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Global climate modeling of Saturn's atmosphere. Part I: Evaluation of the radiative transfer model

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ABSTRACT

We have developed and optimized a seasonal, radiative–convective model of Saturn's upper troposphere and stratosphere. It is used to investigate Saturn's radiatively-forced thermal structure between 3 and 10^{-6} bar, and is intended to be included in a Saturn global climate model (GCM), currently under development. The main elements of the radiative transfer model are detailed as well as the sensitivity to spectroscopic parameters, hydrocarbon abundances, aerosol properties, oblateness, and ring shadowing effects. The vertical temperature structure and meridional seasonal contrasts obtained by the model are then compared to Cassini/CIRS observations. Several significant model-observation mismatches reveal that Saturn's atmosphere departs from radiative equilibrium. For instance, we find that the modeled temperature profile is close to isothermal above the 2-mbar level, while the temperature retrieved from ground-based or Cassini/CIRS data continues to increase with altitude. Also, no local temperature minimum associated to the ring shadowing is observed in the data, while the model predicts stratospheric temperatures 10 K to 20 K cooler than in the absence of rings at winter tropical latitudes. These anomalies are strong evidence that processes other that radiative heating and cooling control Saturn's stratospheric thermal structure. Finally, the model is used to study the warm stratospheric anomaly triggered after the 2010 Great White Spot. Comparison with recent Cassini/CIRS observations suggests that the rapid cooling phase of this warm "beacon" in May–June 2011 can be explained by radiative processes alone. Observations on a longer timeline are needed to better characterize and understand its long-term evolution.

1. Introduction

Saturn's upper tropospheric and stratospheric thermal structure is governed by radiative and dynamical processes, both controlled by seasonal variations in insolation over the course of Saturn's 29.5 year orbit. Radiative cooling occurs primarily through thermal emission of hydrocarbons (mainly methane, ethane and acetylene) along with collision-induced absorption (CIA) by H_2–H_2 and H_2–He in the thermal infrared. Radiative heating mainly results from absorption of visible and near-infrared solar photons by methane and aerosols. Seasonal and orbital variations in insolation have a direct effect on the net heating rates, through variations in solar energy deposition, as well as an indirect effect due to the modulation of photochemical activity, impacting hydrocarbon and aerosol abundances (and hence the associated radiative cooling/heating rates). Furthermore, aerosols and hydrocarbons can be transported by Saturn's large-scale circulation, which in turn impacts the radiative budget and the temperature fields.

Over the last decade, ground-based and space-based spectroscopic infrared mapping of Saturn's atmospheric thermal structure and composition have been obtained with unprecedent details. In particular, the Composite Infrared Spectrometer (CIRS) instrument onboard Cassini has been acquiring data for 8 years (2004–2013), long enough to monitor seasonal variations in temperature and composition (Fletcher et al., 2010; Sinclair et al., 2013).

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These observations reveal that Saturn's lower stratosphere exhibit large temperature contrasts with latitude and season. For instance, in 2005 (solar longitude $L_S = 300°$), a pole-to-pole temperature contrast of 40 K was measured at the 1-mbar level between the southern (summer) and northern (winter) hemispheres (Fletcher et al., 2007). Following the 2009 equinox, high southern latitudes have cooled down by 10–15 K as they were entering autumnal darkness, while northern mid-latitudes have warmed by 6–10 K as they emerged from ring-shadow to spring-time conditions (Fletcher et al., 2010; Sinclair et al., 2013). In contrast, tropospheric temperatures exhibit moderate hemispherical asymmetries (10 K at 100 mbar at $L_S = 300°$) and seasonal variations (only 2–3 K over 4 years), consistent with the longer radiative time constants at higher pressures.

On top of these overall seasonal trends, the observed temperature fields display several anomalies, which are thought to be of dynamical origin. The temperature in the equatorial region features a remarkable periodic oscillation characterized by the superposition of warm and cold regions, associated with a strong vertical wind shear of 200 m/s (Fouchet et al., 2008; Orton et al., 2008; Guerlet et al., 2011; Schinder et al., 2011). This pattern is reminiscent of analogous periodic oscillations in the Earth's stratosphere (the Quasi-Biennial Oscillation and the Semi-Annual Oscillation), which are governed by interactions between vertically-propagating waves and the mean zonal flow (Baldwin et al., 2001). Other thermal anomalies on Saturn include the observation of polar hot spots at both poles, supposedly linked to the polar vortices (Fletcher et al., 2008), and the occurrence of a spectacular stratospheric warming at 40°N (called "beacon") following Saturn's tropospheric Great White Storm in December 2010, still visible in 2012 (Fletcher et al., 2012).

