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2D photochemical modeling of Saturn's stratosphere. Part I: Seasonal variation of atmospheric composition without meridional transport

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ABSTRACT

Saturn's axial tilt of 26.7° produces seasons in a similar way as on Earth. Both the stratospheric temperature and composition are affected by this latitudinally varying insolation along Saturn's orbital path. A new time-dependent 2D photochemical model is presented to study the seasonal evolution of Saturn's stratospheric composition. This study focuses on the impact of the seasonally variable thermal field on the main stratospheric C2-hydrocarbon chemistry (C_2H_2 and C_2H_6) using a realistic radiative climate model. Meridional mixing and advective processes are implemented in the model but turned off in the present study for the sake of simplicity. The results are compared to a simple study case where a latitudinally and temporally steady thermal field is assumed. Our simulations suggest that, when the seasonally variable thermal field is accounted for, the downward diffusion of the seasonally produced hydrocarbons is faster due to the seasonal compression of the atmospheric column during winter. This effect increases with increasing latitudes which experience the most important thermal changes in the course of the seasons. The seasonal variability of C_2H_2 and C_2H_6 therefore persists at higher-pressure levels with a seasonally-variable thermal field. Cassini limb-observations of C_2H_2 and C_2H_6 (Guerlet, S. et al. [2009]. Icarus 203, 214–232) are reasonably well-reproduced from the equator to 40° in both hemispheres in the 0.1–1 mbar pressure range. At lower pressure levels, the models only fit the Cassini observations in the northern hemisphere, from the equator to 40°N. Beyond 40° in both hemispheres, deviations from the pure photochemical predictions, mostly in the southern hemisphere, suggest the presence of large-scale stratospheric dynamics.

1. Introduction

Observations of Saturn in the infrared and millimetric range, performed by ISO or ground-based facilities gave us access to its disk-averaged stratospheric composition (see the review of Fouchet et al. (2009) for a complete list of observations), for which 1D photochemical models have done a fairly good job reproducing it (Moses et al., 2000a,b). Close-up observations, performed by the Voyager missions as well as recent ground-based observations, have unveiled variations with latitude of the temperature and the stratospheric composition (Ollivier et al., 2000a; Greathouse et al., 2005; Sinclair et al., 2014). The Cassini probe has now mapped (as a function of altitude and latitude) and monitored for almost 10 years, i.e., 1.5 Saturn season, the temperature and the main hydrocarbon emissions in Saturn's stratosphere (Howett et al., 2007; Fouchet et al., 2008; Hesman et al., 2009; Guerlet et al., 2009, 2010; Li et al., 2010; Fletcher et al., 2010; Sinclair et al., 2013, 2014).

We now have an impressive amount of data for which 1D photochemical models (e.g., Moses et al., 2000a,b, 2005; Ollivier et al., 2000b) have become insufficient in predicting the 3D properties of Saturn's stratosphere, especially in terms of dynamics (diffusion and advection). On the other hand, general circulation models (GCM) are being developed for Jupiter (Medvedev et al., 2013) and Saturn (Dowling et al., 2006, 2010; Friedson and Moses, 2012; Guerlet et al., 2014). Such models usually focus on dynamics and therefore are restricted in their description of the atmospheric chemistry as they are limited to only a few reactions, if any at all.

Liang et al. (2005) and Moses and Greathouse (2005) made the first attempts to construct latitude-altitude photochemical models for the giant planets, followed by Moses et al. (2007) who built a

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2D-photochemical model for Saturn and who accounted for simple Hadley-type circulation cells as well as meridional diffusive transport. The quasi-two-dimensional model developed by Liang et al. (2005) does not fully account for the latitudinal transport as a diffusive correction is added at the end of the one-dimensional calculations. This model also does not account for evolution of the orbital parameters. Due to its very low obliquity, the seasonal effects on Jupiter should be mainly caused by its eccentricity and might be non negligible. On the other hand, the model developed by Moses and Greathouse (2005) accounts for the seasonal evolution of the orbital parameters as well as the variations in solar conditions. They have shown that, for Saturn, the seasonal effects on atmospheric composition are important, as Saturn's obliquity is slightly larger than the Earth's. Their model consists of a sum of 1D-photochemical model runs at different solar declinations and conditions. It does not include meridional transport processes nor the calculation of the actinic fluxes in 2D/3D. Saturn's high obliquity similarly impacts the stratospheric temperatures (Fletcher et al., 2010). This effect was accounted for by Moses and Greathouse (2005) in their photochemical model as part of a sensitivity case study, by locally warming their nominal temperature profile at two latitudes, according to the observations of Greathouse et al. (2005). In this sense, the photochemical model in Guerlet et al. (2010) represents an improvement from the previous model of Moses and Greathouse (2005) as it includes the latitudinal thermal gradient observed both by Fletcher et al. (2007) and Guerlet et al. (2009), but held constant with seasons. Finally, Moses et al. (2007) accounted for the meridional transport in a 2D-photochemical model, but similarly neglected the seasonal evolution of the stratospheric temperature. They were unable to reproduce the ground-based hydrocarbon observations prior to Cassini mission (Greathouse et al., 2005). After 10 years of Cassini measurements, data has shown that Saturn's stratospheric thermal structure is complex, with a 40 K pole-to-pole gradient after solstice (Fletcher et al., 2010), and thermal oscillations in the equatorial zone (Orton et al., 2008; Fouchet et al., 2008; Guerlet et al., 2011).

