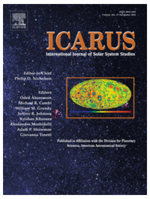
Icarus 302 (2018) 437–450

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Seasonal radiative modeling of Titan’s stratospheric temperatures at low latitudes

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ARTICLE INFO

Article history:
Received 27 July 2017
Revised 10 November 2017
Accepted 27 November 2017
Available online 29 November 2017

Keywords:
Titan, atmosphere
Atmospheres, structure
Atmospheres, dynamics

ABSTRACT

We have developed a seasonal radiative–dynamical model of Titan’s stratosphere to investigate the temporal variation of temperatures in the 0.2–4 mbar range observed by the Cassini/CIRS spectrometer. The model incorporates gas and aerosol vertical profiles derived from Cassini/CIRS and Huygens/DISR data to calculate the radiative heating and cooling rate profiles as a function of time and latitude. At 20°S in 2007, the heating rate is larger than the cooling rate at all altitudes, and more specifically by 20–35% in the 0.1–5 mbar range. A new calculation of the radiative relaxation time as a function of pressure level is presented, leading to time constants significantly lower than previous estimates. At 6°N around spring equinox, the radiative equilibrium profile is warmer than the observed one at all levels. Adding adiabatic cooling in the energy equation, with a vertical upward velocity profile approximately constant in pressure coordinates below the 0.02-mbar level (corresponding to 0.03–0.05 cm s^{-1} at 1 mbar), allows us to reproduce the observed profile quite well. The velocity profile above the ~0.5-mbar level is however affected by uncertainties in the haze density profile. The model shows that the change in insolation due to Saturn’s orbital eccentricity is large enough to explain the observed 4-K decrease in equatorial temperatures around 1 mbar between 2009 and 2016. At 30°N and S, the radiative model predicts seasonal variations of temperature much larger than observed. A seasonal modulation of adiabatic cooling/heating is needed to reproduce the temperature variations observed from 2005 to 2016 between 0.2 and 4 mbar. At 1 mbar, the derived vertical velocities vary in the range −0.05 (winter solstice) to 0.16 (summer solstice) cm s^{-1} at 30°S, −0.01 (winter solstice) to 0.14 (summer solstice) cm s^{-1} at 30°N, and 0.03–0.07 cm s^{-1} at the equator.

1. Introduction

Due to Saturn’s obliquity of 26.7°, Titan experiences large seasonal variations of insolation. The 0.056 eccentricity of Saturn’s orbit adds a significant modulation to this insolation. Above the 10-mbar level, Titan’s radiative time constant is less than a Titan year (29.5 Earth years) (Strobel et al., 2009; Flasar et al., 2014) so that significant seasonal variations of temperature are expected in the mid-stratosphere and mesosphere.

Infrared observations by the IRIS instrument aboard the Voyager 1 spacecraft in November 1980 pointed out a north-to-south asymmetry of temperatures in the 0.4–1 mbar region, with temperatures at 55°S being higher than at 55°N by 4 and 8 K at 1 and 0.4 mbar respectively (Flasar and Conrath (1990)). These observations occurred shortly after northern spring equinox, at a heliocentric longitude $L_s \approx 9°$ Flasar and Conrath (1990) proposed that the asymmetry was due to a phase lag in the response of the atmosphere to the seasonally-varying insolation due to dynamical inertia. On the other hand, Bézard et al. (1995) suggested that the asymmetry results from the larger concentrations of infrared radiators (photochemical gases and aerosols) present at high northern latitudes.

