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BACK TO THE BASICS: IMPROVING THE PREDICTION OF TEMPERATURE, PRESSURE AND WINDS IN THE LMD GENERAL CIRCULATION MODEL

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Introduction: The Mars atmosphere General Circulation Model (GCM) [1] developed at the Laboratoire de Météorologie Dynamique in collaboration with several teams in europe (LATMOS, University of Oxford, The Open University, the Instituto de Astrofisica de Andalucia), and with the support of ESA and CNES. is currently used for many kind of applications. It has become a "Mars System Model" which, for instance, includes the water cycle [see , e.g. abstract by *Madeleine et al.*, this issue] the dust cycle [*Mulholland et al.*, this issue], the Photochemistry [*Lefevre et al.* this issue], the release and transport of Radon [*Meslin et al.*, this issue], a thermosphere and a Ionosphere [*Gonzalez-Galindo et al.*, *Chauffray et al.*, this issue]. It can be also used to explore Mars past climates [see e.g. *Wordsworth et al.*, this issue] or the transport of volcanic ashes [*Kerber et al.* this issue]. Moreover the outputs of the GCM are available to the community and to engineers through the Mars Climate Database, as described in *Millour et al.* [this issue].

For all these applications, it is more important than ever that the model accurately simulates the "fundamentals" of the Martian meteorology: pressure, temperature, winds. Below we describe several improvements that we have performed to improve the realism and thus the accuracy of the LMD GCM.

Improved Dust radiative properties

For many years, a recurrent problem we have faced was the inability to predict realistic temperatures while using both the observed radiative properties and column dust opacities. For instance, we had to multiply the imposed dust opacity measured by TES by a tunable parameter to reach an agreement with the simultaneously measured temperatures, thereby losing consistency with part of the observations. We found that the problem was partly due to our radiative transfer model (which we modified and validated against reference Monte-Carlo simulations), and partly to the dust radiative properties previously used [e.g. 2, 3]. We found that using the most recent radiative properties derived by Mike Wolff [4,5] greatly improved this problem (figure 1a, green curve).

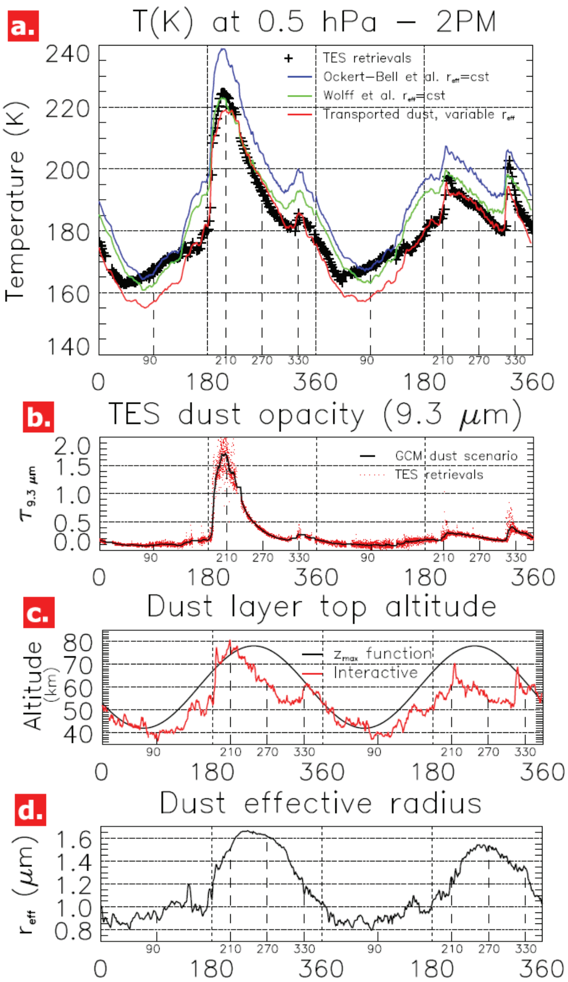

Figure 1. (a) Zonally averaged equatorial temperature at 2 PM for the 0.5 hPa pressure level from TES climatology [6] (crosses), martian year 25 and 26, and as predicted by the new LMD/GCM for three different cases : a simulation using the Ockert-Bell radiative properties [2] (blue curve), another simulation using the Wolff et al. properties [4,5] (green curve) and a simulation using a semi-interactive dust model (red curve). **(b)** Dust opacity at 9.3 µm used to guide the model (in black), compared to the raw TES dataset at 2 PM (red points). **(c)** Analytical "top of the dust layer" used for simulation 1 and 2 (black line), compared to the dust layer top altitude actually predicted by the semi-interactive dust model. **(d)** Dust effective radius predicted by the GCM at the 0.5 hPa level for the semi-interactive dust simulation. All the variables are taken at the equator. Figure from [7].

