LMD MARS GCM SIMULATIONS AT HIGH OBLIQUITY USING AN IMPROVED CLOUD MODEL.

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Introduction: Under various latitudes, the martian surface shows evidence for glaciations in the last hundreds of millions of years of the planet's history. The glacial features are diverse (tropical mountains glaciers, lobate debris aprons, lineated valley fill, concentric crater fill, see [1] for a more complete description), and provide precious constraints on the paleoenvironment in which they formed.

The goal of our study is to analyze the response of the Mars climate system to changes in the orbital conditions and climate parameters in order to better understand glacial cycles and the associated geological record. To do so, we model the past climate of Mars by using the LMD (Laboratoire de Météorologie Dynamique) Global Climate Model (GCM) and by including the various processes which are necessary to simulate the Mars past climate. In this abstract we focus on the effects of a new cloud scheme and of Radiatively Active Clouds (RAC) on a typical paleoclimate simulation at 35° obliquity.

The new version of the LMD/GCM: We have been working on developing a new version of the LMD Mars GCM [2] which includes different new processes (see Fig. 1):

Water-ice cloud formation: A new cloud scheme has been developed and includes the nucleation and growth of the ice crystals, as well as the scavenging of dust particles. The distribution of the dust particles in the atmosphere is made possible by a semi-interactive dust transport scheme described in [3]. These dust particles serve as condensation nuclei for water-ice cloud formation and can be scavenged by the predicted clouds.

Interactive aerosols: Both dust particles and water-ice crystals can scatter radiation depending on their size. The radiative effect of clouds has a dramatic impact on the temperatures of the atmosphere and the surface under present-day conditions, and this is even more the case under paleoclimatic conditions.

Near-surface convection: A new parameterization of the convection in the boundary layer has been developed [4] and accounts for the turbulent mixing produced by local thermals.

Ice deposition and surface properties: A new soil conduction model allows us to account for the changes in surface thermal inertia due to ice deposition, meaning that the thermal-inertia feedback is active. Also, the coupling between the dust cycle and the water cycle gives access to the amount of dust which is included in the ice deposits, and provides an assessment of the stratigraphy.

Coalescence of ice crystals: We also plan to include the coalescence of ice crystals, which may not be negligible under past conditions. This work is still underway.

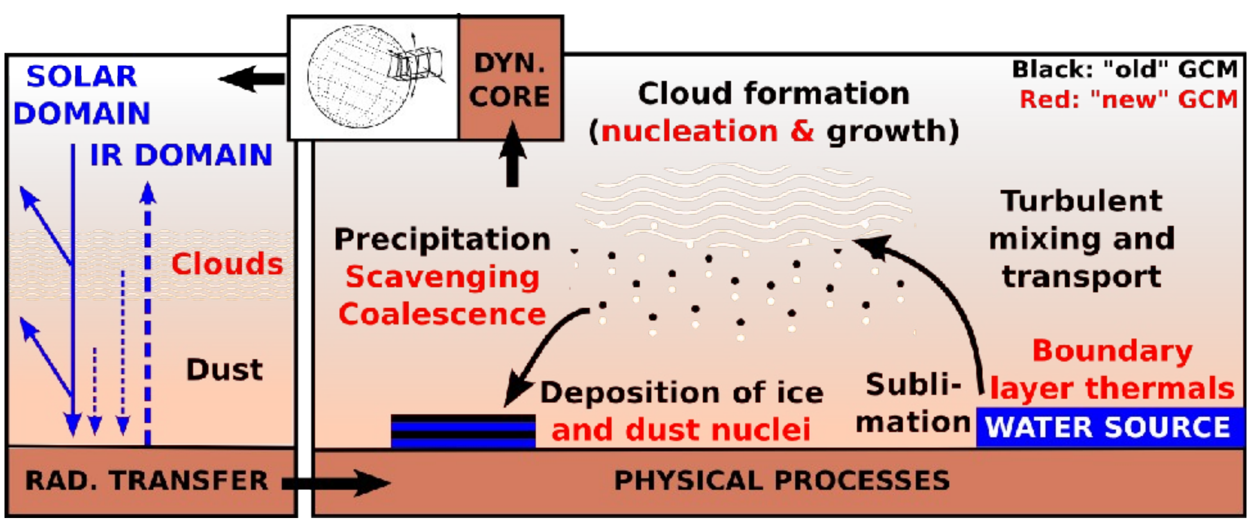

Figure 1: Diagram showing the main components of the LMD/GCM (the dynamical core, the radiative transfer code and the physical processes) as well as the new physical processes (in red) that have been recently implemented in the model.

