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Atmospheric dynamics on tidally locked Earth-like planets in the habitable zone of an M dwarf star

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Abstract. We investigated the large scale atmospheric circulation of Gl581g, a potentially habitable planet around an M dwarf star, using an idealized dry global circulation model (GCM) with simplified thermal forcing as a first step towards a systematic extended parameter study. The results are compared with the work of Joshi *et al.* (1997) who investigated a tidally-locked habitable Earth analogue with less than half the rotation period of Gl581g. The extent, form and strength of the atmospheric circulation in each model generally agree with each other, even though the models differ in key parameters such as planetary radius, surface gravity, forcing scheme and rotation period. The substellar point is associated with an uprising direct circulation-branch of a Hadley-like cell with return flow over the poles. It is compelling to assume that the substellar point of a tidally locked terrestrial exoplanet behaves dynamically like the Earth's tropic associated with clouds and precipitation, making it an ideal target for habitability.

Keywords. planetary systems

The 3D general circulation model MITgcm † was adapted to investigate the atmosphere of Gl581g, assuming an Earth-like composition (Tables 1 and 2).

Table 1. Planetary Parameters of Gl581g (Vogt *et al.* 2010)

Planetary mass and radius	$M_{pl} = 3.1\ M_{Earth}$ and $R_{Pl} = 1.45\ R_{Earth}$
Surface gravity	$g = 14.3\ m/s^2$
Planetary rotation and orbital period	$P_{rot} = P_{orb} = 36.5$ days.
surface pressure	$P_0 = 1$ bar
specific (dry) gas constant	$R = 287\ \frac{J}{kg\,K}$

Table 2. Model parameters

Horizontal resolution	128×64 using a C32 cubed sphere prescription (Adcroft 2001)
Vertical resolution	$20 \times \Delta P = 50$ mbar
Rayleigh friction at surface	$\tau_{drag} = 1$ d at surface, $\tau_{rad} = 0$ d for $P \leqslant 700$ mb (Held & Suarez, 1994)
Radiative relaxation time scale	$\tau_{rad} = 4$ d at surface, $\tau_{rad} = 40$ d for $P \leqslant 700$ mb (Held & Suarez, 1994)

Following the description of Held & Suarez (1994), temperatures are relaxed towards T_{force} via Newtonian cooling with $\tau_{rad} = 4 - 40$ days (Tab. 2). T_{force} is based on the prescription developed by Heng & Vogt (2011):

$$T_{force} = \left[T_0' + \Delta T_{EP}\cos(\Theta - 180^\circ)\cos\Phi - \Delta T_z ln\left(\frac{P}{P_0}\right)\cos^2\Phi - T_{mod}\right]\left(\frac{P}{P_0}\right)^{2/7}$$

where Θ and Φ denote the longitude and latitude, and P and P_0 are the pressure and surface pressure, respectively. $T_0' = 268$ K is the surface temperature at the poles,

† http://mitgcm.org

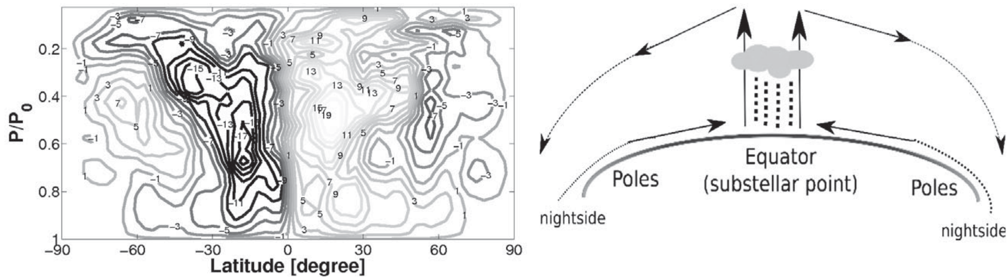

Figure 1. Left: Meridional mass overturning from our Gl581g model in units of 10^{10} kg/s agrees qualitatively with Joshi *et al.* (1997). Negative values (dark gray) indicate northward circulation, positive values (light gray) indicate southward circulation. **Right:** More schematic view of the circulation shown left with upwelling at the equator and return flow over the poles.

$\Delta T_{EP} = 10$ K is the temperature difference between the equator and the poles, and $\Delta T_z = 10$ K is a static stabilizing term along the equator. This model contains no stratosphere, yet. T_{mod} was added to suppress static instabilities at the substellar point by ensuring that the rate of decrease of temperature with respect to height, $-dT/dz$, is smaller than the dry adiabatic lapse rate.

$$T_{mod} = 10K\ ln\left(\frac{P}{P_0}\right) max(0, cos\Theta)$$

While horizontal flow patterns may differ between models e.g., Heng & Vogt (2011) and Joshi *et al.* (1997), the 3D atmospheric circulation observed in our model agrees generally with the results of Joshi *et al.* (1997), who investigated a tidally locked Earth analogue planet in the habitable zone of an M dwarf with $P_{rot} = P_{orb} = 16$ days.

In both models, the air mass transport is dominated by two large Hadley-like circulation cells, one fore each hemisphere, as highlighted in Fig. 1 left that shows a 'cross section' of meridional air mass circulation versus latitude and height in pressure. Fig. 1 right shows a simplified view of the two dominant circulation cells that transport heat from the surface of the hot substellar point at the equator towards the poles. The agreement in extent, form and strength of the circulation cells is compelling, even though the models differ in schemes used for thermal forcing and friction with the surface, and in planetary parameters like rotation, semi major axes, surface gravity and radius.

The upwelling at the substellar point makes this region an Earth tropic analogue, which could be associated with clouds and precipitation, if the temperatures at the surface allow for liquid water. This may be observed by 'probing' the substellar point of transiting terrestrial planets for water clouds by secondary transit observations or could be confirmed by increased albedo due to the clouds at the substellar point derived from high precision photometric light curves that the PLATO mission will provide†.

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