Mars in the glacial ages of the past millions of years: modeling a planet partially mantled by dust and ice

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Mars Global Climate Models (GCMs) have been successful in explaining a wide variety of glacial deposits, from the tropical mountain glaciers to the mid-latitude glaciers. However, the more recent ice ages, reflected in the latitude dependent mantle, were more enigmatic, and their origin was more difficult to explain. In recent years, Mars GCMs underwent a new phase of development allowed by the results of various missions, including Mars Global Surveyor and Mars Climate Sounder. The dust and water cycle are now better described, and a lot of new physical parameterizations are still underway. Among the most paleoclimatically relevant improvements made to the LMD (Laboratoire de Météorologie Dynamique) Mars GCM are the better representation of the dust cycle coupled to a new microphysical scheme for water-ice cloud formation.

In this abstract, we revisit the recent past climate of Mars in the light of these new developments, and study the sensitivity of the martian climate to different climate scenarios.

Model improvements

The version of the LMD/GCM used in this study is based on the model described in [1] and [2], to which has been added a set of new physical processes: a semi-interactive dust scheme [3], a new cloud microphysics scheme [4], Radiatively Active Clouds [RACs, 5], a parameterization of the mixing by thermal plumes in the boundary layer [6] and the ice-thermal inertia feedback [7].

Compared to previously published paleoclimate simulations [e.g. 8, 9, 10, 7], the dust cycle is still following a specified visible dust opacity τ_{dust}, but in a “semi-interactive” way. Instead of using an analytical dust profile [modified Conrath profile, see 1], we constrain the GCM to specified dust column averaged contents according to a given paleoclimatic scenario while at the same time simulating the transport to interactively compute the vertical distribution of the particles. This dust scheme is coupled to a new cloud microphysics scheme that accounts for nucleation and growth of water ice particles onto dust nuclei (with a constant contact parameter of 0.95) as well as scavenging of dust particles by clouds. The radiative effect of water-ice clouds is taken into account, and depends on the size of the particles [5].

Geological constraints and simulation setup

The main remnant of the recent ice ages is the Latitude Dependent Mantle (LDM), which is characterized by a succession of meters-thick surface deposits that are draped over the topography and ice-rich when formed [12, and references therein]. The blue dotted line in Figure 1 represents the limit of the LDMs in each hemisphere and is based on the diffuse roughness boundary [11], which is consistent with the presence of the LDM. The ages of the LDM suggest that it was forming during the past five million years, at periods when the obliquity was ranging from 15° to 35°.

Therefore, we ran a set of simulations and studied the sensitivity of the climate system to: 1) the obliquity, 2) the source of water vapor (north or south polar cap), 3) the eccentricity of the orbit, 4) the dust content of the atmosphere, and 5) the ice albedo. In this abstract, we only present some of these simulations (summarized in Figure 1) and the main outcomes of the sensitivity study.

The simulations are run with a resolution of 32×24 and with 29 vertical levels going up to 80 km. The polar caps are simulated by setting source points for latitudes poleward of ±80°.

In order to accurately represent nucleation and cloud opacity in the model, a time-splitting method was introduced in the microphysics scheme for present-day simulations [4]. The same method is applied to the paleoclimate simulations presented here to make sure that clouds are correctly represented. The values of albedo and thermal inertia used for the polar caps are set to 0.35 and 800 J $s^{-1/2}$ m^{-2} K^{-1}, respectively, as it is the case in simulations of the present-day water cycle. When more than 5 μm of water ice is deposited on the ground, the albedo is set to a new value A_{ice}, that we varied from 0.35 to 0.7, depending on the simulation. The thermal inertia of the different subsurface layers is set to 800 J $s^{-1/2}$ m^{-2} K^{-1} as ice accumulates [7]. In order for equilibrium to be reached, the results shown are those obtained after more than 5 Martian years of simulation.

