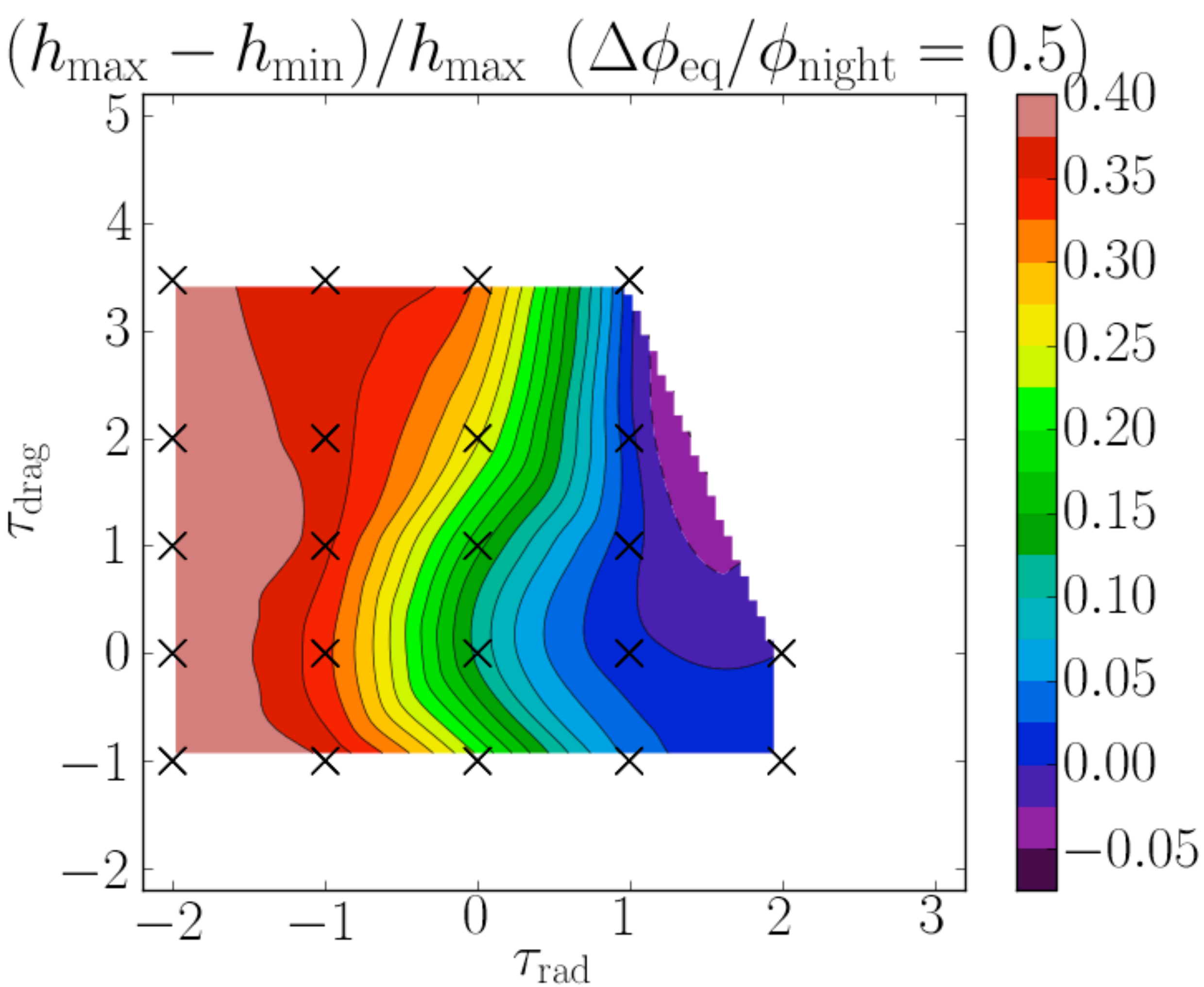
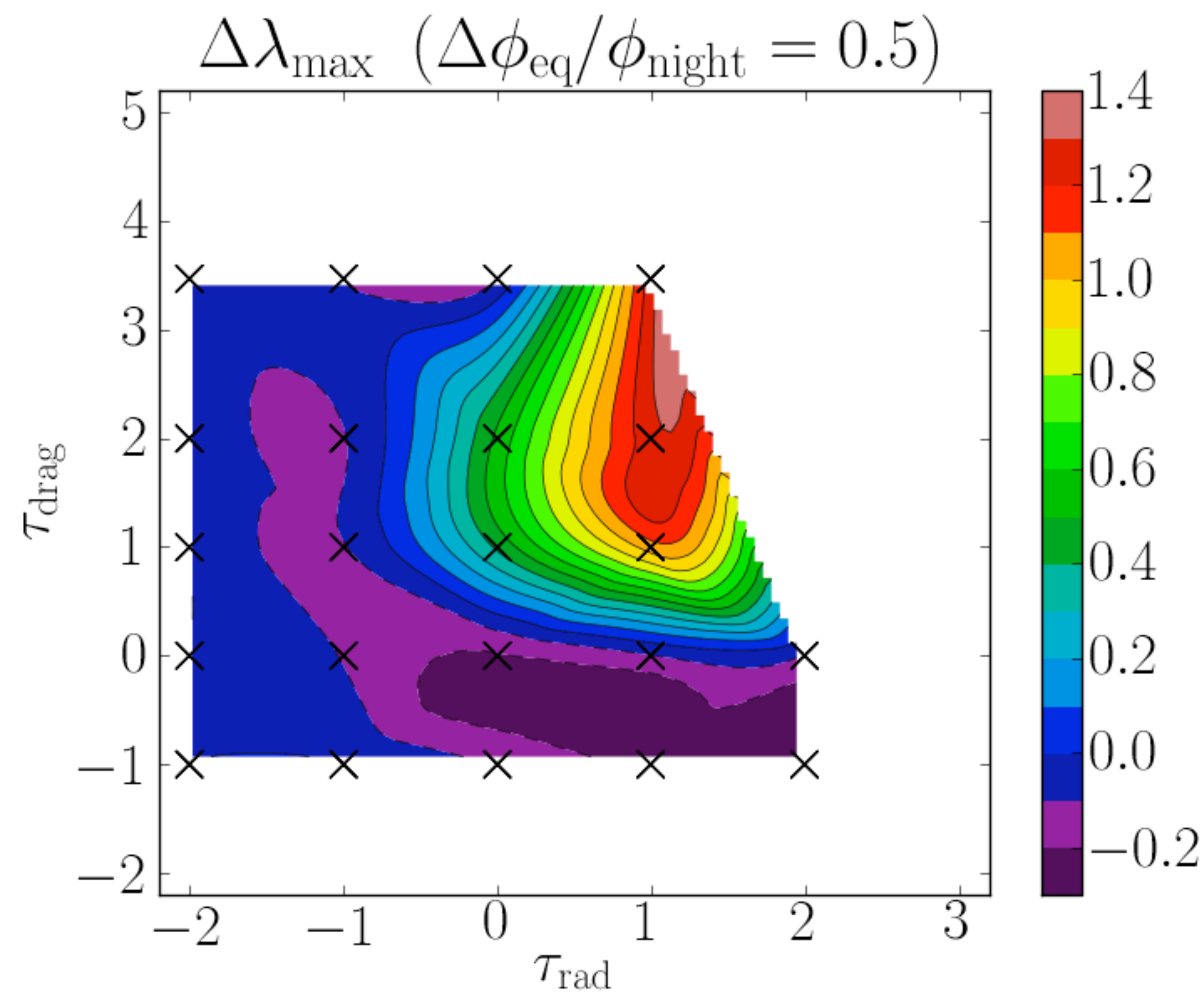
Preliminary result: Lightcurves



Preliminary result: Lightcurves as a function of τ_{rad} and τ_{drag}



fractional day-night temperature contrast



phase shift of hot spot

Conclusions

Gravity wave adjustment can be an effective heat transport mechanism on hot Jupiters.

Our model can qualitatively explain the transition from small to large day-night temperature contrast, depending on the relative value of radiative and drag timescales.

Our 2D shallow water models suggest that hot spot shifted westward of the substellar point is possible, albeit with a (possibly undetectable) small amplitude.