Icarus 242 (2014) 149–157

Contents lists available at ScienceDirect

Icarus

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

Parameterization of radiative heating and cooling rates in the stratosphere of Jupiter

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ARTICLE INFO

Article history:
Received 1 January 2014
Revised 26 July 2014
Accepted 3 August 2014
Available online 20 August 2014

Keywords:
Jupiter, atmosphere
Solar radiation
Radiative transfer

ABSTRACT

We present a newly developed parameterization of radiative heating and cooling for Jupiter's upper troposphere and stratosphere (10^3 to 10^{-3} hPa) suitable for general circulation models. The scheme is based on the correlated *k*-distribution approach, and accounts for all the major radiative mechanisms in the jovian atmosphere: heating due to absorption of solar radiation by methane, cooling in the infrared by methane, acetylene, ethane, and collisionally-induced molecular hydrogen–hydrogen, and molecular hydrogen–helium transitions. The results with the scheme are compared with line-by-line calculations to demonstrate that the accuracy of the scheme is within 10%. The parameterization was applied to study the sensitivity of the heating/cooling rates due to variations of mixing ratios of hydrocarbon molecules. It was also used for calculating the radiative–convective equilibrium temperature, which is in agreement with observations in the equatorial region. In midlatitudes, the equilibrium temperature is approximately 10 K colder. Our results suggest that the radiative forcing in the upper stratosphere is much stronger than it was thought before. In particular, the characteristic radiative relaxation time decreases exponentially with height from 10^8 s near the tropopause to 10^5 s in the upper stratosphere.

1. Introduction

The stratosphere of Jupiter extends for more than 300 km above the visible cloud layers, and covers the pressure range between $\sim 1-3 \times 10^2$ and $\sim 10^{-3}$ hPa (Moses et al., 2004). Unlike the circulation in the troposphere, which is driven by interior heat and radiative effects in clouds, and the transport in the thermosphere, where the main sources of energy are solar ultraviolet radiation and Joule heating, the stratospheric dynamics is strongly influenced by radiative effects of molecules: heating due to absorption of solar near-infrared radiation and cooling in the mid-infrared. Development of general circulation models (GCMs) for Jupiter and other gas giants requires fast (several orders of magnitude faster than line-by-line (LBL) calculations) and accurate (within 10–20% accuracy of LBL) parameterizations for computing heating and cooling rates in the atmospheres. Our paper addresses this problem, and presents a new radiation scheme suitable for GCMs.

Although the jovian stratosphere consists mainly of H_2 and He (volume mixing ratios are 86.4% and 13.6%, respectively, according to the measurements of Galileo probe (von Zahn et al., 1998)), the main absorber of solar radiation there is methane. Most of the cooling is created by radiative transfer in IR bands of hydrocarbon molecules (CH_4, acetylene C_2H_2 and ethane C_2H_6), in addition to collisionally-induced transitions H_2–H_2 and H_2–He (Yelle et al., 2001; Moses et al., 2004). Although C_2H_2 and C_2H_6 are less abundant than CH_4, the former molecules have more efficient emission bands in mid-IR wavelengths than CH_4. The observed mixing ratios of CH_4 are about 2.1×10^{-3} in the upper troposphere (Niemann et al., 1998; Encrenaz et al., 1999). In the stratosphere, photochemical models give for CH_4 1 to 2×10^{-3} at all altitudes (Wong et al., 2000; Moses et al., 2005). The volume mixing ratio of C_2H_2 is $\sim 3 \times 10^{-9}$ near the tropopause, and increases with height to $\sim 5 \times 10^{-6}$, according to the observations with the Composite Infrared Spectrometer aboard the Cassini spacecraft (Cassini/CIRS) (Nixon et al., 2007, 2010). These observations showed also a latitudinal anomaly with higher mixing ratios in low latitudes. Earlier measurements with the Infrared Interferometer Spectrometer onboard Voyager missions (Voyager/IRIS) provided overall lower values for C_2H_2 than the Cassini/CIRS: $\sim 1 \times 10^{-9}$ at the tropopause, $\sim 2 \times 10^{-6}$ at the 10^{-1} hPa level, and smaller latitudinal anomaly (Nixon et al., 2010). Cassini/CIRS and Voyager/IRIS have also detected the volume mixing ratio of C_2H_6, which is 2 to

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http://dx.doi.org/10.1016/j.icarus.2014.08.001

5×10^{-7} at the tropopause, and 5 to 10×10^{-7} at ~1 hPa (Nixon et al., 2010). Unlike for C_2H_2, the mixing ratios of C_2H_6 are larger at higher latitudes (Nixon et al., 2007, 2010).

