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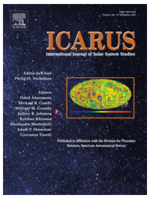

Seasonal stratospheric photochemistry on Uranus and Neptune

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ABSTRACT

A time-variable 1D photochemical model is used to study the distribution of stratospheric hydrocarbons as a function of altitude, latitude, and season on Uranus and Neptune. The results for Neptune indicate that in the absence of stratospheric circulation or other meridional transport processes, the hydrocarbon abundances exhibit strong seasonal and meridional variations in the upper stratosphere, but that these variations become increasingly damped with depth due to increasing dynamical and chemical time scales. At high altitudes, hydrocarbon mixing ratios are typically largest where the solar insolation is the greatest, leading to strong hemispheric dichotomies between the summer-to-fall hemisphere and winter-to-spring hemisphere. At mbar pressures and deeper, slower chemistry and diffusion lead to latitude variations that become more symmetric about the equator. On Uranus, the stagnant, poorly mixed stratosphere confines methane and its photochemical products to higher pressures, where chemistry and diffusion time scales remain large. Seasonal variations in hydrocarbons are therefore predicted to be more muted on Uranus, despite the planet's very large obliquity. Radiative-transfer simulations demonstrate that latitude variations in hydrocarbons on both planets are potentially observable with future JWST mid-infrared spectral imaging. Our seasonal model predictions for Neptune compare well with retrieved C_2H_2 and C_2H_6 abundances from spatially resolved ground-based observations (no such observations currently exist for Uranus), suggesting that stratospheric circulation — which was not included in these models — may have little influence on the large-scale meridional hydrocarbon distributions on Neptune, unlike the situation on Jupiter and Saturn.

1. Introduction

Infrared and ultraviolet observations reveal that the stratospheric composition of Uranus and Neptune is being altered by solar-driven photochemistry, despite the great distance of these planets from the Sun (see the reviews of Atreya et al., 1991; Bishop et al., 1995; Yung and DeMore, 1999). Methane photolysis by solar ultraviolet radiation triggers the production of acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), methylacetylene (CH_3C_2H), diacetylene (C_4H_2), and other complex hydrocarbons, many of which have been observed on Uranus and Neptune (see Burgdorf et al., 2006; Orton et al., 2014c, and references therein). These photochemically produced species are radiatively active at mid-infrared wavelengths and can affect many aspects of the planetary atmosphere, such as its thermal structure, aerosol structure, energy balance, dynamical motions, and ionospheric structure. A full understanding of the three-dimensional (3D) time-variable behavior of photochemically produced species is therefore important for understanding many aspects of atmospheric physics and chemistry on Uranus and Neptune.

The non-zero obliquity (axial tilt) of Uranus and Neptune results in a seasonal dependence of solar insolation (see Fig. 1) that affects the production and loss rates of photochemically active constituents. Uranus, with its extreme ∼97.8° obliquity and rotational pole nearly in line with its orbital plane, experiences very unusual seasons compared to other Solar-System planets. Averaged over a year, high latitudes on Uranus receive greater solar insolation than low latitudes (see Fig. 2). Much of the planet alternates between being almost fully illuminated and being in almost complete darkness for half a year at a time (with one year on Uranus being equal to 84 Earth years), creating an opportunity for dramatic changes in hydrocarbon production as a function of season. Neptune's more moderate 28.3° obliquity results in seasonal forcing similar to that

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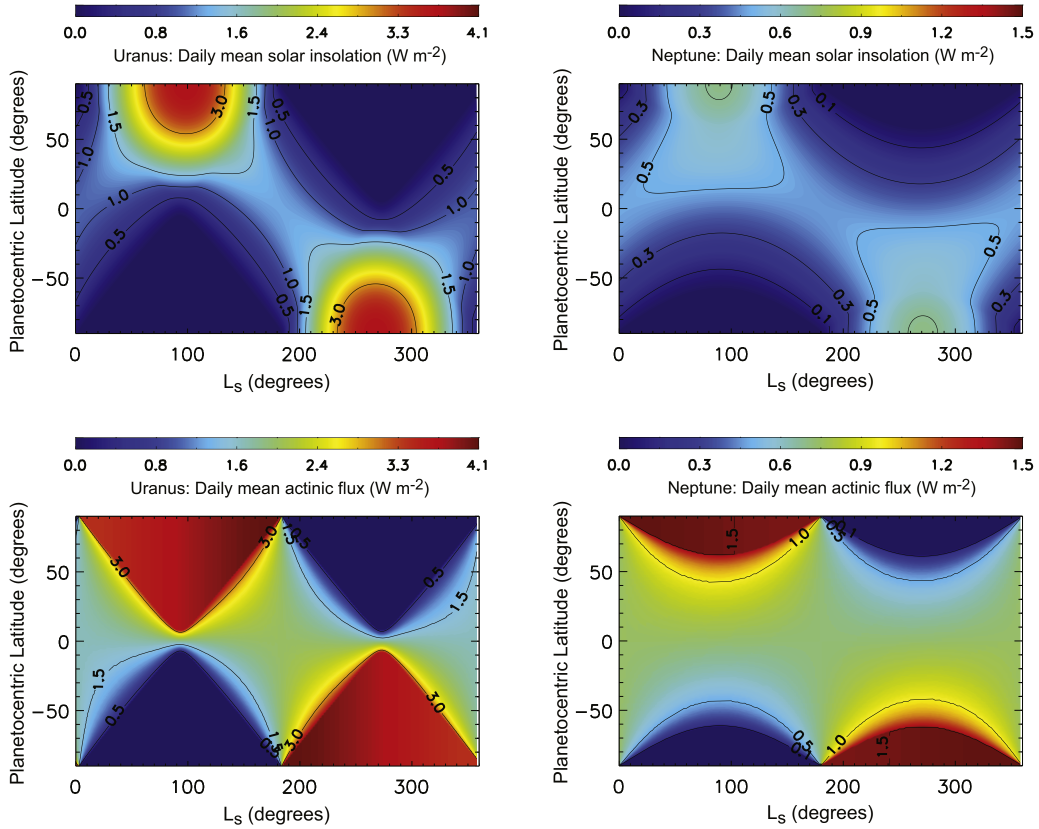

