

THEORETICAL 1-D MODEL OF THE ENERGETICS, COMPOSITION AND VERTICAL TRANSPORT OF THE MARTIAN UPPER ATMOSPHERE..

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1. Introduction

A 1-dimensional non-stationary model of the energetics, transport and chemistry of the Martian atmosphere is being currently developed at the Instituto de Astrofísica de Andalucía. It is part of a joint project with the Laboratoire de Meteorologie Dynamique in Paris and with Oxford University, and sponsored by ESA and CNES, in order to extend existing general circulation models (GCM) to the Martian upper atmosphere. The model is intended to be used, first, to develop detailed routines of the different physical and chemical processes in the upper Martian atmosphere, and secondly, to design and test fast schemes and parameterizations which can be implemented in the GCMs.

Based on a previous 1-D convective and radiative-equilibrium time-marching model of the Martian middle atmosphere (Lopez-Valverde *et al.*, 2000), at present the model incorporates a chemical code of the neutral atmosphere and a number of transport schemes for thermal conduction and for molecular and eddy diffusion. No magnetospheric effects or auroral processes are considered. Although the atmospheric region of our largest interest is above about 60 km, the model is run from the surface up to 250 km, with 1-km thick layers.

Below we describe, in turn, the different processes as they are included in the detailed 1-D model. Their parameterizations will be described elsewhere.

2. Radiation

The radiative processes considered are (i) the solar absorption and heating rate in the UV+EUV, (ii) the direct absorption and the thermalization of the solar radiation in the most important CO₂ near-IR bands (1-5 μm), (iii) and the IR emission and thermal cooling by CO₂ at 15- μm . Auroral emissions are considered here to have negligible effects on thermal budget even at high latitudes.

Regarding the UV model and the photochemical scheme, these are presented in a companion presentation by Gonzalez-Galindo and Lopez-Valverde, but we outline here some ideas. We include the strongest absorption at thermospheric altitudes from CO₂, O₂, atomic oxygen and H compounds. A variable spectral resolution up to 0.1 nm is used in order to account for overlapping between gases and high spectral resolution runs; this resolution being usually imposed by the solar flux

data that are used. Here we use the SOLAR 2000 data set (Tobiska *et al.*, 2000), which is a proxy model including several components of the solar irradiance variability in the UV (Woods and Rottman, 2002). A geometric line-of-sight computation is not performed but a more approximate treatment using a Chapman function is followed for high solar zenith angles. Once the initial absorption is computed, a constant UV heating efficiency of 0.15 is used at all heights and frequencies, following usual thermospheric practice (Bougher and Roble, 1991; Fox and Bougher, 1991).

Regarding the CO₂ radiative balance, we compute it allowing for non-LTE situations by using a detailed model previously developed in our group (Lopez-Valverde and Lopez-Puertas, 1994; Lopez-Puertas and Lopez-Valverde, 1995). Alternatively, fast schemes for CO₂ non-LTE heating rates are also available in the code: one for the solar heating term in the near-IR CO₂ bands, following Lopez-Valverde *et al.*, 1998, and another one for the thermal 15- μm component following Lopez-Valverde and Lopez-Puertas, 2001.

3. Chemistry

Regarding the chemical scheme, this includes 11 major constituents of the C, O and H families in the upper atmosphere, and 25 reactions between them. No attempt is made to simulate a detailed chemistry in the lower atmosphere, although we need to account for the chemical recovery of CO₂ via catalytic recombination in the troposphere, as well as for the important vertical transport of carbon monoxide, atomic oxygen and hydrogen in the middle and upper atmosphere (Nair *et al.*, 1994). For these purposes, only the most relevant reactions of the odd-hydrogen compounds (H, OH, HO₂) are included. Although suggestions have been made that catalytic recovery of CO₂ may require heterogeneous chemistry or adsorption of CO, O or HO_x compounds into dust particles (Atreya and Gu, 1994; Nair *et al.*, 1994) these ideas are not considered here. The photochemical scheme is self-consistent in the sense that all the abundances required are evaluated internally. However, any of them may be fixed or taken from other sources or models. This supplies flexibility and the possibility to couple it to more sophisticated chemical schemes in the lower atmosphere.

