

The first Mars thermospheric general circulation model: The Martian atmosphere from the ground to 240 km

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[1] The Martian general circulation model (GCM) at the Laboratoire de Météorologie Dynamique (LMD) has been extended up to approximately 240 km and it is now the first GCM to fully simulate the Martian atmosphere from the ground up to the thermosphere. In this paper we summarize the processes that have been added and give a first simple study of the effects of parameterized orographic gravity waves on the zonal mean fields. This first study clearly emphasizes the coupling between the different atmospheric regions and notes the importance of having fully coupled models to simulate the atmosphere of Mars. **Citation:** Angelats i Coll, M., F. Forget, M. A. López-Valverde, and F. González-Galindo (2005), The first Mars thermospheric general circulation model: The Martian atmosphere from the ground to 240 km, *Geophys. Res. Lett.*, *32*, L04201, doi:10.1029/2004GL021368.

1. Introduction

[2] The atmosphere of Mars, like the Earth's, is a complex system with distinct characteristics. It can be divided into different regions that share a common behaviour and display certain traits. The different nature of the various atmospheric regions leads to interesting coupling between them, and the effects of variations in one of them can be felt in distant parts of the others [Bougher *et al.*, 1993; Keating *et al.*, 1998; Withers *et al.*, 2003]. It is therefore crucial to the goal of a complete understanding of the atmosphere of Mars to include all regions in its study. This is the philosophy followed at LMD where the MARS GCM has been extended to thermospheric heights and can now simulate the full atmosphere from the ground to 240 km. This is an important step in the development of numerical models since the couplings and feedbacks of the various regions are intrinsic to the model and the issue of their inclusion as boundary conditions is eliminated. Problematic differences in radiative parameterizations between coupled models are also eliminated in an extended model as a consistent radiative transfer treatment can be used. A self-consistent ground-to-thermosphere model will help improve our understanding of the Mars' atmosphere as a whole and will benefit the planning of future aerobraking missions to the planet. Further motivation for the extension of the model to

thermospheric heights is the analysis of the new mesospheric and thermospheric data from Mars Express, in particular from SPICAM and OMEGA (two instruments that will measure the composition of the Martian atmosphere) and the possible study of thermal escape of species at high altitudes.

2. The Model

[3] The thermospheric Mars GCM is an extended version of the model described by Forget *et al.* [1999] and Angelats i Coll *et al.* [2004] from approximately 120 km to 240 km. It is a grid point model in σ coordinates that can be run at different resolutions. In the lower atmosphere it includes the radiative heating due to dust and CO₂ as well as the cooling induced in the 15 μ m thermal IR of CO₂. These radiative processes have been extended to thermospheric heights and include non-LTE considerations at higher altitudes. Exchanges between the atmosphere and the surface are also included. Parameterized subgrid processes include: boundary layer turbulence, convection, relief drag and gravity wave drag. CO₂ condensation is also included in the model as it is important in a CO₂ dominant planet. Condensation is then calculated in the atmosphere and on the surface and it accounts for CO₂ snowfall effects. The reader is referred to Forget *et al.* [1999] and Angelats i Coll *et al.* [2004] for more in-depth discussion of the lower atmosphere part of the model up to 120 km. In what follows we will center our description on the added processes relevant to the thermosphere.

2.1. Chemistry

[4] Chemical species have been added to the simulations to model the neutral atmosphere in the upper atmosphere. There are a total of 11 components in the carbon, oxygen and hydrogen families that are now transported, diffused and modified through chemical reactions. Specifically, the chemical species included are: CO₂, CO, O₂, O(³P), O(¹D), H₂, H, OH, H₂O, HO₂, H₂O₂. Molecular nitrogen is also included but is treated as inert and has no part in the chemical reaction process. Addition of species requires the variation of various parameters in the upper atmosphere as the region is no longer homogeneous in species concentration. Calculations at each time step and grid point for the gas specific heat at constant pressure c_p , gas constant R and mean molecular mass \bar{m} are now required.

[5] In the upper atmosphere, the model accounts for 22 chemical reactions between the 11 chemically active spe-

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cies mentioned above, including photodissociations. No ion chemistry is included in the model at this point. The reactions included are summarized in Appendix A. Details on reaction and photodissociation rates are given by F. González-Galindo et al. (Fast scheme for computing UV heating and photochemistry within General Circulation Models of the Martian upper atmosphere, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as González-Galindo et al., submitted manuscript, 2004).