Excursion at moderate obliquity simulated by the previous version of the model: In order to understand the effect of RAC (Radiatively Active Clouds) and of the new cloud scheme on the paleoclimate simulations, we first run a reference simulation using the previous version of the GCM and paleoclimatic conditions. These conditions will be the same for all the simulations presented in this report. The obliquity is set to 35°, and the eccentricity of the orbit is set to 0.1, which is closed to the present-day value of 0.093. The L_s of perihelion is set to 270°, which is again close to the present-day value of 251°. Finally, the visible dust opacity at the 610 Pa pressure level is assumed to be equal to 1, to portray the effect of an enhanced meridional circulation on the dust cycle when the obliquity is increased [5]. The initial state is extracted from a present-day simulation and will be the same for the three simulations discussed in this abstract.

	Orbital conditions	Cloud scheme	Radiatively Active Clouds (RAC)
1st sim.	ε=35°, e=0.1, L_p=270°	Simplified	No
2nd sim.	Same	Simplified	Yes
3rd sim.	Same	Improved	Yes

Table 1: Parameters used for the three simulations described in this abstract.

This first version of the model uses the cloud scheme described in [6] and the dust transport scheme described in [3]. It is worth mentioning that it is not strictly equivalent to the model which was applied to the tropical mountain glaciers in [7] or to the mid-latitude glaciers in [8]. Indeed, it is different because the dust cycle, and especially the vertical distribution of the dust particles, is predicted by the dust transport scheme, which was not the case in the previous version of the model, where a modified Conrath profile was assumed. This more accurate description of the dust layer tends to cool the atmosphere around 30 km, as discussed in [3].

The water cycle predicted by this version of the model (which does not include RAC or the new cloud scheme yet) is represented in Fig. 2.a. It is similar in many aspects to the present-day water cycle, summarized for example in [9]. When the obliquity is increased, the polar cap is more exposed to sunlight (see for example [10, Fig.6]) and more water vapor enters the atmosphere. Therefore the water vapor column (in pr.µm) shown in Fig. 2.a. is approximately two times that of the present-day water cycle in the north polar regions and in the tropics. The corresponding cloud column (also in pr.µm) is shown in Fig. 3.a. Again, the cloud distribution is similar to the present-day one, with thick clouds in the polar regions during winter and thinner clouds in the tropics which form in the uprising branch of the Hadley cells.

