The Stable Atmospheric Dynamics of Hot Jupiters

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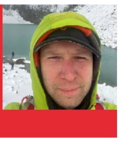


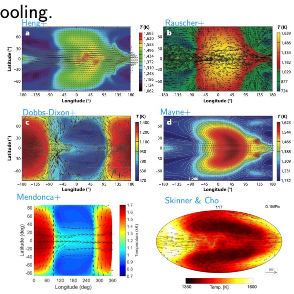
Standard model of hot Jupiter atmospheric circulation

Current 3D General Circulation Models (GCMs) of hot Jupiters are in broad agreement, all finding:

1) ~km/s winds, characterized by a broad **superrotating equatorial jet**.

2) Eastern equatorial **hot spot offsets** driven by the eastward equatorial jet

3) **Large day-to-night temperature contrasts** due to efficient radiative cooling.



Temperature and wind maps from simulations of prototypical hot Jupiters by various groups. All simulations show a super-rotating equatorial jet, eastward hot spot offsets, and large day-to-night temperature contrasts. Figure adapted from [1,2]

Potential for hysteresis in tidally locked GCMs

Three potential circulation regimes

1) Slow rotator:
Dynamical length scales >> planetary radius — dynamics unaffected by rotation

2) Rhines rotator:
The Rossby deformation radius is smaller than the planetary radius:

$$\lambda_R = \sqrt{\frac{NH}{2\beta}} < a\,.$$

3) Rapid rotator:
Both the Rossby deformation radius and the Rhines scale,

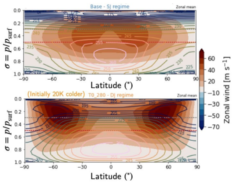
$$\lambda_\beta = \pi\sqrt{\frac{U}{\beta}},$$

are smaller than the planetary radius.

Terrestrials

Hot Jupiters

Zonal-mean zonal wind from [3] for two simulations of TRAPPIST-1e with varying initial temperature profiles:



Rocky planets: TRAPPIST-1e lies at the boundary between Rhines and Rapid rotators, and displays a dependence on initial conditions (i.e., hysteresis) [3,4,5].

Gas giants: Long-duration GCM simulations of both sub-Neptunes and hot Jupiters with deep atmospheres have found a transition in the deep flow that may be linked to a dynamical bifurcation [6,7].

Theoretical regime transitions

The Rhines scale is approximately equal to the planetary radius when:

$$\sqrt{\frac{U}{\beta}} = \sqrt{\frac{Ua}{2\Omega\cos(\phi)}} \approx a\,.$$

The planet rotation period that corresponds to this transition is:

$$P_\beta \approx \frac{4\pi a}{U}\,.$$

Using Kepler's third law and the inverse-square law, the orbital period is:

$$P_{\mathrm{orb}} = \frac{\pi^{1/4}}{\sqrt{2GM_\star}}\left(\frac{L_\star}{F_\star}\right)^{3/4}\,.$$

Equating the orbital and rotational periods and substituting the full-redistribution equilibrium temperature, we find the T_{eq} at the transition:

$$T_{eq,\beta} \approx 1300\ \mathrm{K}\left(\frac{M_\star}{M_\odot}\right)^{-1/6}\left(\frac{L_\star}{L_\odot}\right)^{1/4}\left(\frac{a}{1.38\ R_{\mathrm{Jup,eq}}}\right)^{-1/3}\left(\frac{U}{4\ \mathrm{km\ s^{-1}}}\right)^{1/3}\,.$$

Thus, hot Jupiters with $T_{\mathrm{eq}} \gtrsim 1300\ \mathrm{K}$ should be in the "rapid rotator" regime, while hot Jupiters with $T_{\mathrm{eq}} \lesssim 1300\ \mathrm{K}$ should be in the "Rhines rotator" regime.

