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Effects of Bulk Composition on the Atmospheric Dynamics on Close-in Exoplanets

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Abstract

Depending on the metallicity of the protoplanetary disk, the details of gas accretion during planetary formation, and atmospheric loss during planetary evolution, the atmospheres of exoplanets could exhibit a variety of bulk compositions (e.g., Moses et al., 2013). Examples include hydrogen-dominated atmospheres like Jupiter, more metal-rich (but still hydrogen-dominated) atmospheres like Neptune, evaporated atmospheres dominated by helium in analogy to helium white dwarfs, or of course carbon dioxide, water vapour, nitrogen, and other heavy molecules as exhibited by terrestrial planets in the solar system. Despite differing opacities that will impact the radiative energy deposition (e.g., Lewis et al., 2010; Kataria et al., 2014), differing bulk compositions also differ in molecular weight and specific heat. The latter two fundamental parameters might have crucial effects on various aspects of atmospheric structure and dynamics. For example, a lower specific heat from molecules such as carbon dioxide implies a steeper dry adiabatic temperature gradient; this implies that, for a given vertical temperature profile, atmospheres with differing molecular weights exhibit different Brunt–Väisälä frequencies and therefore gravity wave speeds. Molecular weight also influences the scale height of the atmosphere, which could range (for typical exoplanet gravities) from ten km for high-molecular-weight compositions to hundreds of km for hydrogen-dominated cases. A lower molecular weight or a lower specific heat would likely cause a larger deformation radius in which the atmospheric flow is more significantly influenced by the gravity and buoyancy effects instead of the rotation effects. In this study we use a three-dimensional general circulation model (GCM) to simulate generic exoplanets with different compositions, emphasizing close-in, synchronously rotating super Earths whose atmospheric composition is the most uncertain and which will be the focus of characterization studies over the next decade. This study mainly focuses on the effect of molecular weight and specific heat, and systematically demonstrates how different composition will affect the atmospheric dynamics and general circulation pattern on those planets.

1. Model and Results

We solve the 3D primitive equations using the MITgcm, which is a state-of-the-art circulation model (Adcroft et al. 2004) that Showman et al. (2009) adapted for application to exoplanets. We specify the radiative heating/cooling using a Newtonian cooling scheme. The scheme relaxes the temperature toward a specified radiative equilibrium temperature profile that characterizes a hot dayside and cold nightside for a tidally locked planet. For details, see Liu and Showman (2013). Using the Newtonian cooling scheme allows us to separate the radiative effect from the specific-heat effect and the molecular-mass effect. The planet parameters are set as the super earth GJ1214b by default. Figure 1 illustrates two typical simulations. The upper panel represents a hydrogen-dominated atmosphere and the lower is a CO_2-dominated atmosphere with identical thermal forcing. It is clearly shown that, for a higher molecular weight atmosphere, the day-night temperature contrast is larger, and the wind speed is lower. We will provide a physical interpretation of this behavior (and other interesting dynamical behaviors) in these simulations.

2. Figures

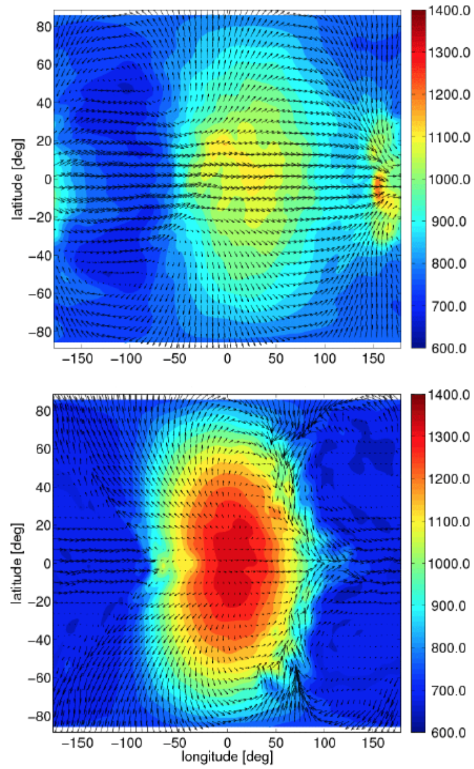

Figure 1: Temperature at 7 mbar (color scale, in K) and winds (arrows) for two typical simulations. The upper panel represents a hydrogen-dominated atmosphere and the lower is an otherwise identical CO_2-dominated atmosphere.

Acknowledgements

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