The Cassini Composite Infrared Spectrometer (CIRS) aboard Cassini allowed us to monitor the thermal structure of Titan’s stratosphere from July 2004 to September 2017, which corresponds to $L_s \approx 293°$ Combining limb- and nadir-viewing observations between 2004 and 2006, Achterberg et al. (2008a) retrieved the temperature field over the pressure range 5×10^{-3}–5 mbar from about 75°S to 75°N. The corresponding season was around northern midwinter ($L_s = 293$–$323°$). Compared with Voyager 1 observations, the north-to-south asymmetry was stronger and temperatures at 55°S were higher than at 55°N by about 18 and 11 K at 1 and 0.4 mbar

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https://doi.org/10.1016/j.icarus.2017.11.034

respectively. Compared to southern latitudes, high northern latitudes were then experiencing reduced solar heating and enhanced abundances of photochemical gases and aerosols, both of which likely contribute to the lower temperatures. Besides this asymmetry, mid-stratosphere temperatures on Titan were reaching their maximum at latitudes 0–30°S. On the other hand, the stratopause was found higher and warmer beyond 50°N than anywhere else on the satellite, which very likely results from adiabatic heating from downwelling air at winter polar latitudes. Achterberg et al. (2011) extended the analysis of Achterberg et al. (2008a) using Cassini/CIRS data up to December 2009, i.e. shortly after northern spring equinox ($L_s \approx 4°$). Between 2004 and 2009, a large decrease of temperatures in the stratopause region (above the 0.1-mbar level) was found beyond 30°N. Elsewhere in the stratosphere and lower mesosphere, the temperature variations did not exceed 5 K.

The temporal and latitudinal variations of temperature observed in the stratosphere and lower mesosphere result from combined variations of the insolation, modulating the solar heating rate, of the atmospheric composition, which governs the radiative cooling and solar heating rates, and of dynamical motions, which provide adiabatic heating and cooling. To try to assess the relative importance of these actors, it is first necessary to constrain as precisely as possible the radiative forcing terms, which requires a good knowledge of the distribution of the radiatively-active gases and aerosols. Such information is available from Cassini/CIRS, which measures in nadir- and limb-viewing geometry the thermal emission spectrum of Titan from 10 to 1495 cm^{-1}. This allows the retrieval of the gas concentration and aerosol extinction profiles that contribute to the radiative cooling between approximately 130 and 450 km (5–0.005 mbar) (e.g. Vinatier et al., 2010a, 2010b; 2015). The Descent Imager/Spectral Radiometer (DISR) aboard the Huygens probe measured the optical properties and vertical distribution of haze particles between 0 and ≈150 km (Tomasko et al., 2008c; Doose et al., 2016) on 14 January 2005 near 10°S. Used with a correct representation of the methane opacity, these results allow us to compute the solar heating rate profile as a function of zenith angle. Combining Huygens/DISR and Cassini/CIRS data, Tomasko et al. (2008b) were able to investigate the heat balance at the location and time of the Huygens descent. They inferred that the day-averaged solar heating rate profile exceeded the cooling rate profile by a maximum of 0.5 K/Titan day (0.03 K/Earth day) near 120 km altitude (5.5 mbar) and concluded that the general circulation must redistribute this heat to higher latitudes.

In Titan's stratosphere, a meridional circulation, similar to Hadley cells on Earth, is driven by the latitude-dependent solar heating (see a review of Titan's general circulation in Lebonnois et al. (2014)). General Circulation Models (GCMs) have been developed to investigate Titan's dynamics, in particular the superrotation characterized by prograde zonal winds up to ~200 m s^{-1} in the winter stratosphere (see Newman et al. (2011), Lebonnois et al. (2012) and Lora et al. (2015) for recent three-dimensional GCMs). These models show a pole-to-pole circulation, particularly in the stratosphere, with rising motion in the summer hemisphere and subsidence in the winter hemisphere except around equinox, when a more symmetric equator-to-pole circulation takes place throughout the atmosphere. They generally succeed in reproducing at least qualitatively the dominant features of Titan's atmospheric structure, such as the zonal wind pattern and temperature field, but suffer from approximations in the treatment of the radiative transfer and/or various other simplifications. The strong subsidence at high winter latitudes predicted by the GCMs is confirmed by the high temperatures and the large enrichment in minor photochemical species observed in the upper stratosphere and mesosphere (Achterberg et al., 2011; Teanby et al., 2007, 2009; Vinatier et al., 2007, 2010a). The temperature anomalies observed in winter around the north pole have been used to estimate downward vertical velocities of ~10 cm s^{-1} around 0.01 mbar in 2005–2007 (Achterberg et al., 2011). Changes in the vertical abundance profiles of minor species observed near the south pole in autumn were also used to derive the following vertical velocities: from 0.1 to 0.4 cm s^{-1} near 0.003 mbar in 2010–2011 and 2011–2012 (Teanby et al., 2012; Vinatier et al., 2015), 0.25 cm s^{-1} near 0.01 mbar in 2011–2012, and 0.4 cm s^{-1} near 0.02 mbar in 2015 (Vinatier et al., 2017a).