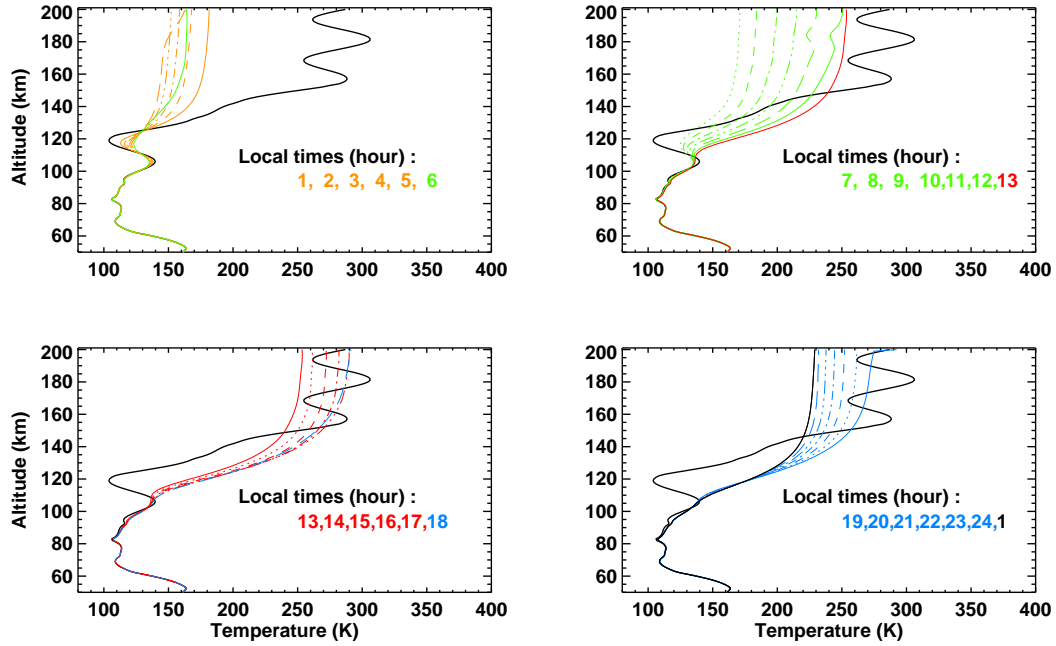


Figure 1: Evolution of the Martian thermospheric temperature during 24 hours, starting at midnight with a wavy profile.

4. Dynamics

No attempt is made in the 1-D model to study the effects of gravity waves or tides on the upper atmosphere of Mars. We include the vertical transport that results from molecular and turbulent diffusion, thermal conduction and convection.

Regarding convection, this is implemented following an instantaneous adjustment of static instabilities to the dry adiabatic lapse rate, with conservation of radiative fluxes at the top of the convective region (Goody and Yung, 1987). This is a particular case of a more general procedure available in the model which allows for a time evolution of that adjustment. This method, inspired in the mixing length theory, is based on a theoretical parameter describing the strength of the recovery (a convective flux of heat) and whose value can be fixed by the user. There is a practical difficulty in using this time-marching convection given the lack of a realistic estimation (based on data) of the strength of convection (of the value of that convective coefficient) at different altitudes. The current assumption corresponds to the extreme case of an instantaneous adjustment (approximation of a very strong convection).

Thermal conduction is modeled in a separate routine with a strategy similar to all dynamical routines, i.e., given composition, pressure and thermal structure, its

governing equation is solved, Fourier's law in this case. To illustrate the efficiency of this heat transport mechanism controlling the thermal structure of the thermosphere, we show in Fig.1 the thermal evolution of the atmosphere during a full Martian day (24 curves, 1-hour time step) starting from an arbitrary wavy profile. In this simulation the energy budget is reduced to UV heating and thermal conduction only, in order to isolate and illustrate their effects more clearly. We observe the well known effect: the solar UV and EUV deposited at high altitudes is transported down by thermal conduction to the vicinity of the mesopause. Notice how efficiently this vertical transport of heat eliminates waves and structures in the thermosphere, producing a positive temperature gradient at all heights.

We can observe in Figure 1 an interesting behavior that is basic to any simulation of the thermospheric thermal structure. In stationary conditions, once the thermal conduction balances the UV solar flux, the temperature follows a regular daily cycle in the middle-upper thermosphere (above about 150 km). However, the thermal structure around 120 km seems to be continuously increasing with time. This is because in our simulation no IR heating and cooling by CO_2 is included. In the lower thermosphere the IR balance is very important and in the absence of a proper computation of these energy terms, the thermal structure would not be described correctly. Once both energy sources are included, in the IR and in

