Improving the Uranus and Neptune PlanetGRAMs with 2D Zonally-Averaged Atmospheric Variabilities.

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Introduction: We developed an open-source Python package (tweModel.py[1]) that generates the 2D zonally-averaged atmospheric structure of Jupiter, Saturn, Uranus, and Neptune to be used as reference bases for NASA's Planetary Global Reference Atmospheric Model (PlanetGRAM) Suite. The package outputs temperatures, pressures, densities, and zonal winds as functions of altitude and latitude given an input cloud-top zonal wind profile and a zonally averaged temperature map using a discretized form of the geostrophic thermal wind equation (TWE). We present 2D atmospheric structure outputs for Uranus and Neptune in detail. Our results will be incorporated in the PlanetGRAM Suite to aid in the development of future in-situ missions in the outer solar system including the recently prioritized Uranus Flagship mission.

Methods: The geostrophic form of the TWE describes the relationship between the latitudinal temperature gradient and vertical wind shear assuming geostrophic and hydrostatic balance. The textbook form of the TWE[2] is:

$$\left(\frac{\partial T_v}{\partial y}\right)_p = \frac{pfm_d}{k}\left(\frac{\partial u}{\partial p}\right)_y$$

where Tv is virtual temperature, y is the "northward distance" between two latitudes, p is pressure, m_d is the mass per molecule of dry air, k is the Boltzmann constant, u is the zonal wind, and f is the Coriolis parameter:

$$f = 2\Omega \sin\phi$$

where Ω is the planet's rotation rate and φ is the latitude. We use the TWE to calculate the expected vertical wind shear given measured latitudinal temperature gradients to extend cloud-top winds to depth. The discretized form of the TWE implemented in tweModel.py is multiplied by an additional tuning parameter to "turn off" the contribution from the Coriolis parameter near the equator to prevent u from exponentially growing to infinity as f approaches zero. It is given by:

$$\left(\frac{\arctan\left[c_1\phi\right]}{\frac{\pi}{2}}\right)$$

where c_1 is a tuning parameter that determines how fast the term grows. Cloud-top temperatures are extrapolated to a user-defined depth by assuming a constant Brunt-Väisälä (BV) frequency. Near the high pressure boundary we apply a smoothing function such that the horizontal temperature gradient approaches zero. This results in latitudinally homogeneous temperatures at depth as predicted by deep convective models. Further details may be found in the theory.md file in tweModel.py's documentation[1].

Results for Uranus: We generated 2 cases of the zonally-averaged atmospheric structure of Uranus from 1.0 bar to 100 bar at 1000 pressure levels on 1 degree latitude grids. Input zonally averaged cloud-top temperatures were taken from Flasar et al. 1987 Voyager observations[3]. We assumed a constant BV frequency of 0.002 s^{-1} when extrapolating temperatures to depth. Input cloud-top winds were from two sources: Voyager winds from Karkoschka 2015[4] and winds from Sromovsky et al. 2015[5] which used Keck and Gemini AO observations combined with the Karkoschka data. The two input zonal wind sources resulted in similar output zonal winds near the equator; however, the Sromovsky et al. wind input data extends closer to the north pole and its output is more symmetric about the equator than Karkoschka's winds.

Results for Neptune: Similar to our Uranus cases, we generated 2 cases of the zonally-averaged atmospheric structure of Neptune from 0.1 bar to 100 bar at 1000 pressure levels on 1 degree latitude grids. Input zonally averaged cloud-top temperatures were obtained from Roman et al. 2022's model based on observations from the Keck LWS, Gemini-North Michelle/TEXES, Gemini-South T-ReCS, VLT VISIR, Subaru COMICS, and Spitzer IRS[6]. Two temperature map epochs were input: 2003 and 2018. We assumed a constant BV frequency of 0.0025 s^{-1} when extrapolating temperatures to depth. Input cloud-top winds were from Sromovsky et al. 1993 Voyager images[7]. Output zonal winds from the 2003 temperature map were generally higher than that of the 2018 case. This was especially seen at the southern eastward jet where 2003's zonal wind speeds were ~150 m/s faster at 100 bar.

Future Work: Improvements to our method under consideration include using a moist adiabat to extend temperatures rather than assuming a constant BV frequency, using a different form of the TWE which addresses the equatorial region without removing contributions from the Coriolis parameter, and improved validation against observations at multiple altitudes.

References: [1] Garland, J. and Sayanagi, K., M. (2022) https://github.com/PlanetaryGarland/tweModel [2] Holton, J. R. (2004) *An Introduction to Dynamic Meteorology*. [3] Flasar, F. M. et al. (1987) *J. Geophys. Res., 92(A13)*, 15011–15018. [4] Karkoschka, E. (2015) *Icarus, 250*, 294-307. [5] Sromovsky, L. A. et al. (2015) *Icarus, 258*, 192-223. [6] Roman, M. T. et al. (2022) *PSJ, 3*, 78. [7] Sromovsky, L. A. et al. (1993) *Icarus, 105*, 110-141.