2.2. Molecular Viscosity and Thermal Conduction

[6] Molecular viscosity and thermal conduction are solved in the same manner in the model as the two processes are described by an equation of the same form. For the thermal conduction process, the expression is as follows:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho c_p} \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right)$$

where k is the thermal conduction coefficient which is expressed as $k = AT^{0.69}$ with

$$A = \sum A_i \frac{n_i}{\sum n_i}.$$

This is a weighted average of the various thermal conductivities to yield a general coefficient that is dependent on the relative species concentrations. Similarly, for the molecular viscosity process one can write:

$$\frac{\partial \bar{U}}{\partial t} = \frac{1}{\rho} \frac{\partial}{\partial z} \left(\mu \frac{\partial \bar{U}}{\partial z} \right)$$

where \bar{U} denotes the horizontal wind components. From kinetic theory, the Eucken formula is used to relate the thermal conduction coefficient to the molecular viscosity coefficient (μ). This formulation is a good approximation for monoatomic, diatomic or weak dipolar molecules [Chapman and Cowling, 1960], and in terms of the heat capacity at constant pressure and the gas constant is expressed as $k = \frac{1}{4}[9c_p - 5(c_p - R)]\mu$.

2.3. Molecular Diffusion

[7] As height increases and density decreases, molecular diffusion becomes an important process in the upper atmosphere. It is this process that is responsible for the characteristic individual scale height that species have in their concentration profile at high altitudes above the homosphere. In most simple situations, species are diffused independently of the other species under the assumption of a background gas at rest. The approach here is to diffuse all species simultaneously as a more accurate solution with the use of the exact theory of multicomponent molecular diffusion [Dickinson and Ridley, 1972; Dickinson et al., 1984; Vlasov and Davydov, 1982]. In order not to limit the timestep required in the simulations, an implicit scheme is employed which can handle any given time increment.

2.4. UV and EUV Heating

[8] The model computes the absorption by CO_2 , O_2 , O , H_2 , H_2O and H_2O_2 in the spectral range between 0.1 and 337.7 nm. The heating rate is obtained through the use of the monochromatic photoabsorption coefficient after an appropriate spectral integration. This coefficient is dependent on the solar flux incident at the given height and the cross section of the specific absorber. The calculation of the monochromatic photoabsorption coefficient is useful for the UV heating calculation as well as for the photochemical routine, as it indicates how many photons are absorbed per unit time by a given molecule and therefore it can be used to compute how many molecules dissociate. More details on the parameterization used for the EUV and UV absorption calculations are given by González-Galindo et al. (submitted manuscript, 2004).

2.5. Thermal Escape

[9] Atomic and molecular hydrogen are allowed to escape the Martian atmosphere following Jeans thermal escape [Hunten, 1973]. The escape flux at the top of the atmosphere is calculated as a function of time and location and is used as a boundary condition for the diffusion routine for the two mentioned species. Non-thermal losses of H_2 are not accounted for and therefore its escape values represent a lower limit at this point. Other species are assumed to be in diffusive equilibrium at the top boundary of the model.

3. Results

[10] The fully coupled Mars LMD GCM is a new tool for the study of the interactions and feedbacks between different atmospheric regions. Results obtained in the absence of certain processes or when specific factors are modified allows for a deeper understanding of the atmosphere as a whole. As way of example, a comparison between simulations with and without parameterized orographic gravity waves is presented here (A description of the parameterization can be given by Forget et al. [1999]). The effects of topography-induced gravity waves is shown in Figure 1. Zonal mean horizontal winds and temperature are shown for Southern Summer conditions ($L_s = 270$) and solar medium conditions ($F_{10.7} = 115$ at Earth). Zonal winds (Figure 1 (top)) have a strong eastward jet in the winter hemisphere and the westward winds are found to extend to high polar winter latitudes and dominate in the thermosphere. The presence of westward winds at high winter latitudes is the result of a strong tidal wave forcing of the mean flow. The structure of the zonal mean fields follows from absolute momentum conservation considerations along with thermal wind balance and tidal forcing. As can be seen from Figure 1, the general structure of the zonal mean winds and temperature is not strongly affected by the suppression of parameterized small-scale gravity waves. The effects of these waves are better observed in Figure 1 (right) where the difference fields are depicted. Below 90 km, zonal winds are decelerated as the gravity waves have zero phase speed. Above this height at polar winter latitudes, gravity waves reduce the mean meridional circulation and produce diminished westward winds. This