Global climate modeling of Saturn's atmosphere is needed in order to better interpret the observed temperature fields, their seasonal variations, and disentangle the effects of radiative and dynamical processes. In the 1980s, following Voyager fly-bys, several 2D radiative–convective models have been developed, including or not seasonal effects (Appleby and Hogan, 1984; Bézard et al., 1984; Bézard and Gautier, 1985). Since then, major updates in the knowledge of hydrocarbon abundances (in particular obtained from Cassini observations), and their spectroscopic properties, have motivated a revision of these early models. For instance, Greathouse et al. (2008) have developed a seasonal radiative transfer model of Saturn's stratosphere and used it to interpret Cassini/CIRS observations in the 5–0.5 mbar pressure range (Fletcher et al., 2010).

Our aim is twofold: first, to build an up-to-date and versatile radiative–convective climate model of Saturn's upper troposphere and stratosphere that allows for comparison with temperature profiles measured in the full range of Cassini/CIRS vertical sensitivity (500–0.01 mbar). Secondly, to make this seasonal model fitted for implementation in a dynamical global climate model (GCM) of Saturn's atmosphere, with the aim of better understanding Saturn's stratospheric circulation, still poorly known.

Several numerical challenges arise when developing a Saturn GCM: on the one hand, a 3D numerical grid of high spatial resolution is needed to resolve dynamical processes (at least 512 × 384 elements in longitude × latitude, as constrained by Saturn's Rossby deformation radius); on the other hand, the long timescales of the seasonal radiative forcing compared to the short timescales of some atmospheric motions imply running simulations for several Saturn years, with calculations of radiative forcings every few Saturn days. Hence, there is a need for developing a fast and robust radiative transfer model for Saturn's atmosphere, in order to accurately compute atmospheric heating and cooling rates on each grid point of a GCM. Modeling efforts in this field are very recent, as most existing giant planet's dynamical models focus on the tropospheric layer (Morales-Juberias et al., 2003; Liu and Schneider, 2010; Lian and Showman, 2010), where radiative processes represent a minor contribution in the energy balance. Recently, Friedson and Moses (2012) presented results from a 3D GCM of Saturn's upper troposphere and stratosphere, which included a full radiative transfer scheme (using *k*-distributions). While the authors focused on deriving the effective advective circulation and eddy transport coefficients, specific aspects pertaining to the optimization and validation of the radiative transfer were not covered.

Here we report on the development and optimization of a radiative–convective model that uses up-to-date, state-of-the-art gaseous and aerosol opacities. This model can be used independently to study Saturn's radiatively-forced thermal structure, while it also meets the accuracy and computational efficiency required for an implementation in a Saturn 3D GCM, which will be detailed in a future manuscript. The main elements of the radiative transfer model are reviewed in Section 2, along with several sensitivity studies to, for instance, spectroscopic parameters and aerosol scenarios. In Section 3, the vertical and seasonal thermal contrasts obtained by the radiative–convective model are described, and the impact of ring shadowing and aerosols on the upper tropospheric and stratospheric temperature are evaluated. In Section 4, these results are discussed and compared to Cassini/CIRS observations. Finally, this model is applied to the study of the warm stratospheric anomaly triggered after the 2010 storm in Section 5, before concluding in Section 6.

2. A radiative–convective model of Saturn's atmosphere

2.1. Overall description

The radiative–convective model employed in this study is derived from existing tools developed as part as a generic version of the Laboratoire de Météorologie Dynamique (LMD) global climate model (GCM), used to simulate the radiative forcing and large-scale circulation of terrestrial exoplanets (Wordsworth et al., 2011; Leconte et al., 2013a,b) and primitive atmospheres (Charnay et al., 2013; Forget et al., 2013; Wordsworth et al., 2010a). The radiative part uses a two-stream approximation to solve the radiative transfer equations including multiple scattering as proposed by Toon et al. (1989). Rayleigh scattering is included following the method described in Hansen and Travis (1974). As line-by-line calculations are too time-consuming for GCM applications, a *k*-distribution model (described in Section 2.2) is used to compute gaseous opacities (Goody and Yung, 1989; Wordsworth et al., 2010b). Tests are performed to assess the importance of the diurnal cycle, which is found negligible. Rather, given Saturn's long radiative timescales, a daily-averaged solar flux is considered and calculations of the radiative heating and cooling rates are performed typically once every 10 (Saturn) days.

In this study, focused on the radiatively-forced thermal structure, computations in the dynamical part of the LMD GCM are not performed. A convective adjustment scheme relaxes the temperature profile towards the adiabatic lapse rate (g/C_p, with g the gravity and C_p the specific heat capacity) when an unstable temperature lapse rate is encountered after the radiative calculations (Hourdin et al., 1993).

The above-mentioned generic model is adapted to match Saturn's atmospheric conditions (composition, temperature and pressure) and external forcings. The nominal model includes opacities due to CH_4, C_2H_6, C_2H_2, collision-induced absorption by H_2–H_2, H_2–He and two aerosol layers. Hydrogen and helium fractions are set to, respectively, 0.86 and 0.1355 consistently with an analysis of Voyager measurements by Conrath and