Fig. 1. (Top) Mean daily solar insolation (W m^{-2} per planetary day) incident onto a unit horizontal surface at the top of the atmosphere of Uranus (Left) and Neptune (Right) as a function of planetocentric latitude and season, where season is represented by solar longitude L_s. (Bottom) Mean daily actinic flux (W m^{-2} per planetary day) at the top of the atmosphere of Uranus (Left) and Neptune (Right) as a function of planetocentric latitude and season. Note that a molecule being photodissociated does not care what direction the photon is coming from, just what the local photon flux is; therefore, the actinic flux, which is the solar flux without accounting for the cosine dependence of the solar zenith angle, is more relevant to the photochemistry discussion than the insolation at a "surface."

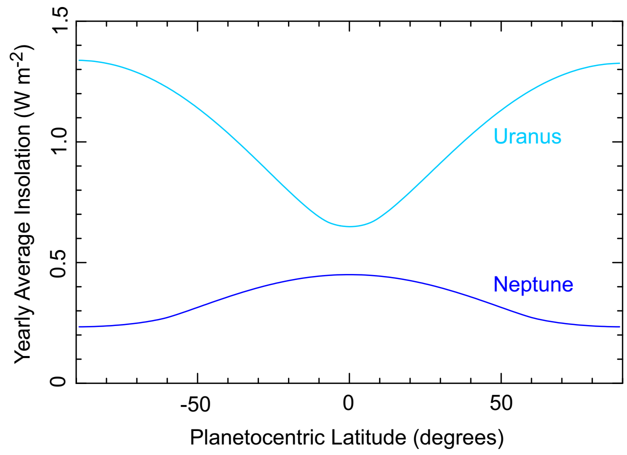

Fig. 2. Annual average solar insolation at Uranus and Neptune as a function of latitude. Unlike the situation on other planets in the solar system, the polar regions of Uranus receive a higher annual average insolation than the equatorial region.

on the Earth, Mars, and Saturn, with low latitudes receiving a greater annual average solar insolation than high latitudes. Thus, averaged over a year, hydrocarbon production rates on Neptune will be greater at low latitudes than high latitudes. Given that a Neptune year is 165 Earth years, the winter high-latitude regions on Neptune endure long periods of time without sunlight, and the reduction in photochemical production of stratospheric hydrocarbons during the long polar winter could potentially affect global hydrocarbon abundances and/or result in different meridional distributions of hydrocarbons than shorter-period planets with similar obliquities, such as Saturn.

Although several one-dimensional (1D) photochemical models for Uranus and Neptune have been developed in the past (e.g., Atreya and Ponthieu, 1983; Romani and Atreya, 1988; 1989; Romani et al., 1993; Summers and Strobel, 1989; Bishop et al., 1990; 1992; 1998; Moses et al., 1992; 1995; 2005; Lellouch et al., 1994; Dobrijevic and Parisot, 1998; Dobrijevic et al., 2010; Bézard et al., 1999; Schulz et al., 1999; Orton et al., 2014c; Moses and Poppe, 2017), all previous models were designed for either global-average conditions or specific latitudes and times. Here, we present results from a 1D time-variable model that tracks the seasonal variation of photochemically produced hydrocarbons as a function of altitude for different latitudes. The models are similar to those of Moses and Greathouse (2005) in that the 1D models for the different latitudes are not connected to each other via atmospheric circulation or any type of meridional transport, and the temperature structure is kept constant with latitude and time. Hue et al. (2015) show that for Saturn, the expected seasonal variations in stratospheric temperatures have only a minor influence on the abundances of the observable hydrocarbons, except in high-latitude regions during winter, where downward diffusion of hydrocarbons is faster as a result of atmospheric compression due to the lower temperatures. On the other hand, atmospheric dynamics can alter the vertical and meridional distribution of stratospheric constituents in potentially more significant ways. Comparisons of seasonal 1D photochemical models with the observed vertical and meridional distribution of hydrocarbon