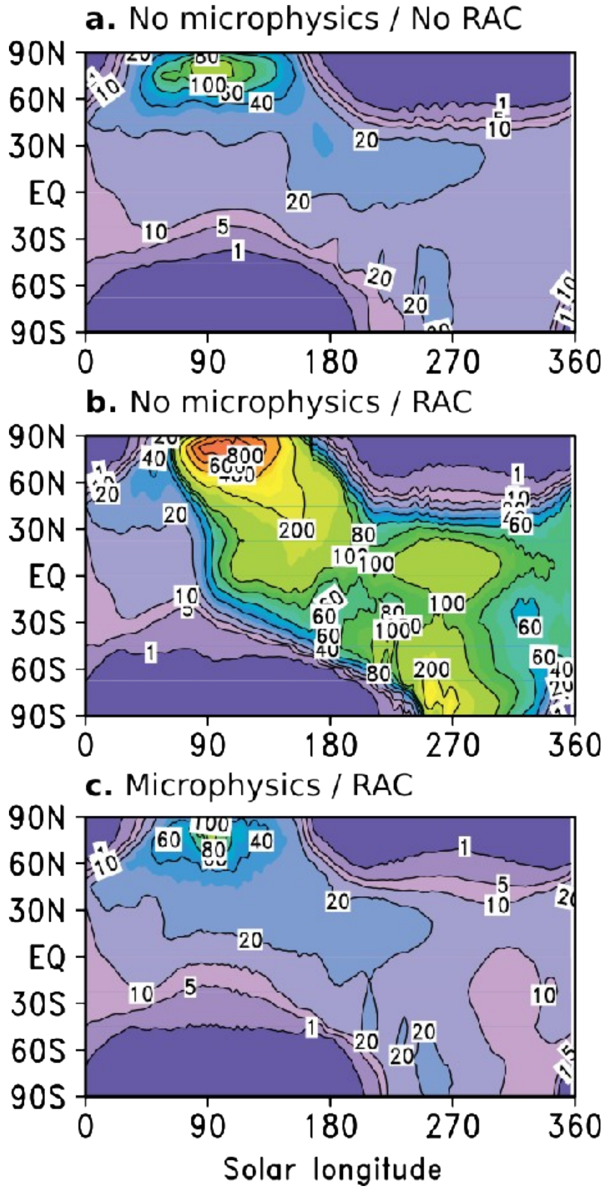

Figure 2: Latitudinal evolution of the water vapor column over one martian year for the three simulations described in Table 1. The water vapor column is given in pr.µm and at 2PM.

Impact of RAC on the paleoclimate simulations: What happens if the clouds become radiatively active? Fig. 2.b. represents the water cycle when the clouds are radiatively active, all other parameters being equal, and keeping the same cloud scheme as previously used. The first observation to be made is that the amount of water vapor coming from the sublimation of the north polar cap increases by almost one order of magnitude, and the same can be said of the amount of water vapor in the tropics. The amount of water that condenses to form clouds is also greater, and Fig. 3.b. shows an increase in the cloud column of one order of magnitude as well.

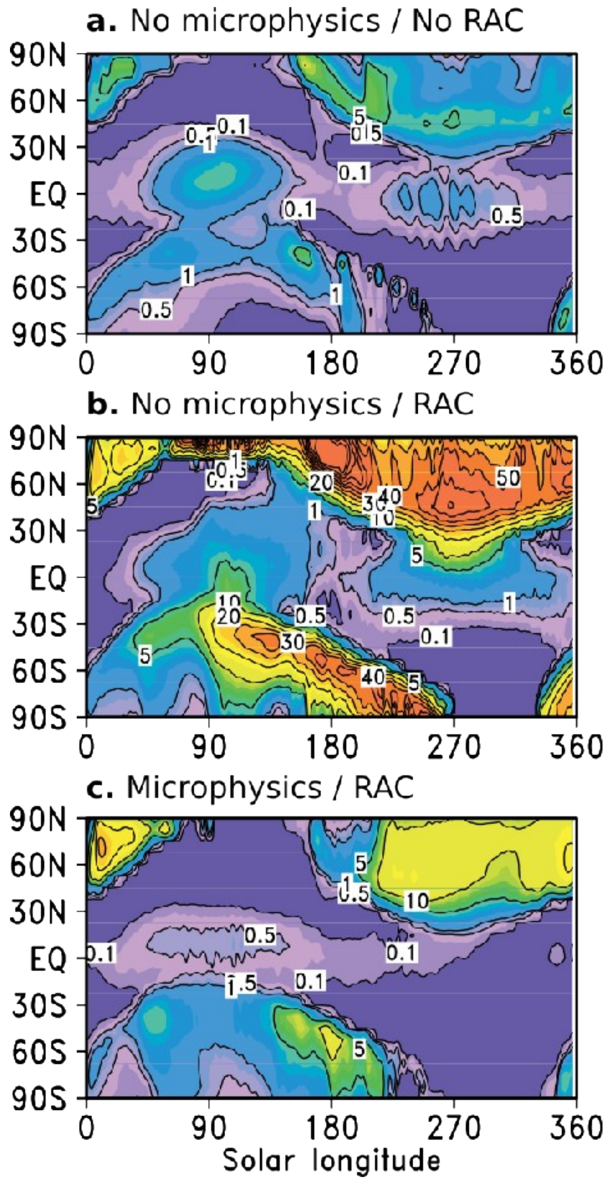

Figure 3: Same as Fig. 2, but showing the water ice column in pr.µm and at 2PM.

