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Impact of variations of gravitational acceleration on the general circulation of the planetary atmosphere

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ABSTRACT

Fundamental to the redistribution of energy in a planetary atmosphere is the general circulation and its meridional structure. We use a general circulation model of the atmosphere in an aquaplanet configuration with prescribed sea surface temperature and investigate the influence of the gravitational acceleration g on the structure of the circulation. For $g = g_0 = 9.81$ m s^{-2}, three meridional cells exist in each hemisphere. Up to about $g/g_0 = 1.4$ all cells increase in strength. Further increasing this ratio results in a weakening of the thermally indirect cell, such that a two- and finally a one-cell structure of the meridional circulation develops in each hemisphere. This transition is explained by the primary driver of the thermally direct Hadley cell: the diabatic heating at the equator which is proportional to g. The analysis of the energetics of the atmospheric circulation based on the Lorenz energy cycle supports this finding. For Earth-like gravitational accelerations transient eddies are primarily responsible for the meridional heat flux. For large gravitational accelerations, the direct zonal mean conversion of energy dominates the meridional heat flux.

1. Introduction

Since the discovery of the first giant planet outside of our Solar System in 1995 (Mayor and Queloz, 1995) methods to detect and characterise new planets have been continually developed (e.g. Malbet et al., 2012). Physical parameters of exoplanets such as angular velocity, size and mass, can now be estimated and the composition of an atmosphere can be constrained (e.g. Deming et al., 2005; Berta et al., 2012; Kreidberg et al., 2014). The increasing number of newly detected planets and their characteristics raises questions on whether other habitable worlds might exist.

Apart from the Earth, Venus, Mars, and Titan are planets or moons with substantial atmospheres (e.g. Svedhem et al., 2007; Lewis et al., 1999). The corresponding atmospheric circulations differ from each other due to different characteristics and physical parameters of the planets and moons, such as the atmospheric composition, distance to the star, angular velocity, size, obliquity, and composition of the planetary body - the latter determining the gravitational acceleration at the surface. The atmospheric circulation is the primary process to transport heat meridionally; therefore, planetary habitability is directly dependent on this parameter.

The purpose of this study is to investigate the effect of changes in the gravitational acceleration on the atmospheric dynamics associated with the general circulation. We employ a three-dimensional atmospheric general circulation model (GCM) of intermediate complexity in an aquaplanet configuration (Lunkeit et al., 2011). A set of sensitivity simulations is performed varying only the gravitational acceleration and keeping the atmospheric mass constant. The analysis focuses on the meridional circulation and the different drivers. The consideration of the energy budget based on Lorenz (1955) provides a deeper understanding of the atmospheric conditions of an exoplanet, a prerequisite to assess habitability.

On Earth, the meridional energy imbalance between equator and poles induces a heat transport that is essential for the formation of the atmospheric circulation (e.g. Holton, 2004). The meridional circulation consists of a three-cell structure: a thermally direct Hadley cell, a thermally indirect Ferrel cell, and a thermally direct polar cell in each hemisphere. Quantification of the strength of the individual drivers of these cells provides an understanding of the sensitivity of the meridional circulation to changes in external parameters such as the gravitational acceleration. For the thermally direct Hadley cell, the diabatic and latent heating are essential, while for the thermally indirect Ferrel cell the eddy momentum and heat fluxes are the dominant drivers (e.g. Holton, 2004). The zonal drag force balances the resulting zonal component of Hadley

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circulation and the eddy momentum flux of the Ferrel cell.

The energy cycle as presented by Lorenz (1955) considers different forms of energy in the atmosphere, the associated transfer fluxes, and sources and sinks of energy on a global scale. On Earth, available potential energy is generated by diabatic and latent heating, then converted into kinetic energy and finally dissipated by friction and turbulence. The circulation is separated into three components: zonal mean flow, transient eddies and stationary eddies (Peixoto and Oort, 1992). Stationary eddies are caused by zonal asymmetries primarily due to land-sea distribution and orography. On an aquaplanet, stationary eddies were found to be negligible (Manabe and Terpstra, 1974; Grose and Hoskins, 1979; Held et al., 1983).

Early attempts to assess the atmospheric dynamics in particular the meridional circulation were made by Held and Hou (1980). They qualitatively estimated the width of the thermally direct cell for different terrestrial planets from basic principles. Caballero et al. (2008) further developed the findings of Held and Hou (1980) and introduced a semi-analytical theory for the depth, width and strength of the thermally direct cell, which are in good agreement with GCM simulations of Mars and Snowball Earth.

The dependence of the thermally driven flow under various rotation frequencies (e.g. Williams and Holloway, 1982; Williams, 1988a, 1988b; Read, 2011; Kaspi and Showman, 2015; Chemke and Kaspi, 2015 and references therein), and for tidally locked configurations (e.g. Joshi et al., 1997; Joshi, 2003; Merlis and Schneider, 2010) were investigated using GCMs. For a slowly rotating planet, the meridional atmospheric circulation consists of just one thermally direct cell, which extends from the equator to the pole and maintains the meridional heat flux. In the Northern Hemisphere, the increase of the angular velocity leads to a deflection of poleward (equatorward) moving air to the East (West) in the upper (lower) troposphere due to the Coriolis acceleration. The faster the planet rotates, the more important baroclinic eddies become for the meridional heat transport in the mid-latitudes. The thermally direct cell gradually weakens, and a three-cell structure develops, similar to that observed on the Earth. However, for rotation rates larger than the one on Earth, the baroclinic eddies become less efficient, since eddy length scales become small.

