THE TEMPERATURES IN THE THERMOSPHERE AS GIVEN BY THE LMD-MGCM: VARIATIONS AND COMPARISONS WITH DATA

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Introduction

During the last decade, much valuable information has been gathered about the previously almost unexplored Martian upper atmosphere. During its aerobraking phase, Mars Global Surveyor retrieved the density in the lower thermosphere. A longitudinal variation of the density, mainly composed of waves 2 and 3 was observed [1], and later attributed to the interaction of solar illumination with the topography and to non-linear wave interactions [2,3]. An increase of the thermospheric density coincident with a dust storm was another interesting finding [1]. Mars Odyssey detected, also during its aerobraking phase, an increase of temperature in the lower thermosphere when moving towards the polar night at perihelion [4]. This increase of temperature is originated by an adiabiatic warming in the polar winter. The convergence and downwelling of air from the upper thermosphere due to an enhanced interhemispheric transport produces ultimately the adiabatic warming [5]. SPICAM on board Mars Express has used the stellar occultation technique to retrieve density and temperature profiles between 60 and 130 km [6]. This instrument has also detected NO nightglow emissions for the first time on Mars [7].

A common point between all these observations is that they show a dynamically complex upper atmosphere, strongly affected by the interactions between different radiative, dynamical and chemical processes and by the interaction with the lower atmosphere.

In order to understand this region is thus very important to take into account these couplings between processes and layers. Is for that reason that the Mars General Circulation Model developed at the Laboratoire de Météorologie Dynamique (LMD, Paris, France) has been extended up to the thermosphere in the frame of an international collaboration with the Instituto de Astrofísica de Andalucía (IAA, Granada, Spain). This is the first single Martian GCM able to self-consistently study the whole atmospheric range from the surface up to the upper thermosphere.

In this work we will review the main characteristics of this model and will present the results of a simulation for a full Martian year.

The model

The model presented here is the extension to the thermosphere of the LMD-MGCM described in [8]. It includes the most relevant processes in the 0-80 km altitude range. In particular, it considers the effect of CO_2 and suspended dust over the radiative balance, a realistic CO_2 condensation scheme, a water cycle, a photochemical scheme for the lower atmosphere and a number of sub-grid scale processes. The extension to the thermosphere was performed in two steps. First, it was extended up to about 120 km by adding NLTE corrections to the CO_2 IR radiative balance [3]. And second, it was extended to the thermosphere by adding the relevant physical processes at those altitudes, in particular UV heating, thermal conduction, molecular diffusion and a photochemical model appropriate for the upper atmosphere [9,10].

Thermospheric temperature: variations

The LMD-MGCM extended to the thermosphere has been integrated during a full Martian year. To our knowdledge, it is the first time that a thermospheric Martian GCM has been used for such a simulation. We have used the climatology of the dust observed by TES on board MGS between 1999 and June 2001, and a UV solar flux appropriate for solar average conditions as input conditions. The variability with solar cycle has also been explored.

This simulation allows us to study aspects such as the seasonal, day-night and day-to-day variations of the thermospheric temperatures. Some of the key results are summarized below:

Regarding the seasonal variation of the temperatures, we have found that, as expected, thermospheric temperatures are maximum during perihelion and minimum during aphelion. The magnitude of this seasonal variation is of about 100 K overall, and it depends on latitude and local time. As an example, the seasonal variation of the global mean temperatures at the upper thermosphere for two different local times can be see in fig. 1. This seasonal variation of the thermospheric temperatures can be due to the variations of the Sun-Mars distance and/or to the variability of the dust amount in the lower atmosphere. The contribution of each of these factors to the

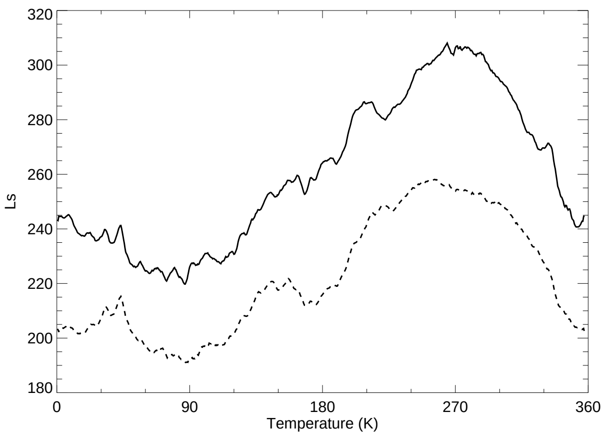

Figure 1: Seasonal variation of the global mean temperatures at the a constant pressure level in the upper thermosphere (P=10^{-6} Pa), at Local Time=14 (solid line) and Local Time=2 (dashed line), given by the LMD-MGCM

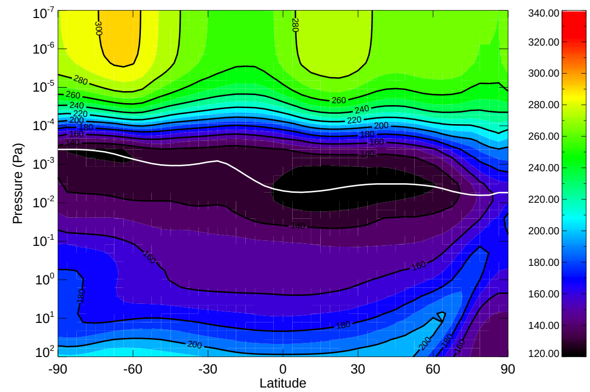

Figure 2: Vertical and latitudinal variation of the zonal mean temperature for L_s=240-270. The while line indicates the position of the mesopause

simulated temperature variation will be explored.