Conducting a similar analysis for when the equatorial Rossby deformation radius, $\lambda_R = \sqrt{\frac{NH}{2\beta}}$, is equal to the planetary radius, I find that typical hot Jupiters should not cross into the "slow rotator'" regime of [5]:

$$T_{eq,R} \approx 796.1\ \mathrm{K}\left(\frac{M_\star}{M_\odot}\right)^{-1/5}\left(\frac{L_\star}{L_\odot}\right)^{3/10}\left(\frac{a}{1.38\ R_{\mathrm{Jup,eq}}}\right)^{-2/5}\,.$$

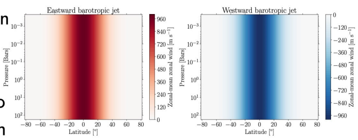
Numerical setup and parameter sweeps

n.b.: This work is undergoing extensive revision at AAS Journals, which will result in an extended parameter sweep (see "Avenues for future work" at the bottom right) for GCM Suite 2.

I conducted two suites of GCM simulations with the **MITgcm**:

Suite 1: Extends [8] to study the effect of initial jet direction on dynamics with weaker bottom Rayleigh drag. See Figure on the right for the two initial jet configurations, which were run alongside simulations initialized at rest.

Longitudinally constant initial wind profiles:



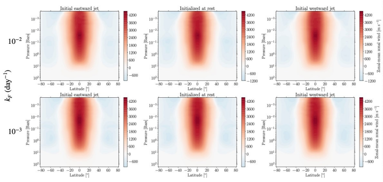
Suite 2: Extends [9] to study the effect of initial temperature profiles on the resulting atmospheric dynamics. Simulations were conducted for five separate equilibrium temperatures crossing the predicted Rhines to rapid rotator transition for two choices of initially cold and hot temperature profiles.

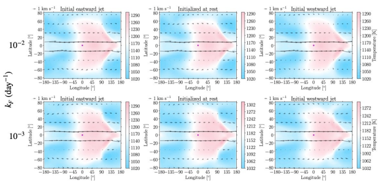
Parameter choices for GCM suites:

Suite 1 parameters	
Initial peak zonal wind velocity	[0, +1, -1] m s^{-1}
Basal drag constant (k_F)	$[10^{-2}, 10^{-3}]$ day^{-1}
Rotation period	3.5 days
Suite 2 parameters	
Equilibrium temperature	[1100, 1200, 1300, 1400, 1500] K
Rotation period	[5.93, 4.57, 3.59, 2.88, 2.34] days
Initial temperature	$[T_{\mathrm{eq}}/\sqrt{2},\ \sqrt{2}T_{\mathrm{eq}}]$
Parameters common to all simulations	
Upper boundary pressure	0.183 mbars
Lower boundary pressure	200 bars
Dynamical time step	15 s
Shapiro filter order	4
Shapiro filter timescale	25 s

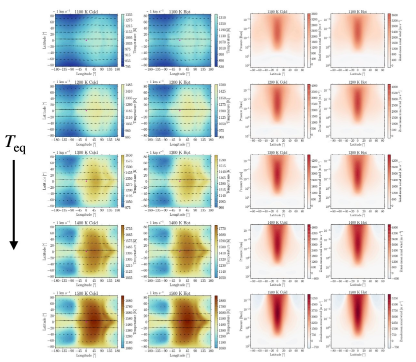
Results: Varying initial jet direction (Suite 1)

Simulations conducted at a given basal drag coefficient k_F all have similar resulting zonal-mean zonal wind patterns as well as temperature and wind maps after ~25,000 Earth days of simulation time regardless of the initial wind profile. This extends the finding of [8] that hot Jupiter atmospheric circulation is broadly insensitive to the initial wind profiles to weaker basal drag coefficients than considered in [8].



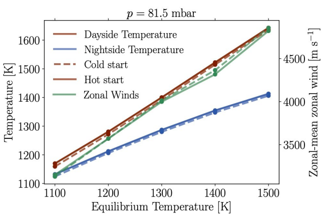


Results: Varying initial temperature structure (Suite 2)



Cases with different initial temperature profiles have nearly equivalent temperature and wind patterns after ~5,000 Earth days of simulation time, implying that there is no hysteresis across the Rhines-to-rapid rotator transition.

The dayside-averaged and nightside-averaged near photospheric temperature and zonal winds show no dependence on initial conditions. Slight differences in the results are due to continued equilibration of the model due to the long radiative adjustment timescale at depth.



