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Three-dimensional turbulence-resolving modeling of tidally locked exoplanetary atmosphere.

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Abstract

The role that convection play in cloud feedback on Earth is still not fully understood [1]. Numerous observed exoplanets are in synchronous rotation with its host star. To understand the impact on climate of such extreme insolation Global Circulation Model (GCM) are used. The representation of turbulence require in such model a subgrid parametrization that are based on Earth convection. The extreme insolation on those exoplanets could lead to different convective activity. This difference in the turbulence could change the height and thickness of the cloud layer and lead a change in the stability of the surface liquid water [2, 3]. Zhang et al [4] model for the first time the convective activity around M Dwarfs star. We propose here to revisit the study of the convection regime of such extreme environment using turbulent-resolving model with a realistic radiative transfer and microphysics (Figure 1).

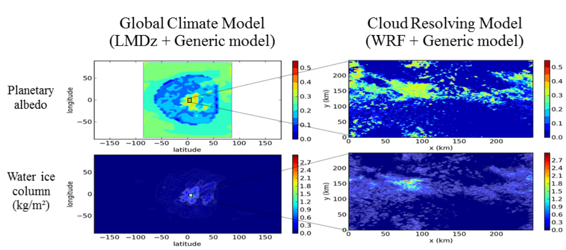

Figure 1: Schematic representation of the model discussed here, on the left side the planetary albedo and water column ice generated by LMDz generic circulation model and on the right the same fields are displayed with turbulence resolved by the non-hydrostatic core WRF with a resolution of 1 km.

1. Model description

In order to study the convective activity at the sub-stellar point we use WRF [5] compressible and non-hydrostatic dynamical core in Large-Eddy Simulation (LES) mode coupled to LMD Generic physics [6]. The radiative scheme is based on correlated-k and can performed calculation on a various a temperature/pressure range for selected atmospheric compositions. Processes such as the radiative effect of clouds or Rayleigh scattering are taken into account. The emission spectrum can be chosen from several star-type, solar-type or M-star for exemple. Melting, freezing, condensation, evaporation, sublimation, and precipitation of water are included in the model. As the width of the grid is small there is no cloud nebulosity. Heating from the large-scale dynamics as well as water advection are taking into account with tendency vertical profile applied in the domain that can vary during the simulation.

2. Earth Test-case

To ensure the performance of the model in extreme exoplanetary environment the model has been tested in Earth tropics condition. Vertical profiles from TOGA-COARE measurement campaign [7] are used as input. The emission spectrum of the Sun is used to compute shortwave heating rate with 24h cycle. The width of the mesh is 1 km over 151 km on the horizontal and the vertical domain extends from the ground to 25 km over 65 layers.

Figure 2 shows a snapshot of the vertical cross-section of the liquid/ice water content (kg/kg) for the TOGA-COARE case. There is formation of cumulonimbus cloud associated with deep convective activity. The characteristics in terms of vertical wind, cloud fraction and precipitation are consistant with observations. The model is therefore able to reproduce convective activity and rain precipitation comparable to mean tropics behaviour with realistic radiative transfer and a general water microphysics.

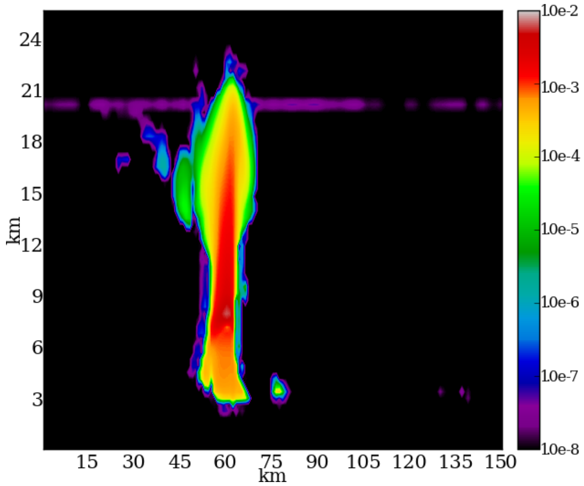

Figure 2: Vertical cross-section of the liquid/ice water content (kg/kg) for the TOGA-COARE case.

3. Exoplanetary environment

The model is initialized with output from LMD Generic model [8] and the atmospheric constant (gravity, heat capacity, mean molecular mass) are modified to match case studied. The emission spectrum of Proxima Centauri is used to compute shortwave heating rate with constant flux. The width of the mesh is 1 km over 151 km on the horizontal and the vertical domain extends from the ground to 30 km over 81 layers.

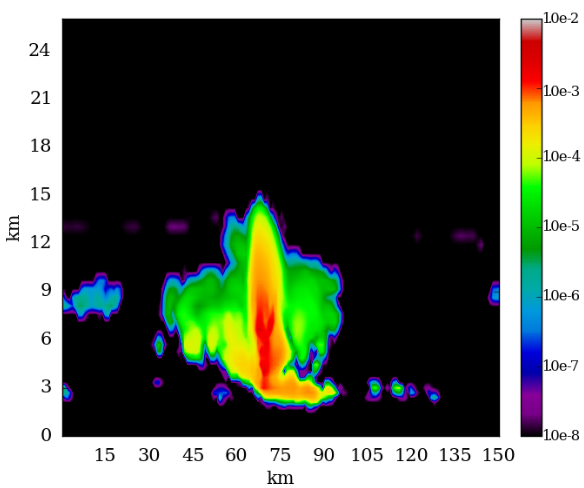

Figure 3: Vertical cross-section of the liquid/ice water (kg/kg) for the Proxima-b case.

Figure 2 shows a snapshot of the vertical cross-section of the liquid/ice water content (kg/kg) for the TOGA-COARE case. Deep convection is visible with associated vertical transport of water but the vertical extent of the clouds is smaller compared to the earth case.

Simulations with a flux ranging from 850 W m^{-2} to 3000 W m^{-2} were performed to quantify the effect of incoming flux. The sensitivity to the surface temperature is also taken into account by varying the greenhouse gas content. Moreover the impact of the rotation rate of the planet is quantified.

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