Improving the dust vertical distribution and particle size using a dust transport model.

When keeping a constant particle size in the entire atmosphere and using a prescribed vertical distribution, we found that significant temperature biases remained, especially above the 1 hPa pressure level.

To improve the realism of the model, we developed a semi-interactive dust model that simulates the vertical distribution and size of the dust particles but can use the observed dust column opacities to adjust the dust content. The evolution of dust particles sizes is computed using a so-called two moments scheme, in which in any atmospheric boxes the size of the dust particles is described by a lognormal distribution. Then three parameters are sufficient to describe the dynamics of the whole particle population. Transporting the mass mixing ratio and the number mixing ratio assuming a constant variance of the distribution allows to realistically simulate the variations or the particle sizes once the size segregation is properly calculated in the gravitational sedimentation scheme.

The radiative properties are updated online and follow the 4D variations in dust particle sizes. We found that using this technique allows a better agreement with the observations, thereby underlining the role of the dust layer thickness and particle sizes in shaping the thermal profile. The GCM is now able to predict good temperatures (figure 1, red curve) without any tuning of the dust opacity used to guide the model at least during the dusty, relatively cloud-free seasons. However, when clouds are known to be present, it was necessary to take into account their radiative effect.

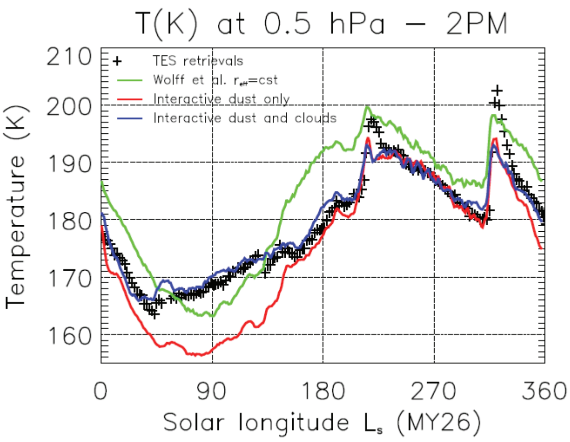

Figure 2. Same as figure 1a for Martian year 26, showing the improvement of the thermal structure when taking into account the radiative effects of clouds predicted by the GCM. See *Madeleine et al.* [this issue] for more details.

Taking water ice clouds into account.

The simulation of clouds and of their impact on the thermal structure of the atmosphere is detailed in *Madeleine et al.* [This issue]. As for dust, the radiative model takes into account the 3D variations of the clouds particles size and opacities. Clouds have a significant direct impact on the local thermal structure (mostly by enhancing the exchange of thermal infrared radiation with the surface and space). Their presence also influences significantly the temperature in the upper atmosphere even when they are not present through their impact on thermal tides and the Hadley circulation. As expected, parameterizing the radiative effect of clouds strongly improves the temperature predictions of the model (figure 2, blue curve).

A new parameterization of the near surface convection.

The Martian near-surface atmosphere has been shown to be alternatively "ultra-unstable" and "ultra-stable". This is a challenge for boundary layer schemes originally developed for the Earth case. In particular, during the day, in the first meters above the ground, the atmosphere temperature profile is probably super-adiabatic, in spite of an active convection. In the previous versions of the model we employed a "convective adjustment" scheme which assumes instantaneous mixing of any unstable section of the atmosphere. Therefore, the convecting atmosphere was always close to the adiabatic lapse rate on average. This resulted in an unrealistic temperature profile in the boundary layer, i.e in the first kilometres above the surface (figure 3, orange and yellow curves).

