General Circulation Modeling of Close-in Extrasolar Planets

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1. Introduction

- Many of the observed extrasolar planets orbit very close to their host star
- This can lead to the planet having permanent day/night sides -- due to tidal locked illumination
- *How will the atmospheric flow and temperature distribution evolve under this heating condition?*
- We use a 3-D general circulation model (GCM) to perform numerical simulations to address this question

2. 3-D General Circulation Model

- We use the NCAR Community Atmosphere Model (CAM)
- It solves the primitive equations of fluid dynamics, using a pseudospectral method

$$
\begin{aligned}
\frac{D\mathbf{v}}{Dt} + \left(\frac{u}{R_p}\tan\phi\right)\mathbf{k}\times\mathbf{v} &= -\nabla_p\Phi - f\mathbf{k}\times\mathbf{v} + \mathcal{D}_v \\
\frac{\partial\Phi}{\partial p} &= -\frac{1}{\rho} \\
\frac{\partial\omega}{\partial p} &= -\nabla_p\cdot\mathbf{v} \\
\frac{DT}{Dt} - \frac{\omega}{\rho c_p} &= \frac{\dot{q}_{\rm net}}{c_p} + \mathcal{D}_T \\
p &= \rho R T
\end{aligned}
$$

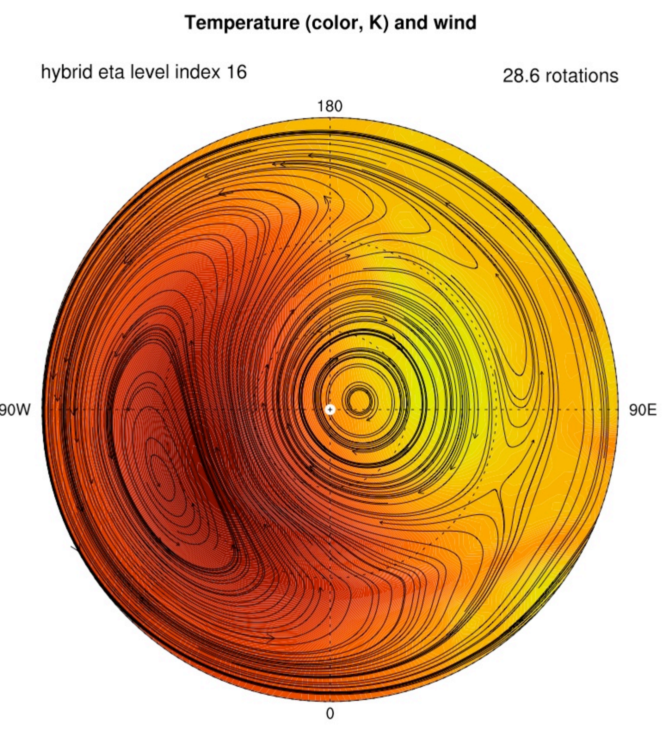
The primitive equations with standard notation.

3. Hot Jupiter Simulations - Set-up

- The effect of heating from the star is represented with an idealized “Newtonian relaxation” model. The temperature is relaxed to an “equilibrium” profile T_e on a thermal drag time scale τ
- We input planetary parameters based on observations of the planet HD209458b (84 h period, 1.3 Jupiter radii)
- The vertical domain is from ~ 1-1000 mbar, resolved by 26 vertical levels and 42^2 (128x64) and 85^2 (256x128) modes (grid points) in the horizontal

4. Results

- Low number of jets (~3)
- Large scale vortices
- Strongly homogenized temperature -- e.g., ~10^3K day-night difference in T_e leads to only a few hundred K difference locally
- Flow and temperature patterns variable in time

