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2D photochemical modeling of Saturn's stratosphere. Part II: Feedback between composition and temperature

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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. The atmospheric thermal structure is controlled and regulated by the amount of hydrocarbons in the stratosphere, which act as absorbers and coolants from the UV to the far-IR spectral range, and this structure has an influence on the amount of hydrocarbons. We study here the feedback between the chemical composition and the thermal structure by coupling a latitudinal and seasonal photochemical model with a radiative seasonal model. Our results show that the seasonal temperature peak in the higher stratosphere, associated with the seasonal increase of insolation, is shifted earlier than the maximum insolation peak. This shift is increased with increasing latitudes and is caused by the low amount of stratospheric coolants in the spring season. At 80° in both hemispheres, the temperature peak at 10^{-2} mbar is seen to occur half a season (3–4 Earth years) earlier than was previously predicted by radiative seasonal models that assumed spatially and temporally uniform distribution of coolants. This shift progressively decreases with increasing pressure, up to around the 0.5 mbar pressure level where it vanishes. On the opposite, the thermal field has a small feedback on the abundance distributions. Accounting for that feedback modifies the predicted equator-to-pole temperature gradient. The meridional gradients of temperature at the mbar pressure levels are better reproduced when this feedback is accounted for. At lower pressure levels, Saturn's stratospheric thermal structure seems to depart from pure radiative seasonal equilibrium as previously suggested by Guerlet et al. (2014). Although the agreement with the absolute value of the stratospheric temperature observed by Cassini is moderate, it is a mandatory step toward a fully coupled GCM-photochemical model.

1. Introduction

Similar to the Earth, Saturn's obliquity of 26.7° produces seasons forced by its 29.5 years orbital period. Insolation thus varies with latitude along that cycle. The atmospheric response to this forcing has been witnessed by Cassini spacecraft clearly in the stratospheric temperature and subtly in the chemical composition (Fletcher et al., 2010; Orton et al., 2008; Sinclair et al., 2013).

Saturn's stratospheric thermal structure is controlled by the heating due to near-IR methane (CH_4) absorption bands while the cooling is dominated by mid-IR emission lines of acetylene (C_2H_2), ethane (C_2H_6) and CH_4 (Greathouse et al., 2008). Saturn's stratospheric composition is, on the other hand, controlled by CH_4 photolysis in the UV spectral range. The recombination of the radicals produced by this photolysis initiates the production of numerous hydrocarbons, C_2H_6 and C_2H_2 being the most abundant ones (e.g. Moses and Greathouse, 2005; Hue et al., 2015).

Consequently, there is an interesting feedback to study. The seasonally variable insolation received by Saturn as a function of latitude produces variations in the atmospheric heating/cooling rates, while producing, at the same time, variations in the amount of coolants due to photochemical processes. These processes have different timescales, meaning that only a 3D-GCM that would simultaneously solves the photochemistry, radiative and dynamical

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equations would be accurate. Such a solution requires computational means that are beyond our capabilities at the moment.

Therefore, the problem is usually decoupled using different numerical tools. The effect of the solar energy input on the Saturn's stratospheric temperature is inferred from radiative seasonal models (see e.g. Bézard and Gautier, 1985; Greathouse et al., 2008; Guerlet et al., 2014) while its effect on the atmospheric composition is inferred from photochemical models (Moses and Greathouse, 2005; Dobrijevic et al., 2011; Hue et al., 2015).

The already existing radiative seasonal models generally assume meridionally and temporally constant abundances (Greathouse et al., 2008; Guerlet et al., 2014). These assumed spatial distributions of coolants come from Cassini/CIRS observations (Guerlet et al., 2009, 2010) or ground-based observations (Greathouse et al., 2005). However, the seasonal dependence of the spatial distribution of the coolants have been neglected so far. The main reason being that little temporal coverage of the observed distribution of hydrocarbons exists.

Until recently, the photochemical models published in the literature (e.g. Moses et al., 2000; Moses and Greathouse, 2005) did not account for the temporal evolution of temperature, or only tested the influence of its spatial variability as sensitivity cases. Hue et al. (2015) made a first attempt to use a realistic thermal field, i.e. a thermal field that evolves with latitude and time, in a pseudo-2D photochemical model. In that work, the stratospheric temperatures were computed by the radiative seasonal model of Greathouse et al. (2008). Even in that study, the problem stayed partly uncoupled: the feedback between chemistry and temperature was not fully accounted for. In this paper, we study how the temperature is affected by using a more realistic distribution of atmospheric coolants and how such a temporally variable thermal field impacts the atmospheric composition in return. Furthermore, in the framework of the future development of more complex models that will solve at the same time the hydrodynamical and photochemical equations, we aim to assess if a seasonally repeatable state can be reached with such an approach.