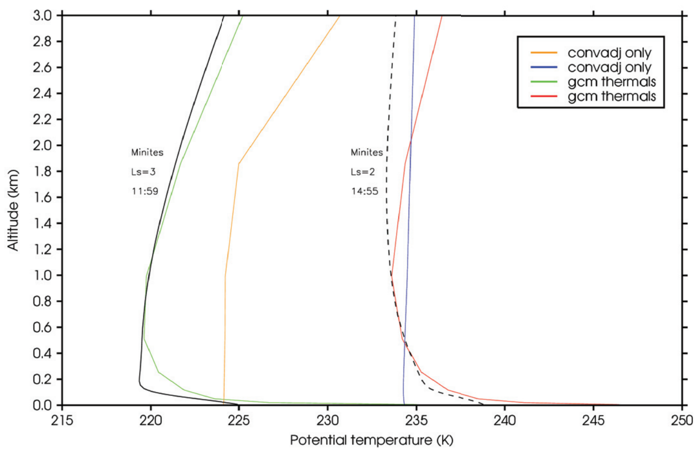

Figure 3. Comparison of two potential temperature profiles observed at two local times (11:59 and 14:55) near spring equinox by miniTES at the Opportunity Landing site [8] with predictions from the LMD GCM using the canonic convective adjustment parameterization ("convadj only") and the new mass flux parameterization scheme ("gcm thermals"). The new scheme significantly improves our ability to simulate the near-surface super-adiabatic lapse rate during daytime.

In order to improve the near surface daytime thermal structure, and also better simulate the transport and mixing by convection, we have implemented the mass flux parameterization of vertical transport in the convective boundary layer developed by [9] which greatly improve the performance of the GCM when compared to temperature profiles obtained by miniTES [8] (figure 3, green and red curves). The formulation of the new parameterization is based on an idealization of thermal cells or rolls. In practice, the atmospheric column is divided into two sub-columns of either rising or subsiding air. A diffusive scheme (based on a Mellor and Yamada 2.5 closure, see [1]) is still active to represent the turbulent mixing.

An improved CO2 cycle for better surface pressures and high latitude temperatures

The atmospheric mass cycle resulting from the CO_2 condensation and sublimation in the polar regions and which controls the surface pressure everywhere on Mars must be well represented in a GCM which aims to realistically represent the Martian climate and meteorology. Moreover, an accurate simulation of the extension of the seasonal polar caps is necessary to accurately estimate the surface temperatures at the edge of the caps and to simulate the water cycle.

To achieve this goal, in addition to the baseline CO_2 condensation/sublimation scheme based on energy balance considerations, the LMD GCM now also includes subsurface water-ice tables in the polar regions, takes into account the impact of CO_2 condensation in the atmosphere (clouds) [10], includes the effect of non-condensable gases [11] and can be guided with the observed solar albedo as recorded by the TES solar band channel.

Non condensable gas enrichment and depletion: The model includes a parameterization of non condensable gas enrichment suitable for GCMs which is combined with a modified convection scheme able to simulate the convection forced by the enrichment of lighter gas near the surface. This scheme, combined with recent improvements of the GCM's dynamical core, yields non condensable gas enrichments which compare well with available data [11]. The variations of the CO2 ice temperature (and thus of the CO2 condensation rate) resulting from the changes of partial pressure can be taken into account.

Thermal conduction in heterogeneous soil with a water ice table: The model had always included thermal conduction in the Martian soil (which acts as a thermal reservoir which stores and restores heat to the surface) but until recently the subsurface was considered to be homogeneous (and of properties set to the known surface values).We have improved the representation of thermal conduction in the subsurface of the model by switching to a scheme which includes the possibility of varying the thermal properties (volumetric specific heat C and conductivity λ, or equivalently thermal inertia $I=(C.\lambda)^{1/2}$) of the soil. With this implementation, we can now directly include some (high thermal inertia) water-ice tables in the GCM.

The importance of the presence of subsurface polar ice tables which act as thermal reservoirs, storing and restoring large amounts of heat, and thus significantly affect the Martian CO_2 cycle, has been demonstrated in [12]. It allows to match the observed global pressure variations without invoking unrealistically low CO_2 ice emissivity to limit the CO_2 condensation rate. To include realistic maps of the ice tables in the model, we have used measurements by the Mars Odyssey Neutron Spectrometer (MONS) of the abundance of hydrogen near the surface [13,14] and an inversion model of the effective depth of the water ice table[15]. These maps describe the shape of the ice tables but not the exact geometrical depth at which they lay (to derive this depth accurately would require precise knowledge of the macroscopic absorption cross section of the ice-poor upper layer of soil). It is however possible to constrain the latter, as discussed in the next paragraphs.