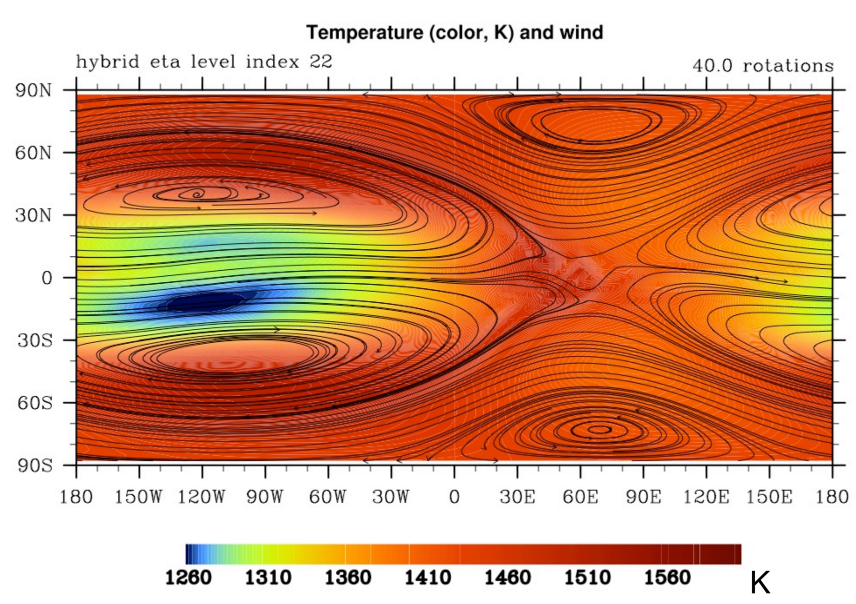


Centered on north pole with the star shining from below

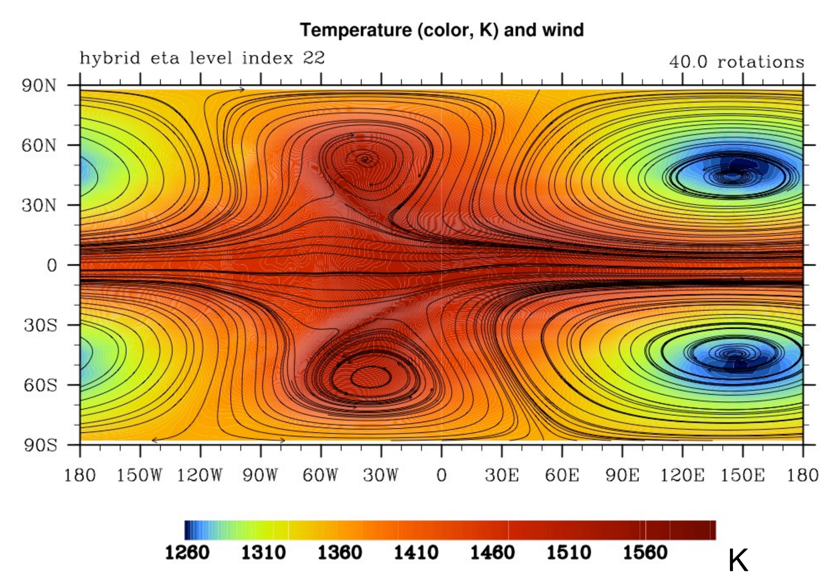
5. Extensive Parameter Study

- Model parameters -- e.g., numerical parameters, thermal forcing (τ, T_e), initial conditions -- varied one by one and the sensitivity/robustness of the resulting flow and temperature patterns studied

