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

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Instrumentation to detect new planets has been continually developed over the last decades. Thus, exoplanets can be characterised in terms of physical parameters, such as size and mass, as well as identify possible atmospheres. The increasing number of newly detected planets raises issues of possible other habitable worlds.

In this study, the atmospheric dynamics of potential habitable planets is investigated using a three-dimensional atmospheric general circulation model (Planet Simulator) of intermediate complexity (Lunkeit et al. 2011). A set of sensitivity simulations varying the gravitational acceleration from $1/4\,g_0$ to $5g_0$ (with $g_0 = 9.81\,ms^{-2}$) are performed in an aquaplanet configuration. Except of that all simulations are performed with Earth-like initial conditions, which reach after 4 to 10 years a steady-state.

The gravitation of a terrestrial planet significantly influences atmospheric dynamics. Up to $1g_0$, the meridional atmospheric circulation is driven by a three-cell structure on one hemisphere: a thermally direct cell between 0°and ±30°(Hadley cell), a thermally indirect cell between ±30°and ±60°(Ferrel cell) and a third cell (polar cell), which is also a thermally direct cell. Further, all cells illustrated by the mass stream function become more intense with increasing gravity from $1/4\,g_0$ to $1g_0$. However, for experiments greater than $1g_0$ the general atmospheric circulation begins to change fundamentally. The thermally indirect cell becomes weaker and vanishes completely with $3g_0$, whereas both direct thermal cells enhance and merge around $3g_0$. Hence, one strong thermally direct cell remains, which becomes stronger with increasing gravity acceleration ($> 3g_0$).

To understand the physical processes leading to a one-cell structure, the main drivers are considered separately: diabatic heating, meridional eddy fluxes of heat and momentum, and zonal shear. The results show that all main processes enhance with increasing gravity up to $1g_0$. For $g > g_0$, both eddy processes, heat and momentum flux, become weaker, whereas the contribution of diabatic heating and zonal shear still increase. The increase of zonal shear is explained by a denser air due to increased gravity. The increase of the diabatic heating caused by an increasing Brunt-Väisälä frequency and the weakening of the eddy processes at the same time lead to a direct thermally driven circulation from the equator to the poles, i.e., a one-cell structure on each hemisphere.

References

Lunkeit, F., et al., Planet Simulator - Reference Manual Version 16, Meteorological Institute, University of Hamburg, 2011.