This dramatic change in the water cycle when clouds are radiatively active comes from a strong positive feedback between cloud formation and surface ice sublimation. Indeed, clouds are strong infrared emitters as well as efficient reflectors of sunlight. Consequently, when clouds are present, daytime atmospheric temperatures tend to be warmer due to the absorption of the infrared radiation coming from the surface, and surface temperature tends to be lowered by the reflection of sunlight. During the night, the opposite phenomenon occurs: atmospheric temperatures are lowered by infrared emission to space, and surface temperature is increased due to the emission by the clouds of infrared radiation toward the surface. Therefore, the surface radiation budget is very sensitive to clouds.

During northern summer, thin clouds form over the polar cap. If the water-ice clouds are not radiatively active, these clouds stay thin and dissipate by L_s=90° (see Fig. 3.a). However, if the clouds are active, they emit infrared radiation toward the surface, warm the surface, and increase the sublimation of the polar cap. More water vapor enters the atmosphere and more clouds form (see the cloud column at the north pole around L_s=90° in Fig. 3.b), thereby increasing again the temperature of the surface and the sublimation of the cap. This strong positive feedback leads to a new equilibrium in which the water cycle is more humid (see Fig. 2.b) and the clouds are thicker, not only at the pole but all over the globe (see Fig. 3.b).

Figure 4.a shows the annual mean surface temperature difference due to RAC. The net effect of clouds is to warm the surface globally by up to 30K. The ice deposits which are formed in non-polar regions are therefore less stable and no net accumulation of ice is predicted over the year. The same warming by clouds is predicted by [11] under similar conditions and discussed in detail in the associated abstract.

Inclusion of the new cloud scheme: In a third simulation, the clouds stay active but the new cloud scheme (which is described at the beginning of this abstract and in detail in [12]) is activated. The conditions are otherwise the same (see Table 1). The corresponding water cycle is represented in Fig. 2.c. This time, the water vapor column is similar to the first simulation in which both the radiative effect of clouds and the new cloud scheme were inactive (compare Fig. 2.c to Fig. 2.a).

Indeed, when the new cloud scheme is used, the strong positive feedback that occurs in the north polar regions between cloud formation and surface ice sublimation is severely reduced by another negative feedback between cloud formation and the amount of dust nuclei. When the new cloud scheme is used, the dust particles that serve as dust nuclei for the polar clouds are scavenged, and the atmosphere is devoid of new dust nuclei to condense onto, which was not the case when using the old cloud scheme.