Scaling theory implies limited hysteresis for hot Jupiters

Combine shallow-water expression for momentum forcing following [10,11]

$$F = \frac{(h_{\mathrm{eq}} - h)}{\tau_{\mathrm{rad}}}\frac{u}{h} + \frac{u}{\tau_{\mathrm{drag}}} \sim \frac{U(h_{\mathrm{eq}} - \Delta h)}{H\tau_{\mathrm{rad}}} + \frac{U}{\tau_{\mathrm{drag}}}\,,$$

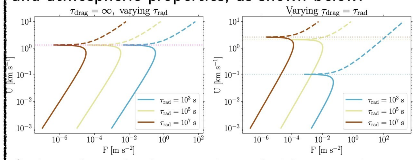
with the scaled steady-state momentum equation coupling day-night forcing and wind speeds:

$$g\frac{\Delta h}{a} \sim \frac{U}{\tau_{\mathrm{drag}}} + fU\,.$$

Solving for the forcing dependence on wind speed I find $F \sim \frac{U}{\tau_{\mathrm{rad}}}\left(\frac{h_{\mathrm{eq}}}{H} - \frac{fU\tau^2_{\mathrm{wave}}}{a}\right) + \frac{U}{\tau_{\mathrm{drag}}}\left(1 - \frac{U\tau^2_{\mathrm{wave}}}{a\tau_{\mathrm{rad}}}\right)$,

with an equilibrium wind speed of $U_{\mathrm{e}} \sim \frac{a}{\tau^2_{\mathrm{wave}}}\left(\frac{\frac{h_{\mathrm{eq}}}{H} + \frac{\tau_{\mathrm{rad}}}{\tau_{\mathrm{drag}}}}{f + \frac{1}{\tau_{\mathrm{drag}}}}\right)$.

This implies that the day-night forcing drives winds to one equilibrium value set by planetary and atmospheric properties, as shown below.



Scaling relationship between the applied forcing and characteristic wind speed. I find that the forcing is positive at wind speeds below where F has a minimum and negative at wind speeds above the minimum in F, implying that the zonal winds only have one characteristic value at equilibrium for a given set of planetary parameters and combination of drag and radiative timescales.

Key takeaways (preliminary)

1) Current models of hot Jupiters are in agreement about their basic-state atmospheric dynamics. This implies that the **fundamental atmospheric circulation of hot Jupiters does not exhibit a strong dependence on model choices**.

2) Two suites of models with realistic radiative transfer designed to search for dependence on initial temperature and wind conditions (i.e., hysteresis) find none. This lack of hysteresis is in agreement with the Newtonian cooling models of [8].

3) Current and future hot Jupiter **model inter-comparisons** (e.g., MOCHA, using the CUISINES framework) **are critical** to assess model agreement at finer detail in the era of JWST and improved ground-based high-resolution observations.

Avenues for future work

1) Expand the parameter sweep conducted in Suite 2 to account for uncertainties in the equilibrium temperature above which planetary scales are greater or less than the Rhines scale.
2) Conduct long-duration simulations with a deep atmosphere in order to determine the extent of hysteresis driven by deep circulation [6,7].
3) Develop a more detailed analytic theory for the forcing regimes that lead to superrotation on hot Jupiters as in [11] in order to further explore the potential for a dynamical bifurcation.

References: [1] Heng & Showman (2015), AREPS, 43, 509. [2] Showman et al. (2020), SSR, 216, 139. [3] Sergeev et al. (2022), PSJ, 3, 214. [4] Wolf et al. (2022), PSJ, 3, 7. [5] Haqq-Misra et al. (2018), ApJ, 852, 67. [6] Carone et al. (2020), MNRAS, 496, 3582. [7] Wang & Wordsworth (2020), ApJ, 981, 7. [8] Liu & Showman (2013), ApJ, 770, 42. [9] Komacek et al. (2017), ApJ, 835, 198. [10] Perez-Becker & Showman (2013), ApJ, 776, 134. [11] Shell & Held (2004), JAS, 61, 2928.