The diurnal cycle is specially strong in the upper atmosphere due to the important forcing by the absorption of UV solar radiation. The extreme (maximum daytime to minimum nighttime) temperature difference is of about 100 K at aphelion and about 200 K at perihelion. When using a global mean, as shown in fig. 1, the day-night temperature difference reduces to about 30 K at aphelion and 70 K at perihelion.

The day-to-day variation of temperature has also been studied. This variation is higher during the perihelion seasons, and increases with altitude. The origin of this day-to-day variability, as well as comparisons with observations, will be studied.

The vertical variation of the temperature shows the usual pattern (see fig. 2 for an example), with temperatures decreasing with increasing altitude in the low-mid atmosphere up to the minimum of temperature of the mesopause. Above, the temperature increases with altitude in the lower thermosphere, tending asymptotically to a constant value in the upper thermosphere. We have studied the seasonal variation of the temperature and altitude of the mesopause, a region that has been observed systematically for the first time by SPICAM on board Mars Express [6]. For example, the location of the mesopause for the L_s=240-270 period can be seen as the while line in fig. 2. Whilst the predicted temperature of the mesopause has a weak seasonal and day-night variation, in good agreement with SPICAM results [6], the pressure level at which the mesopause is located undergoes significant seasonal and day-night variations, depending on the latitude.

The balance between the different heating terms in the upper atmosphere confirms previous results obtained with other models [11].

Thermospheric temperature: comparisons with data

We have compared the temperature obtained in this simulation with the latest available data.

The comparisons with SPICAM temperature profiles show that the model tends to underestimate the altitude of the mesopause and to overestimate the temperature in the upper mesosphere-lower thermosphere region in about 20 K in average. The reasons for this underestimation have been studied in [6]. In short, we think that it is due to an underestimation of the 15 μm cooling due to a misrepresentation of the atomic oxygen variations in the NLTE parameterization. This overestimation of the temperatures affects not only the mesopause region, but all the thermospheric range, given that the temperatures in the upper thermosphere are very sensitive to the temperatures of the mesopause/lower thermosphere region.

We have compared the combined seasonal and solar cycle variation of the temperatures in the upper thermosphere given by the model with the temperature obtained from precise orbit determination of MGS [12]. The model reproduces satisfactorily the solar cycle variation of the temperatures, but overestimates the seasonal variability. When using a standard UV heating efficiency of 21%, in good agreement with its theoretical value [13],

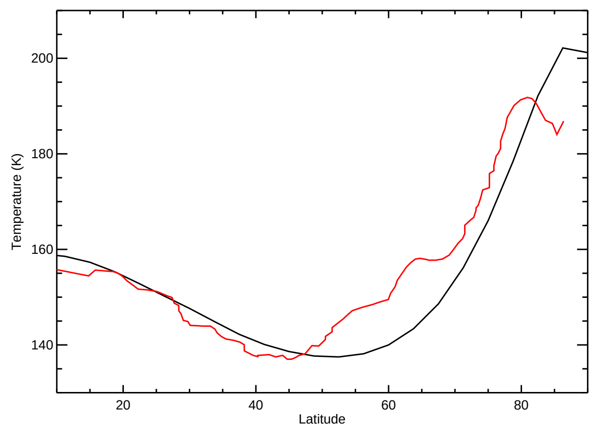

Figure 3: Black line: Temperature predicted by the LMD-MGCM at a constant altitude level of 120 km, for L_s=270-300 and Local Time=2. Red line: Temperature observed by Mars Odyssey for the same conditions, offset by 35 K. Data for the Mars Odyssey observed temperature from fig. 1 in

the model tends to overestimate the absolute value of the thermospheric temperature. For that reason, we have chosen for this study a UV heating efficiency of 16%, lower than its theoretical value heating efficiency. However, this is indicative of an overestimation of the temperatures in the upper thermosphere, linked to the one found in the mesopause/lower thermosphere region, as explained above.

One of the most significant observations of the Martian upper atmosphere is the thermospheric polar warming observed by Mars Odyssey [4]. An analysis of the temperatures given by the LMD-MGCM shows that our model predicts a thermospheric polar warming for the perihelion seasons. The observed magnitude of this warming and its latitudinal variation is well reproduced by our model, as can be seen in fig. 3. However, the absolute value of the predicted temperature is about 35 K higher than observed. This is another proof of the overestimation of the temperatures in this region by the LMD-MGCM.

As shown by other authors [5], this thermospheric polar warming has a dynamic origin: the strong interhemispheric circulation from the summer to the winter hemisphere, that produces a convergence of mass over the winter pole, a descending motion of air and a compressional adiabatical heating. The important role of the tides created in-situ in the upper atmosphere by the absorption of UV and NIR solar radiation in the creation of this strong interhemispheric circulation will be shown.

Summary

The LMD-MGCM has been extended to the thermosphere, becoming the first single ground-to-exosphere Martian GCM. This allows us to study the coupling between the lower and the upper atmosphere. We have presented the results of a 1-Martian year simulation, paying special attention to the seasonal, day-night and day-to-day variability of the temperatures. We have also studied the vertical structure of the temperatures, focusing on the mesopause region.

The comparison with data show that our model reproduces satisfactorily the solar cycle variation of the temperatures in the upper thermosphere, but the amplitude of the predicted seasonal variability seems to be higher than observed. The magnitude and latitudinal variation of the thermospheric polar warming predicted by the model is also in good agreement with the observations by Mars Odyssey. But the most significant difference with the observations happens in the mesopause/lower thermosphere region, where our model overestimates in between 20 to 35 K the temperatures.

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