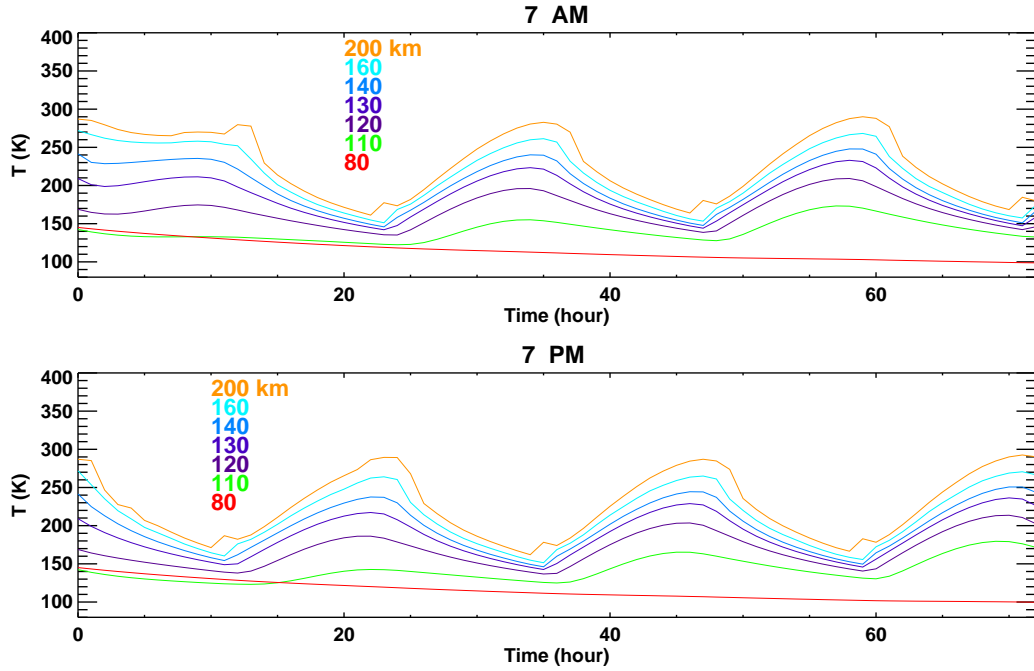


Figure 2: Simulated temperature evolution at 7 selected thermospheric altitudes during 3 days. Two simulations are shown, starting with the same profile but at two local times: at 7 am (upper panel) and at 7 pm (lower panel). See text.

the UV, the temperature regular diurnal cycle is present also in the lower thermosphere.

This is shown in Figure 2, for 3 days of temporal evolution, starting from the wavy profile of Figure 1. We started at two different local times, 7 pm and 7 am. The point to highlight here is the importance to describe the lower thermosphere with accuracy if correct results are desired in the whole thermosphere. First, this is because the thermal structure affects the local density and this, from hydrostatics, affect all layers above. And a second reason for this is that thermal conduction imposes a smoothing process to the thermal structure above the lower thermosphere, producing in theory a fairly constant temperature between the lower thermosphere and the exosphere; therefore if temperatures in lower thermosphere are wrong there will also be wrong results higher up.

In both panels of Figure 2 a given stationary pattern is reached after some time, after less than 1 day of evolution. This happens for a diversity of initial thermal profiles tested with our model. Since the radiative processes have very short lifetimes (seconds) at all heights shown here, Figure 2 basically shows the time constant of the thermal conduction, and how efficient this is in controlling the Martian thermosphere.

Previous one-dimensional models of global mean energy budgets predict dayside exospheric temperature variations between 200 and 350 K during the solar cycle (Bougher and Dickinson, 1988). As in our 1-D model, a small influence from global winds is required if these values are to be realistic. The Mars TGCM (Bougher et al., 1989) produce some lower values, from 115 to 310 K. This Mars TGCM predicts no cryosphere, and day-night contrasts of the order of 115 K for solar average activity. This is about the value observed in Figure 2.

Regarding molecular and turbulent diffusion, in a 1-D frame these are given by the following expression of the vertical continuity equation for the number density of constituent i , n_i ,

$$\frac{dn_i}{dt} = \frac{d}{dz} \left[(D_i + K) \frac{dn_i}{dz} \right] + \frac{d}{dz} \left[\frac{D_i + K}{T} \frac{dT}{dz} + \frac{D_i}{H_i} + \frac{K}{H} \right] n_i$$

where we have neglected thermal diffusion. D_i and H_i are the diffusion coefficient and scale height of that compound, and K and H are the bulk eddy diffusion coefficient and atmospheric scale height. An homopause may be formally defined for each gas as the altitude where $D_i = K$. Above this layer, is the heterosphere, where molecular diffusion dominates the vertical transport, while below we have the well-mixed homosphere. So, the homopause is determined by the strength of the eddy diffusion. In our model this can be decided by selecting an eddy coefficient profile from a number of

previous models (Rodrigo *et al.*, 1990, Nair *et al.*, 1994). The altitudes obtained range from 100 to 130 km.

Computationally, both thermal conduction and molecular/turbulent diffusion are implemented following a diversity of finite-difference schemes of varying degrees of accuracy. The nominal solution allows a user-modifiable implicit scheme with altitude-dependent coefficients to be used. Usual boundary conditions and stability criteria are implemented. All stability criteria are fulfilled for a sufficiently small time step. In the case of diffusion this condition is

$$\Delta t < \frac{(\Delta z)^2}{2(Di + K)}$$

which is of the order of 1 second at the top of the model. The use of Fourier's equation and the diffusion equation mentioned above is justified whenever collisions dominate the dynamics of the fluid, as it is the case in the Martian atmosphere below about 250 km (the Knudsen number becomes larger than one around this altitude). Further improvements to the transport model are envisaged in several directions, but we believe a good computational stability seems guaranteed with the present scheme.

Conclusions

A new 1-D model of the energetics, chemistry and vertical transport of the Martian atmosphere is being developed in order to design parameterizations of thermospheric physics and chemistry for use into thermospheric GCMs. A brief description of the model is presented, with some first results, like the important role of the lower thermosphere in controlling temperatures and densities in the whole thermosphere.

Several improvements and applications of this model are foreseen in the near future, both within its operational aspect and also as a research tool. First, we are aiming at parameterize the physics and create a fast version that can be used within a GCM. Other studies will include the temporal variations in atmospheric temperatures and densities in a global mean fashion, comparisons between 1-D and 3-D simulations, variability in the altitude of the homopause, computation of upward diffusive and escape fluxes, and the design of an airglow predictor tool.

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