Radiative effects of the hydrocarbon molecules in the stratosphere of Jupiter have been studied earlier. Accounting for C_2H_2 and C_2H_6 in the band model of Cess and Chen (1975) (assuming constant mole fractions 5×10^{-7} and 1×10^{-5}, correspondingly) produced up to 20 K colder radiative equilibrium temperature in the stratosphere. A radiative-dynamical model developed by Conrath et al. (1990) considered absorption of solar radiation by CH_4 in 3.3, 2.3 and 1.7 μm bands, and IR emissions by CH_4, C_2H_2 and C_2H_6 in 7.7, 12.2 and 13.7 μm bands. In Conrath et al. (1990) the calculated temperature profile was consistent with the profile retrieved from Voyager 1 ingress radio occultation experiments between 10^2 and 10^3 hPa, but ~20 K colder above this region. Yelle et al. (2001) calculated the radiative heating and cooling rates for the temperature profiles measured by the Galileo probe. They adopted a line-by-line (LBL) technique for more accurate calculations, and accounted for solar absorption by CH_4 in wavelengths between 1 and 4 μm, by aerosols in visible wavelengths, and cooling by CH_4, C_2H_2 and C_2H_6 in the bands between 7.1 and 14.3 μm (700–1400 cm^{-1}) as well as due to H_2–H_2 and H_2–He collision-induced transitions in far IR. They showed that the heating due to absorption of solar radiation by aerosol in visible wavelengths is much smaller than that by CH_4, and cooling due to H_2–H_2 and H_2–He collisions is smaller than by the hydrocarbons, except in the lower stratosphere. Yelle et al. (2001) also showed that C_2H_6 is the primary coolant in the equatorial jovian stratosphere between 0.05 and 10 hPa, and that the stratosphere is in an approximate radiative balance between 0.03 and 100 hPa.

In this study, we present a new broadband radiative transfer model for calculating heating and cooling rates in Jupiter's stratosphere due to all main processes indicated above. This is the first parameterization that is accurate and fast enough to be utilized in Jupiter GCMs. It is based on the correlated *k*-distribution approach (e.g., see, Liou, 1992, for further details), which has been adapted to radiative transfer models for data analyses of Jupiter's atmosphere (Irwin et al., 1996, 2006; Karkoschka and Tomasko, 2010). This approach has become the most widely used method for parameterizing radiative effects in GCMs for the terrestrial atmosphere (e.g., Lacis and Oinas, 1991; Fu and Liou, 1992; Nakajima et al., 2000; Sekiguchi and Nakajima, 2008) as well as for atmospheres of planets like Venus and Mars (e.g., Eymet et al., 2009; Mischna et al., 2012). In particular, a version of the *k*-distribution radiative code "mstrnX" is being utilized in martian GCMs (Kuroda et al., 2005; Hartogh et al., 2005, 2007; Medvedev and Hartogh, 2007). This method can be used within a wide range of temperatures, pressures and mole fractions of molecules, retaining much of the accuracy of precise LBL methods. It combines the accuracy of the LBL with substantially faster calculations.

Table 1
Description of the bands in the band model. IR/SO indicates infrared (IR) and solar (SO) radiation. H_2–H_2 and H_2–He denote the corresponding collision-induced transitions.