Using the Viking Lander surface pressure measurements to constrain model parameters: The Viking Landers have almost continuously monitored the Martian surface pressure over almost two Martian years for Viking Lander 2 and more than three Martian years for Viking Lander 1. This dataset is extremely useful to help constrain and validate GCM parameterizations.

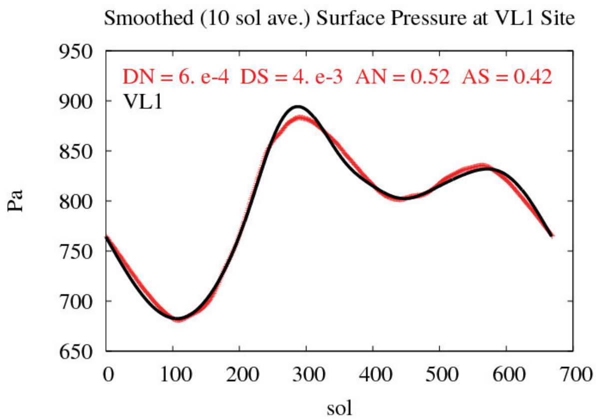

Figure 4: An example of fit of the Viking lander 1 surface pressure (smoothed by a 10 sols boxcar averaged) by the LMD GCM after tuning ice depth correction coefficient *DN* and *DS* and the CO_2 ice cap albedoes in each hemisphere *AN* and *AS.* The CO2 ice emissivity is set to 0.9.

In [16] is described an automatic procedure which minimizes differences between model output (a few control simulations) and Viking Lander 1 surface pressure and yields optimal values of "free" parameters such as polar cap albedos and emissivities. Since (as mentioned above) the exact depth at which the polar H_2O ice tables lay is not known, we have extended the best-fit procedure to include the ice depths parameter as parameters for the fit (the shapes of the ice tables remain those derived by [15]). In a first study, we applied a 4 dimensional fitting process (minimization with respect to Northern cap albedo AN, Southern Cap albedo AS and coefficients DN and DS which represent proportionality constants to apply to the Mars Odyssey maps to determine the true depth at which the ice table of each hemisphere lays. We found that a best fit is obtained when DS is large (i.e. the ice table in the southern hemisphere is buried deep) and DN minimum (i.e. the ice table in the northern hemisphere is barely buried). Interestingly, we found that it was difficult to find any clear minimum for coefficients DS and DN, suggesting that we are still missing some physical processes in our simulations. In particular, preliminary studies suggest that a better behavior could be obtained assuming that the Northern subsurface ice thermal inertia is lower than the southern subsurface ice.

Guiding the seasonal cap ice albedo with TES solar band data. The CO_2 ice albedo is known to strongly vary in time and space. To account for these variations and improve the realism of the modeled CO_2 cycle, when CO_2 ice is present on the surface, we set the surface albedo to the broadband albedo measured by TES solar channel (kindly provided by Tim Titus). The observed albedoes can be multiplied by a tunable coefficient to account for 1) the effect of airborne dust on TES albedo *2)* Non Lambertian behavior of the ice. In both case, the corrective factor must be larger than 1 (the bond albedo of the surface is larger than the reflectance as seen from space at nadir through a dusty atmosphere). Applying our surface pressure best fit procedure to these ice albedo coefficient in addition to the water ice depth coefficient DN and DS showed that values up to 1.4 (i.e. TES albedoes increased by up to 40%) were necessary to yield a good match to the Viking Lander pressure observations.

Other improvements to the GCM include, an improved radiative transfer to calculate the 15 µm infrared cooling in the upper atmosphere [*Lopez-Valverde et al*. this issue], the inclusion of a new surface rugosity map [see *Listowski et al.*, this issue], the updating of the surface albedo and thermal inertia with the latest available maps from the TES team. In the near future, we also plan to include a parametrization of the scavenging of dust by water ice clouds. This will be directly feasible by coupling the semi-interactive dust model that simulates the vertical distribution of the dust with the water ice clouds parametrization. This phenomenon may play a key role in the vertical structure of the Martian atmosphere [see e.g. *Benson et al*., *Heavens et al.*, this issue]. Taking into account the radiative effects of clouds and the scavenging of dust by the water ice particles will also be of key importance when simulating past climates with much thicker clouds and precipitation.

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