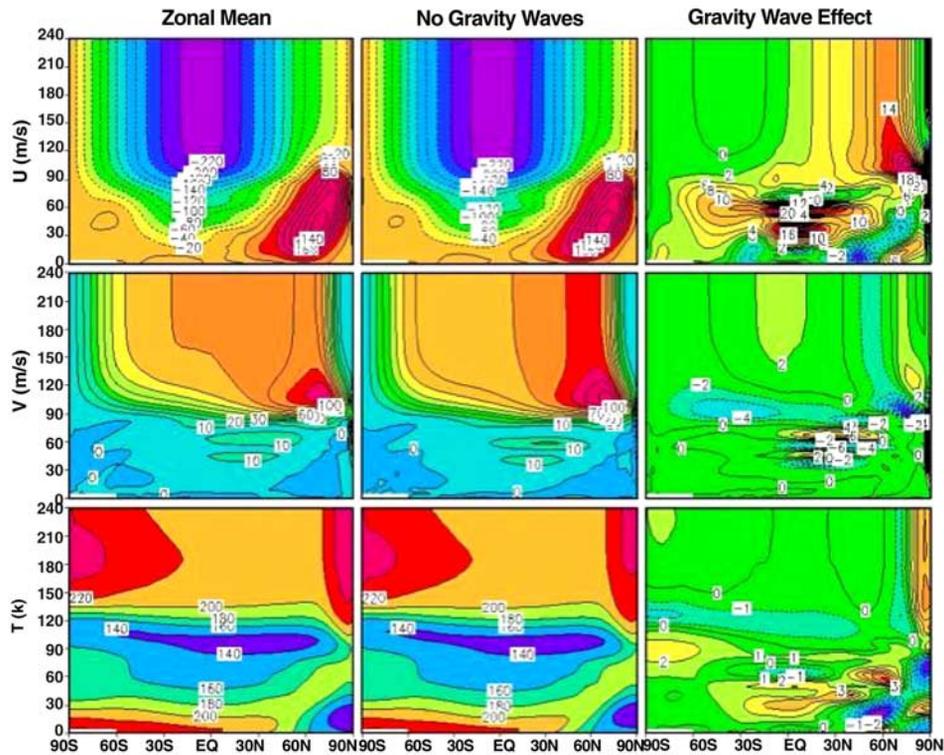


Figure 1. Parameterized orographic gravity wave effects on the zonal mean fields. Latitude-altitude plots of simulations with (left) and without (middle) gravity waves and difference fields (right) for zonal (top) and meridional winds (middle) and temperature (bottom). Winds in m/s and temperatures in K.

effect is suggested to be a result of tide-gravity wave interactions, which reduce tidal momentum deposition in the region. Small-scale orographic gravity waves are also seen not to be responsible for the polar winter warming around 60 km as mentioned by *Forget et al.* [1999].

4. Summary and Future Work

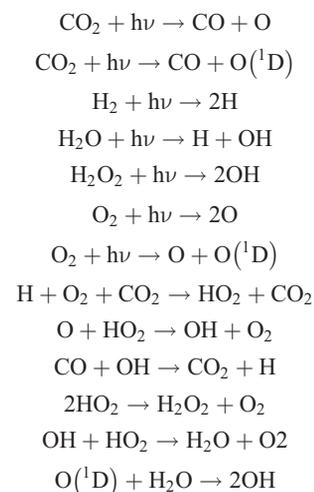
[11] The LMD GCM is the first modelling effort to simulate the Martian atmosphere from the ground to the thermosphere. This extended model allows for the full coupling between atmospheric regions and permits the study of various processes and their effects and feedbacks on the atmosphere. On this simple study we have noted how gravity waves can serve as a coupling mechanism between the lower and upper atmosphere as they modify the zonal mean winds and interact with the tides affecting their momentum deposition at high winter latitudes above the eastward jet. This simple exercise hints at the relevance of such analysis. A more detailed study and understanding of the Martian atmosphere will certainly emerge with the use of this upgraded GCM.

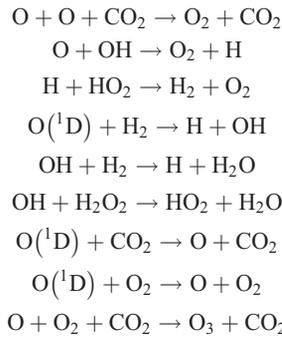
[12] The model is now being transformed to hybrid coordinates, with terrain following sigma coordinates at low altitudes and pressure coordinates above. The simulations are also being improved by extending the chemical calculations all the way to the ground. This will be accomplished with the use of two different schemes optimized for two different altitude regimes as different reactions are dominant at high and low altitudes. This new and improved version of the LMD Mars GCM will certainly be a key

instrument in the study of the Martian atmosphere, such as with simulations of the new mesospheric and thermospheric data from SPICAM and OMEGA onboard of Mars Express. The coupling between atmospheric regions, so relevant on Earth, will be clarified and better investigated with the use of an all-inclusive ground-to-thermosphere model such as this.

Appendix A

[13] Thermospheric chemical reactions now included in the LMD Mars GCM:





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