
Introduction: Future large space telescopes observing terrestrial exoplanets in visible and near-infrared wavelengths, such as the Large Ultraviolet, Optical, and Infrared Surveyor (LUVOIR) or the Habitable Exoplanet Imaging Mission (HabEx), will see a complex spectrum with possibly numerous characteristics of the planet creating degenerate spectral signatures. In addition to well-known factors such as gas abundances, aerosols and clouds, and surface and land patterns, the planetary rotation rate will provide an additional complication. Terrestrial planets in our own star system have sidereal day lengths that vary from ~24 hours (Earth and Mars), to ~16 Earth days for Titan, and ~243 Earth days for Venus. For planets such as Titan and Venus, the surface is obscured in these wavelength ranges. However, for planets such as Earth, the rotation rate directly impacts patterns of clouds and surface ice that effect the reflected spectrum of the planet.

We evaluate the impact of planetary rotation rate on the observed reflected light spectrum of an Earth-like exoplanet using simulations with the Resolving Orbital and Climate Keys of Earth and Extraterrestrial Environments with Dynamics (ROCKE3D) global climate model (GCM) [1] and then feed the GCM output into the Planetary Spectrum Generator (PSG) [2] and Spectral Mapping Atmospheric Radiative Transfer (SMART) [3] radiative transfer models to generate reflected light spectra of our simulated planets.

GCM Simulations: We conducted 11 simulations using the ROCKE3D GCM with varied rotation rates: 1x, 2x, 3x, 16x, 32x, 64x, 128x, 243x (corresponding to a 3:2 spin-orbit resonance), 256x, 365x, and 365x with 0° obliquity (all relative to Earth’s 24 hour day length). All simulations utilize a fully-coupled dynamic ocean, solar insolation, terrestrial obliquity (i.e., 23°, except one of the 365x simulations where it is set to 0°), and Earth atmospheric composition (400 ppm CO₂, prescribed O₃, CH₄, and N₂O). The topography used in the model is Earth-like, but with a “bathtub” ocean bathymetry to eliminate the chance that the ocean freezes to the bottom in shallow water. Surface vegetation is eliminated, a 50/50 sand-clay soil is used, and we employ a uniform land surface albedo of 0.3.

All simulations are run until they reach radiative equilibrium, which is defined as the net radiative balance of the planet being ±0.2 W/m² and then for a further 100 years. This results in each simulation being run for 500-1000 simulated years.

Radiative Transfer Codes: We employ two sophisticated radiative transfer (RT) codes to model the reflected light spectrum from our GCM simulations: the Planetary Spectrum Generator and SMART. These radiative transfer models resolve the structure of molecular bands, surface reflectivity, and cloud scattering in much more detail than native GCM radiative transfer, which enables the study of observables relevant to future space-based, coronagraph-equipped telescopes (e.g. HabEx/LUVOIR). The utilization of two independent RT codes provides confidence in the robustness of the observables. Both codes perform radiative transfer calculations to compute high-resolution spectra via line-by-line. PSG is also publicly available through NASA Goddard, providing a means to develop a GCM-to-PSG pipeline in future that can be shared with the community. SMART has been validated against solar system objects and has been used to study a wide variety of types of atmospheres.

Discussion: The planetary climate undergoes a significant shift as the rotation rate of the planet slows. Rather than having distinct mid-latitude and polar climate zones, the planet moves into an “all tropics” climatic regime where the Hadley cells reach to the poles and the equator-to-pole temperature gradient is markedly reduced (Figure 1). As rotation rate is slowed, equatorial superrotation develops in the upper troposphere and stratosphere at rotation rates of ~16-32x (Figure 2), before dissipating as the rotation rate continues to slow (beyond 32x) and atmospheric motion weakens.

The ocean circulation also undergoes substantial alterations with at first a broadening of the main north-south currents (i.e., the Gulf Stream and Kuroshio currents) and eventually a full reversal of the Antarctic circumpolar current (Figure 3).

References:
Figure 1. Surface air temperature change between a 128x and 1x Earth day rotation rate simulation. The low-and mid-latitudes are substantially cooled while the poles are warmed.

Figure 2. Zonal mean zonal wind at 185mb (top) and 50mb (bottom) for simulations ranging between 1x and 128x Earth day rotate rate. The 16x and 32x simulations exhibit equatorial superrotation at 50mb.

Figure 3. Ocean current vectors and velocity for the 128x Earth day rotation rate simulation. The Antarctic circumpolar current is reversed (i.e. flowing east-to-west) relative to Earth.