Band	IR/SO	Wavenumber range (cm^{-1})	Molecules
1	IR	10–200	CH_4, H_2–H_2, H_2–He
2	IR	200–400	CH_4, H_2–H_2, H_2–He
3	IR	400–600	CH_4, H_2–H_2, H_2–He
4	IR	600–700	CH_4, C_2H_2, H_2–H_2, H_2–He
5	IR	700–860	C_2H_2, C_2H_6, H_2–H_2, H_2–He
6	IR	860–960	CH_4, C_2H_6, H_2–H_2, H_2–He
7	IR, SO	960–1200	CH_4, H_2–H_2, H_2–He
8	IR, SO	1200–1400	CH_4, H_2–H_2, H_2–He
9	IR, SO	1400–1700	CH_4, H_2–H_2, H_2–He
10	IR, SO	1700–2100	CH_4, H_2–H_2, H_2–He
11	SO	2100–3450	CH_4, H_2–H_2
12	SO	3450–4800	CH_4, H_2–H_2
13	SO	4800–6300	CH_4, H_2–H_2
14	SO	6300–7800	CH_4, H_2–H_2
15	SO	7800–9300	CH_4, H_2–H_2
16	SO	9300–10,800	CH_4, H_2–H_2
17	SO	10,800–11,800	CH_4, H_2–H_2

The description of the developed band radiative transfer scheme is given in Section 2. Section 3 presents the results of calculations for the observed temperature profile and distributions of species ("models"), and compares the heating/cooling rates with those from the corresponding LBL calculations. Contribution of various species and processes to the radiative budget is also discussed there. The fast new scheme provides a means for calculating the radiative relaxation time for Jupiter's stratosphere, which is described in Section 4. In Section 5, the radiative scheme was applied to calculations of the radiative equilibrium temperature on Jupiter. The summary is given in Section 6.

2. Description of the band radiative transfer scheme

The band radiative transfer model is based on the "mstrnX" code, which was developed for a terrestrial GCM in Japan (Sekiguchi and Nakajima, 2008). For its application to Jupiter's stratosphere, we have derived the set of *k*-coefficients on 13 pressure levels distributed log-equidistantly between 10^3 and 10^{-3} hPa. They were calculated for 3 characteristic temperatures ($T_1 = 100$ K, $T_2 = 150$ K and $T_3 = 200$ K), and for 17 wavenumber bands. In the calculations of correlated *k*-coefficients for arbitrary pressure and temperature, we adopted a log-linear interpolation for pressure, and a quadratic polynomial scaling for temperature as follows (Zhang et al., 2003):

$$k = k_2 \left(\frac{T}{T_2}\right)^{a+bT}, \tag{1}$$

where

$$a = \frac{\ln(k_3/k_2)}{\ln(T_3/T_2)} - bT_3, \tag{2}$$

$$b = \frac{1}{T_3 - T_1}\left(\frac{\ln(k_3/k_2)}{\ln(T_3/T_2)} - \frac{\ln(k_1/k_2)}{\ln(T_1/T_2)}\right), \tag{3}$$

k_1, k_2 and k_3 are the absorption coefficients at reference temperatures T_1, T_2 and T_3, respectively.

In the band model, we considered infrared absorptions and emissions by CH_4, C_2H_2, C_2H_6, collision-induced transitions of H_2–H_2 and H_2–He, and absorption of solar radiation by CH_4, and collision-induced transitions of H_2–H_2 in near-IR and visible wavelengths. Between 960 and 2100 cm^{-1} (4.7–10.4 μm wavelength), both infrared emission and solar absorption are taken into account. Wavenumber ranges and properties of each band in the model are shown in Table 1. Absorption lines of molecules are taken from the HITRAN 2008 database (Rothman et al., 2009) considering only the primary isotopomer for each molecule. For the CH_4 spectrum in the wavenumbers between 1800 and 9300 cm^{-1}, the HITRAN data are replaced by the more recent M5 line list provided by Sromovsky et al. (2012). The Voigt profile broadening by the terrestrial (N_2-rich) atmosphere was considered for the calculations of spectral lines, with the wing cutoff of 35 cm^{-1} as suggested by Hartmann et al. (2002) to best fit the spectra observed by Voyager/IRIS, for all molecules. Note that the pressure broadening of methane by air or nitrogen and by hydrogen are very similar, as suggested by Fox et al. (1988) and Pine (1992), and our choice of the wing cutoff value (35 cm^{-1}) is comparable to that of preceding studies (see Fig. 2 of Sromovsky et al. (2012)).

Absorption coefficients for collision-induced transitions are taken from Borysow (2002) for H_2–H_2, and Borysow et al. (1988) for H_2–He. For the wavenumber between 9300 and 11,800 cm^{-1},