The goal of this paper is to investigate the heat balance of Titan's stratosphere using a seasonal radiative model based on measurements by Cassini/CIRS of the distributions of the radiative agents and state-of-the-art representation of gas and aerosol spectral properties. We also take into account constraints from Huygens/DISR measurements. We then calculate the season-dependent radiative solution for the temperature profile and compare it with the observed variations of temperature at different levels and latitudes to derive constraints on the dynamical heating/cooling. Here, we restrain our analysis to mid-latitudes (30°S–30°N) where gas and aerosol do not exhibit large seasonal variations. Section 2 describes the temperature data, retrieved from Cassini/CIRS measurements, with which we are comparing our model. Section 3 presents our seasonal radiative model and the gas and aerosol distributions used in the radiative transfer code to calculate heating and cooling rates. Radiative model results are presented in Section 4 and compared with observations to constrain the missing adiabatic heating and cooling terms. Also shown is a calculation of the radiative time constant as a function of pressure level. We discuss these results in Section 5 and present our conclusions in Section 6.

2. Observations

Retrievals of Titan's temperature field are routinely achieved using nadir and limb observations of the ν_4 band of methane through Focal Plane FP4 of Cassini/CIRS. This focal plane covers the interval 1050–1495 cm^{-1} at a spectral resolution adjustable from 15.5 to 0.5 cm^{-1} (apodized). It consists of a 10-pixel linear array, with a 0.27-mrad field of view (FOV) per pixel (Flasar et al., 2004). Temperature maps were retrieved by Achterberg et al. (2008a) for mid-winter conditions (2004–2006) combining nadir-viewing (2.8-cm^{-1} resolution) and limb-viewing (15.5-cm^{-1} resolution) sequences. The nadir data cover latitudes from 90°S to 60°N and yield information in a pressure range of about 5–0.2 mbar while the limb data cover latitudes from 75°S to 85°N and yield information in a pressure range ≈ 1–0.005 mbar. Achterberg et al. (2011) extended the analysis to cover 5.5 years of Cassini/CIRS observations from July 2004 to December 2009, just after northern spring equinox. Here we use a further extended data set encompassing observations up to June 2016, i.e. Titan flybys T0 to T118 (Achterberg et al. in preparation). For each flyby, zonal-mean temperatures were obtained by zonally averaging temperatures retrieved from individual nadir-viewing spectra (2.8-cm^{-1} resolution) using 5° latitude bins with 2.5° spacing and interpolating the retrieved temperatures onto a uniform latitude grid for each flyby. Averaging was done in a reference frame that removes the 4° offset of the stratospheric symmetry axis from the surface pole (Achterberg et al., 2008b). In our analysis, we used temperatures retrieved at 0.2, 0.5, 1, 2 and 4 mbar, which cover the range of maximum temperature information. Note that these temperatures actually represent a vertical average over 1–1.5 scale heights due to the width of the contribution functions in the methane band and the filtering applied in the retrieval process. We restrained our analysis to equatorial and mid-latitudes and selected data at $\theta = 0°$, 30°N and 30°S. For a given latitude θ and a given flyby, we averaged the three temperatures retrieved by Achterberg et al.