initialized with only small noise



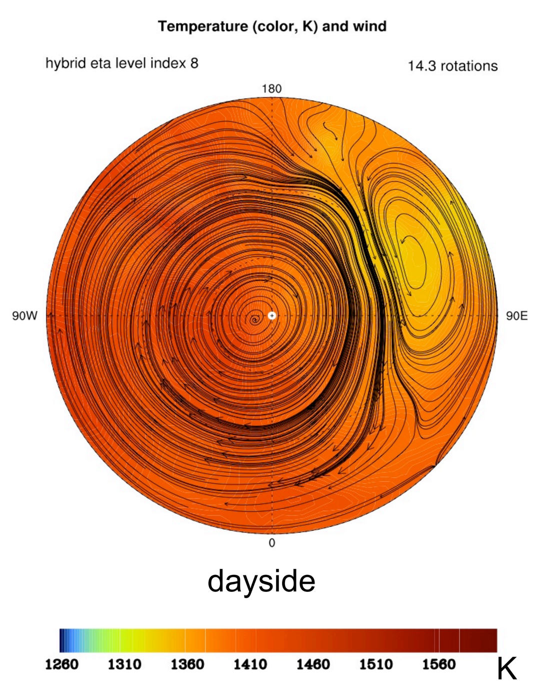
initialized with an eastward jet



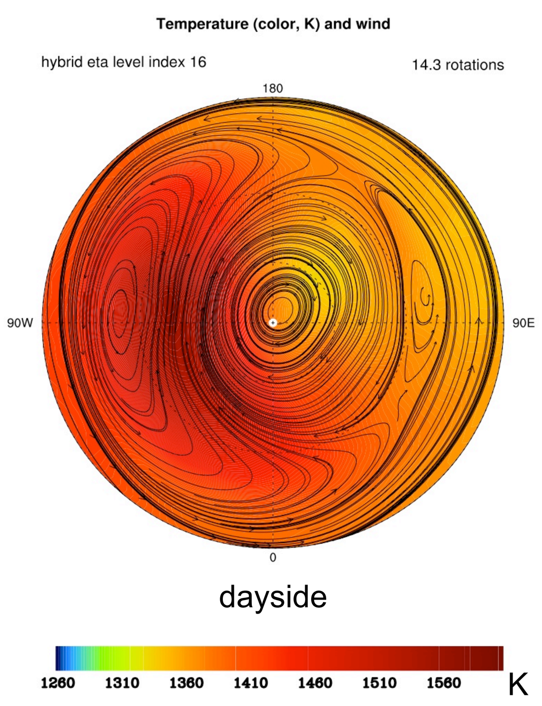
Temperature and streamlines at the same level and time, for two simulations differing only in the initial wind configuration. The sub-stellar point is at the center. The location of hot/cold areas is clearly sensitive to initial conditions.

6. Temperature - Vertical Structure

High up (p ~ 100mb)

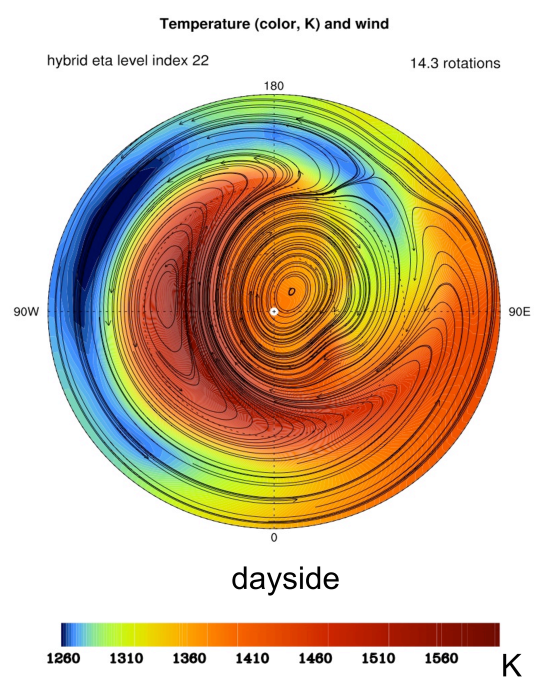


Intermediate height (p ~ 400mb)