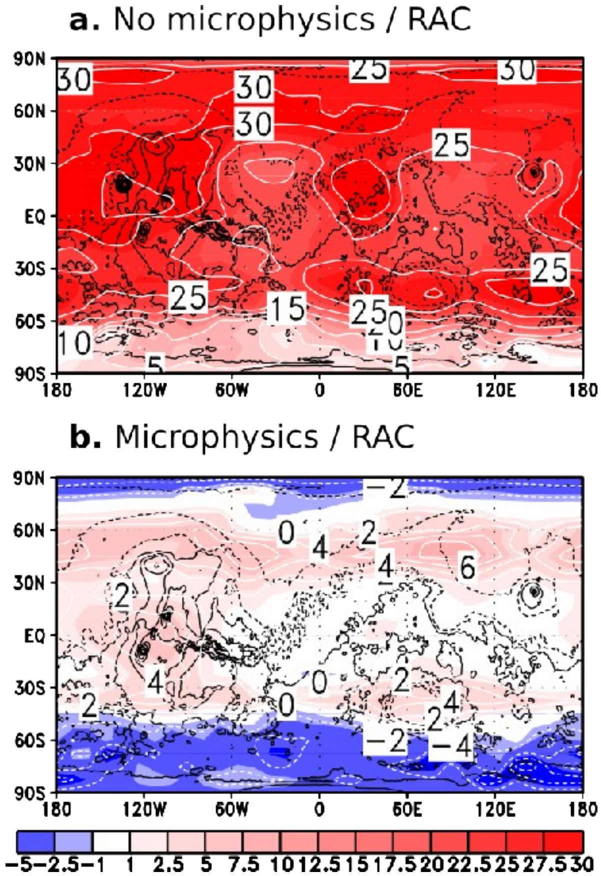

Figure 4: Annual mean surface temperature change induced by the radiative effect of clouds when the simplified cloud scheme is used (a), and when the improved cloud scheme is used (b). The two panels correspond to the 2nd and 3rd simulations, respectively (see Table 1).

Therefore the polar clouds are thinner than in the 2nd simulation, and the feedback between cloud formation and surface ice sublimation is not dominant. The whole water cycle is drier, and the cloud column is closer to the one predicted without RAC.

Apart from the summer clouds in the north polar regions, comparing Fig. 3.c with Fig. 3.a shows that the clouds in the 3rd simulation are thicker than in the 1st simulation during winter in both polar regions, and thinner in the tropics. The clouds formed in the northern and southern polar regions during winter are thicker in the 3rd simulation compared to the 1st simulation because clouds emit infrared radiation to space and cool the atmosphere, thereby favoring their own formation. However, this process is limited by the low amount of dust nuclei, explaining why the winter clouds in the 3rd simulation are not as thick as in the 2nd simulation in which the old cloud scheme was used (see Fig. 3.b). In the tropics, the clouds in the 3rd simulation are thinner than in the 1st simulation because these clouds form at high altitude where there are fewer dust nuclei as well. Therefore the ice particles are larger than in the 1st simulation, fall and sublimate in lower layers.

The global temperature change induced by the clouds in the 3rd simulation is represented in Fig. 4.b. Since the clouds are thinner than in the 2nd simulation, the warming is reduced. At high latitudes, the cooling effect due to the reflection of sunlight even dominates the warming effect due to infrared emissions, and a net cooling is observed. The warming occurs in the tropics, for example east of Alba Patera (6K warming), in Utopia Planitia (8K warming) or on the Tharsis plateau (4K warming). Detailed analysis of these regions reveals a sensitive equilibrium between ice accumulation by precipitation and ice sublimation by infrared emission toward the surface. The radiative effect of water-ice clouds therefore plays a major role in the mass balance of the ice deposits formed in these regions.

Conclusion: This analysis shows how sensitive the Martian climate is to the water-ice clouds, and how crucial it is to simulate the cloud properties accurately. Under paleoclimatic conditions, the amount of water vapor in the atmosphere is increased, and the feedbacks associated with the water cycle are even more pronounced. As we discussed earlier, the GCM can respond in two very different ways depending on the assumptions made regarding the microphysics of the clouds (see for example Fig. 2.b and 2.c). Further validation of the present-day water cycle is underway, and will allow us to refine the parameters of the microphysical scheme and simulate all the properties of the clouds with accuracy (see the companion abstract by [12]). The coalescence of ice particles might also need to be considered for paleoclimate simulations. The new implemented processes have many other paleoclimatic implications which are currently under study and will be discussed in future communications.

References: [1] J. W. Head et al. (2012) This issue. [2] F. Forget et al. (2011) EPSC-DPS Joint Meeting p:1568. [3] J.-B. Madeleine et al. (2011) JGR Planets, 116:E11010. [4] A. Colaitis et al. (2011) EPSC-DPS Joint Meeting p:1061. [5] C. E. Newman et al. (2005) Icarus 174:135. [6] F. Montmessin et al. (2004) JGR Planets, 109:E10004. [7] F. Forget et al. (2006) Science 311:368. [8] J.-B. Madeleine et al. (2009) Icarus 203:390. [9] M. D. Smith (2004) Icarus 167:148. [10] R. M. Haberle et al. (2003) Icarus 161:66. [11] R. M. Haberle et al. (2012) This issue. [12] T. Navarro (2012) This issue.