In the first part of this paper, we describe how our radiative seasonal model and our photochemical model have been coupled. Then, we present the feedback of each model on one another, i.e. the impact of a seasonally variable chemical composition on the predicted stratospheric temperatures and vice versa. Finally, we compare the thermal field that accounts for that feedback with Cassini observations.

2. Description of the model

We first briefly describe here the photochemical model used to compute the chemical composition. Then, we describe the radiative seasonal model used to compute the stratospheric temperature. A more detailed decription of these models can be found in the associated publications.

2.1. Photochemical model

The photochemical model used to compute the chemical abundances is the pseudo-2D (altitude–latitude) time-dependent model presented in Hue et al. (2015). This model accounts for the variation of the seasonally variable parameters such as the subsolar latitude and the heliocentric distance. The ring shadow effects on the atmospheric chemistry are accounted for, following the prescription of Guerlet et al. (2014), and are based on stellar occultation measurements published by Colwell et al. (2010). The chemical scheme used in this model is based on the work of Loison et al. (2015), in which the chemical scheme has been greatly improved thanks to previous work Hébrard et al. (2013) and Dobrijevic et al. (2014). Following the methodology of Dobrijevic et al. (2011), the chemical scheme has been reduced by Cavalié et al. (2015) in terms of number of species and reactions to make it useable by 2D–3D photochemical models of Saturn.

The photochemical model is divided into a spherical atmosphere consisting of 118 altitude levels and 17 latitude cells. The vertical grid span the pressure range of 10^3 mbar to, at least, 10^{-7} mbar in order to fully resolve the depth of absorbed UV flux at the top of the model. The latitude grid ranges from 80°S to 80°N. The model solves the continuity equation using DLSODE from the ODEPACK library (Hindmarsh, 1983).

The photochemical equations were integrated over Saturn's sampled orbit. The hydrocarbon chemistry is mainly driven by methane photolysis that occurs in the higher stratosphere (around 10^{-4} mbar). From there, the produced hydrocarbons diffuse down to the lower stratosphere.

Finally, the pressure–temperature background used in the photochemical model comes from the radiative seasonal model described below.

2.2. Radiative seasonal model

The temperature field is inferred from the multi-layer radiative seasonal model developed by Greathouse et al. (2008). Consistently with the photochemical model presented above, it accounts for the same evolution in the seasonally variable parameters. The ring shadowing effects are accounted for following the formalism of Bézard (1986) and Moses and Greathouse (2005). The heating due to CH_4 absorption in the near-infrared, visible and UV spectral range is included as well as C_2H_2, C_2H_4 and C_2H_6 absorption in the UV range in a direct beam radiative transfer model (following the Beer–Lambert law). Cooling within the mid- to far-infrared range due to CH_4, C_2H_2 and C_2H_6 line emissions is included and follows the formalism of Goukenleuque et al. (2000). The continuum emission in the far-infrared range due to collision-induced absorption of H_2–H_2, H_2–He and H_2–CH_4 is accounted for using the formalism of Borysow et al. (1985, 1988) and Borysow and Frommhold (1986).

The spectroscopic line information are taken from GEISA03 (Jacquinet-Husson et al., 1999), HITRAN (Rothman et al., 2005) and from Vander Auwera et al. (2007). From this information, κ-coefficient tables are produced for each molecule. This allows to modify each molecule abundance within a run independently from one another, while avoiding the re-calculation of the full κ-coefficient tables each time one of the absorbers/coolants abundance is altered. This substantially reduces the computational time.

The C_2H_2 and C_2H_6 distributions which were assumed for the first run come from Cassini/CIRS observations at planetographic latitude of 45°S published by Guerlet et al. (2009). These vertical profiles are kept constant with latitude and time to compute the initial thermal field.

The tropospheric aerosols are not accounted because the seasonal radiative model is focus here on predicting the stratospheric temperatures. The stratospheric aerosols have minor effects on the predicted temperatures and are not accounted here. The addition of the stratospheric aerosols following Karkoschka and Tomasko (2005) increases temperatures by less than 1 K above the 30 mbar level at 83°S. In the equatorial region, the temperatures are increased by less than 0.1 K.

The radiative seasonal model extends from 9 times 10^{-5} mbar to 660 mbar. The model is divided into a plane parallel atmosphere consisting of 83 pressure levels. Local thermodynamic equilibrium (LTE) is assumed throughout. Temperatures are valid up to 10^{-3} mbar where the non-LTE effects start to dominate.