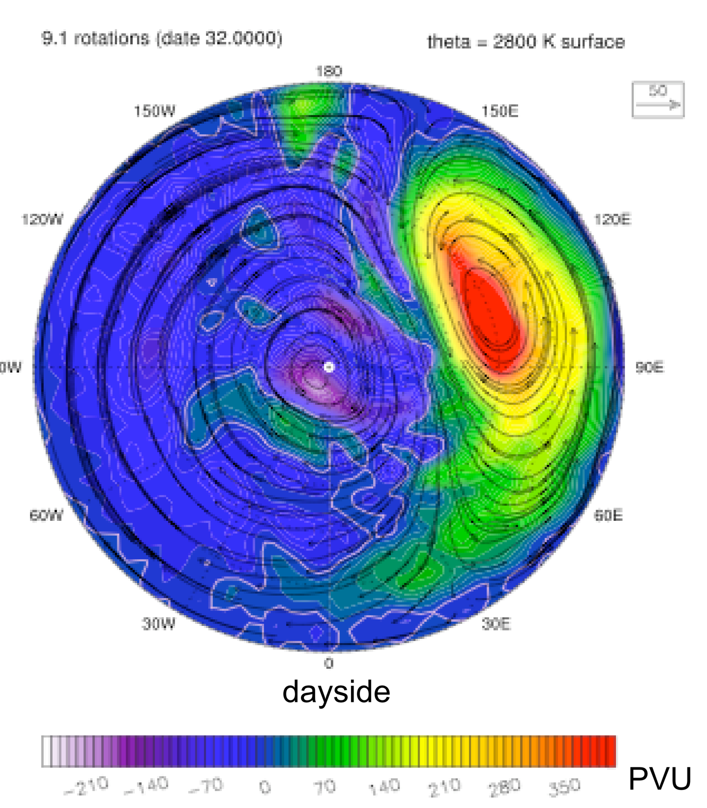
The temperature structure is far from the simple hot dayside - cold nightside scenario

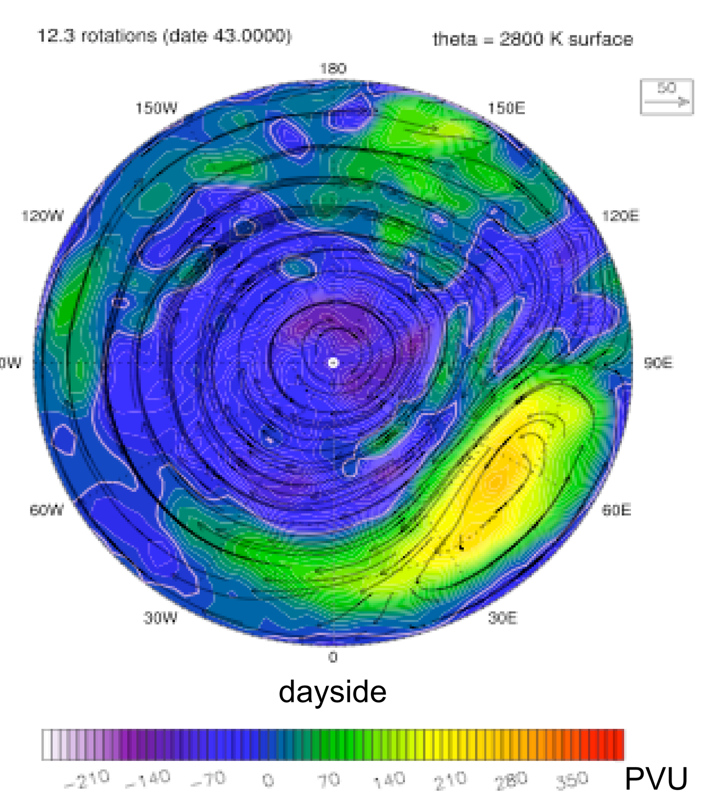
Low down (p ~ 900mb)



Mix of vertical alignment and strong dependence on height, depending on location

7. Storms - Time Variability





Potential vorticity (flow tracer like clouds) at two different stages in time, 3 planet days apart

8. Conclusions

- Hot Jupiter simulations -- main results (robust features)
  - Low number of jets and large vortices
  - Temperature homogenization and hot/cold spots away from sub/anti-stellar points
  - Spatiotemporal variability
- Idealized models -- used by all studies thus far -- should *not* be used to make “hard predictions”, but they are very useful for gaining physical insights and studying mechanisms and flow regimes
- Given the limited observations so far, parameter-space and sensitivity studies like this are essential