Other studies have investigated the impact of size and gravitational acceleration on the atmospheric circulation and temperature distribution (Heng and Vogt, 2011; Kaspi and Showman, 2015). The latter investigated the dependence of the meridional heat flux on a set of basic parameters including atmospheric mass and gravitational acceleration for an aquaplanet configuration. Increasing the atmospheric mass, they found a weakening of the subtropical jet and an intensification of the meridional circulation in response to increasing mass. For larger gravitational accelerations with fixed atmospheric mass, they showed an intensification of the meridional circulation which was in agreement with a growth of eddy energy and an increase of equator-to-pole temperature difference, while the three-cell pattern of the meridional circulation remained unchanged. Here we also explore the atmospheric circulation of potential habitable planets with mean densities at the upper physical limit and focus on underlying mechanisms, an approach missing in earlier studies.

The outline of the study is as follows: Section 2 introduces the model setup, the experimental design, and the analysis methods. In Section 3, the reference and the sensitivity experiments are described, focusing on the meridional circulation and the underlying mechanisms. The energy budget of the reference experiment is compared to the sensitivity experiments in Section 4. Finally, we provide a discussion and concluding remarks in Section 5.

2. Experimental design and methods

2.1. Model

We use the Planet Simulator developed by the Meteorological Institute of the University of Hamburg, Germany (Lunkeit et al., 2011). The spatial fields are represented on a spectral grid T42 which corresponds to a resolution of about 2.8°×2.8°. The model uses 10 sigma levels up to the tropopause (100 hPa for Earth-like conditions). This is a relatively coarse vertical resolution making this a model of reduced complexity.

The dynamical core of the atmospheric model is based on the dimensionless primitive equations (Hoskins and Simmons, 1975). They include the hydrostatic approximation and the conservation of mass, heat, and momentum (Lunkeit et al., 2011).

The shortwave radiation scheme distinguishes between clear (Lacis and Hansen, 1974) and cloudy sky (Stephens, 1978; Stephens et al., 1984). The longwave radiation for the clear sky is described by a broadband emissivity method (e.g. Manabe and Möller, 1961; Boer et al., 1984). Longwave radiation of clouds is approximated as a grey body depending on the cloud liquid water content.

Furthermore, a Kuo-type convection scheme is used (Kuo, 1965, 1974). The horizontal diffusion parameterisation is based on the approach of Laursen and Eliasen (1989). The vertical diffusion, representing the non-resolved turbulent exchange, is applied to the horizontal wind, the potential temperature, and the specific humidity. The turbulent fluxes of zonal and meridional momentum, heat, and moisture are parametrised by linear diffusion along the vertical gradient with exchange coefficients for momentum and heat. Thus, the parameterisation follows the mixing length approach as an extension of the similarity theory used to define the drag and transfer coefficients (Lunkeit et al., 2011; Roeckner et al., 1992). The model includes a seasonal cycle.

2.2. Experimental setup and reference simulation

For the simulations, we use an aquaplanet configuration, which is initialised with no sea ice cover. Further, Earth-like parameters are used, i.e., the radius is 6371 km, obliquity is 23.4°, and angular velocity is $7.29\cdot10^{-5}\ s^{-1}$. The solar constant is set to 1365 W m^{-2} and the CO_2 concentration to 360 ppm. The roughness length at the surface is $1.5\cdot10^{-5}$ m. The surface background albedo for open water is 0.069. The experiments use zonally uniform, prescribed sea surface temperatures (SST) following the approach of Neale and Hoskins (2000):

$$T_s(\varphi) = \begin{cases} T_0 + (T_{max} - T_0)(1 - \sin^2\frac{3\varphi}{2}), & \text{if } |\varphi| < \frac{\pi}{3}, \\ T_0, & \text{otherwise} \end{cases} \tag{1}$$

where φ is the latitude, T_{max}=27 °C, and T_0=0 °C. Thus, SSTs are constant in time representing an ocean with infinite heat capacity.

For the reference simulation the gravitational acceleration is set to $g = \tilde{g} \times g_0$ with $g_0 = 9.81\ m\,s^{-2}$. The atmospheric dynamics on an aquaplanet differ in some important aspects from those on Earth. The atmospheric circulation is nearly symmetric about the equator as the only source for interhemispheric asymmetry are the planetary obliquity of 23.4° and the orbital eccentricity. Fig. 1 shows the 10-year means of the zonal mean temperature and the zonal-mean zonal wind field for $\tilde{g} = 1$. As an aquaplanet has no orography, the zonal wind is generally stronger than on Earth. The lack of orography also implies that stationary eddies are almost absent and, thus, the transport of heat and momentum is dominated by transient eddies (Peixoto and Oort, 1992). Nevertheless, quasi-stationary eddies (up to one month) exist in the reference similar but much weaker and less persistent than in earlier studies (Watanabe, 2005; Zappa et al., 2011).

For the sensitivity experiments, $\tilde{g}$ varies between $\frac{1}{4}$ and 5. Realistic values of $\tilde{g}$ range from 0.4 ($MgSiO_3$, H_2O) to 2.56 (Fe) for an Earth-sized planet (Seager et al., 2007). Pure water/ice planets would have even smaller $\tilde{g}$ (Dressing et al., 2015). The surface pressure is adjusted when changing $\tilde{g}$ so that the atmospheric mass remains constant. All simulations are carried out for 40 model years; typically a steady-state of the atmosphere is reached after 4–10 years.