For the moment, there is no 2D photochemical model that simultaneously accounts for seasonal forcing, meridional transport and the evolution of the stratospheric temperature. In this paper, we present a new step toward this model, applied to Saturn. These latitudinally and seasonally variable 1D models, coupled by a 3D-radiative transfer model, can be seen as an intermediate class of model between the 1D photochemical models that have the most complete chemistries and the GCMs that are focused on 3D dynamics. In this paper, we present a restricted version of our full-2D model. The goal of this preliminary study is to evaluate the atmospheric chemical response to seasonal forcing in terms of solar radiation and atmospheric temperatures. The meridional transport is therefore set to zero for this study in order to focus on photochemical effects. In forthcoming papers we will focus on the effect of 2D advective and diffusive transport on the predicted abundances.

In the first part of this paper, we present in detail how the seasonally variable parameters are accounted for in the model, including Saturn's orbital parameters and the thermal field. Then, we describe the photochemical model, the chemical scheme used in that model and the 3D radiative transfer model used to calculate the attenuation of the UV radiation in the atmosphere. We afterwards describe the seasonal evolution of the chemical composition, first by assuming that the thermal field does not evolve with time and latitude, to compare with previous findings, then by considering a more realistic thermal field with spatio-temporal variations. We underline the effect of such thermal field variations on the chemical composition. Finally, we will compare our results with the Cassini/CIRS observations.

2. Seasonal modeling of the photochemistry

2.1. Introduction

The amount of solar radiation striking the top of the atmosphere at a given latitude varies with seasons because of Saturn's obliquity and eccentricity. Atmospheric heating occurs through methane near-IR absorption of this radiation. Cooling is preponderant in the mid-IR range, mainly through emissions from acetylene, ethane, and, to a lesser extent, methane (Yelle et al., 2001). These IR-emissions increase with increasing atmospheric temperatures and/or abundances of these compounds. Therefore, the temperature field, as a function of altitude and latitude, mostly depends on the seasonal distribution of these species and on their response to the seasonally varying insolation.

Methane, which is generally assumed to be well-mixed in Saturn's atmosphere (see e.g., Fletcher et al., 2009) and optically thick in its IR bands, can be used as a thermometer to constrain the thermal field (Greathouse et al., 2005). Asymmetries in Saturn's atmospheric temperatures have been observed as a function of season, from Voyager (Pirraglia et al., 1981; Hanel et al., 1981, 1982; Conrath and Pirraglia, 1983; Courtin et al., 1984) and ground-based observations (e.g., Gillett and Orton, 1975; Rieke, 1975; Tokunaga et al., 1978; Gezari et al., 1989; Ollivier et al., 2000a; Greathouse et al., 2005). These observations have been reproduced in an approximate sense by radiative transfer model predictions (Cess and Caldwell, 1979; Bézard et al., 1984; Bézard and Gautier, 1985).

The Cassini spacecraft arrived in Saturn's system in July 2004, shortly after its northern winter solstice (see Fig. 1). It has provided full-coverage of the temperatures for the upper troposphere and stratosphere ever since. It has given us the opportunity to observe seasonal changes in the temperature field for over 10 years. For instance, the North/South thermal asymmetry at the northern winter solstice has been observed: the southern hemisphere was experiencing summer and was found warmer than the northern one (Flasar et al., 2005; Howett et al., 2007; Fletcher et al., 2007). Subsequently, Cassini observed how the winter hemisphere evolves when emerging from the shadow of the rings and how the summer hemisphere cools down when approaching equinox (Fletcher et al., 2010; Sinclair et al., 2013).

The main driver for atmospheric chemistry comes from solar UV radiation. This radiation initiates a complex chemistry through methane photolysis leading to the production of highly reactive chemical radicals. The kinetics of the chemical reactions triggered by photolysis generally have a thermal dependence that can impact the overall production/loss rates of atmospheric constituents over the course of Saturn's long seasons.

Since we want to evaluate the atmospheric chemical response to seasonal forcing in terms of solar radiation and atmospheric temperatures, we thus compare the results of our model obtained in two different cases:

- The temperature field consists of a single profile applied to all latitudes and seasons in a similar way to previous 1D studies. This study case will be denoted (U)
- The temperature field is vertically, latitudinally and seasonally variable. This study case will be denoted (S)

We stress again that the latitudes are not connected in the following study, i.e., the meridional transport is set to zero, so as to better quantify the effects of a seasonally variable temperature field on the distribution of chemical species. We defer the study of meridional transport to a forthcoming paper.