Impact of Radiatively Active Clouds (RACs)

The main difference between the simulations presented here and previous studies [for example 13, 14, 8, 15, 9, 7] is the radiative effect of clouds. We find that when clouds are active, the response of the water cycle to a change in obliquity is amplified. Indeed, the formation of the mantle starts with an increase in obliquity during which the polar caps are more exposed to solar radiation. The water vapor content of the atmosphere increases, and optically-thick clouds form. The radiative effect of clouds results in a warming of both the surface and the atmosphere. Surface warming favors further sublimation of the polar caps, whereas atmospheric warming increases the water vapor holding capacity, broadens the Hadley cell and strengthens the meridional circulation by up to a factor of 2, resulting in even more moistening of the atmosphere. A several centimeter-thick ice mantle is then deposited through ice precipitation from a cloud belt present during winter in the 30–50° latitude band of both hemispheres.

Without RACs, the global mean surface temperature would be weakly sensitive to orbital variations, because even though these variations change the latitudinal distribution of insolation, it does not change the global annual mean energy input at the top of the atmosphere. RACs are therefore responsible for a strong internal response of the system to a change in obliquity, because obliquity controls the sublimation of the caps and amount of clouds, which feeds back on the global atmospheric and surface temperatures. These changes of the global energy budget through time are also being analyzed [see 16].

Even though a seasonal ice deposit is formed in winter of both hemispheres, it is not preserved during summer in these two simulations. There is no annual accumulation of ice that could explain the formation of the LDM, and from that respect, the two simulations without and with RACs are similar (see Figure 1a and 1b).

Coupling between the dust and water cycles

Summer sublimation of the mantle is strongly dependent on the amount of dust in the atmosphere. As mentioned above, under non-dusty conditions, the mantle is sublimated and does not accumulate. Therefore, we studied the sensitivity of our results to the dust cycle. In simulation x_2, a seasonal dust cycle is introduced and varies with time in a Gaussian manner between $\tau_{dust} = 0.2$ and $\tau_{dust} = 2$ with a peak at $\mathrm{L}_s = 270°$. The conditions are chosen to favor the preservation of a mantle in the southern hemisphere by also taking into account the effect of climatic precession, which has a period of about 51 kyr [17]. To do so, the eccentricity of the orbit is set to 0.1, the solar longitude of perihelion L_p to 90°, and the L_s of the dust opacity maximum to 270°.

In this case, summer surface temperatures are reduced by 1) obscuration of the surface and 2) a lower cloud greenhouse effect due to a decrease in cloud altitude. Accumulation rates of a few centimeters per year are then predicted in regions where the LDM is observed (see Figure 1c).

Impact of ice albedo

Another key parameter in the preservation of the deposits is the ice albedo. We performed different simulations where the ice albedo is changed. Simulation x_3 is the same as simulation x_2, except that the ice albedo is set to 0.4. In this case, the accumulation is restricted to fewer areas because the effect of the albedo of the source (the north polar cap) dominates. We also performed other simulations where the change in ice albedo is larger and reaches $A_{ice} = 0.7$. This is the case for simulation x_4, where the eccentricity of the orbit is set back to zero and τ_{dust} to a constant value of 0.2. In this case, the system switches to another mode where ice starts to accumulate in the northern hemisphere to form an extension of the north polar cap. Interestingly, if the eccentricity of the orbit is set again to 0.1 and the solar longitude of perihelion to $\mathrm{L}_p = 270°$ to favor ice preservation in the northern hemisphere, the mantle shrinks towards higher latitudes (simulation x_5). This suggests that the summer sublimation of the polar cap is controlling the extent of this mantle, and further analysis is underway to understand the processes at work.

Perspectives

We have shown that a several meters-thick mantle of ice can form at mid-to-high latitudes on Mars during the last few million years when obliquity approached 35°. This mantle is mainly sensitive to the dust cycle and ice albedo. Depending on the parameter configuration, two modes of accumulation are observed, either in the same or in the opposite hemisphere as the polar cap used as a source of water. Therefore, during recent excursions at high obliquity, the LMD/GCM confirms that the formation of a several centimeter-thick mantle is possible, and this mantle can cover both hemispheres down to around 45° latitude.

Future improvements of the LMD/GCM regarding the dust cycle and its coupling to the water cycle as well as the implementation of new microphysical processes such as the coalescence of ice particles should allow us to explore the past climatic excursions of Mars in more detail, and further understand the role of clouds in the past. A better representation of the sublimation of both the polar caps and the mantle is also required to further understand their long-term evolution, and explore how we transitioned from the recent ice ages to the present interglacial age.

References

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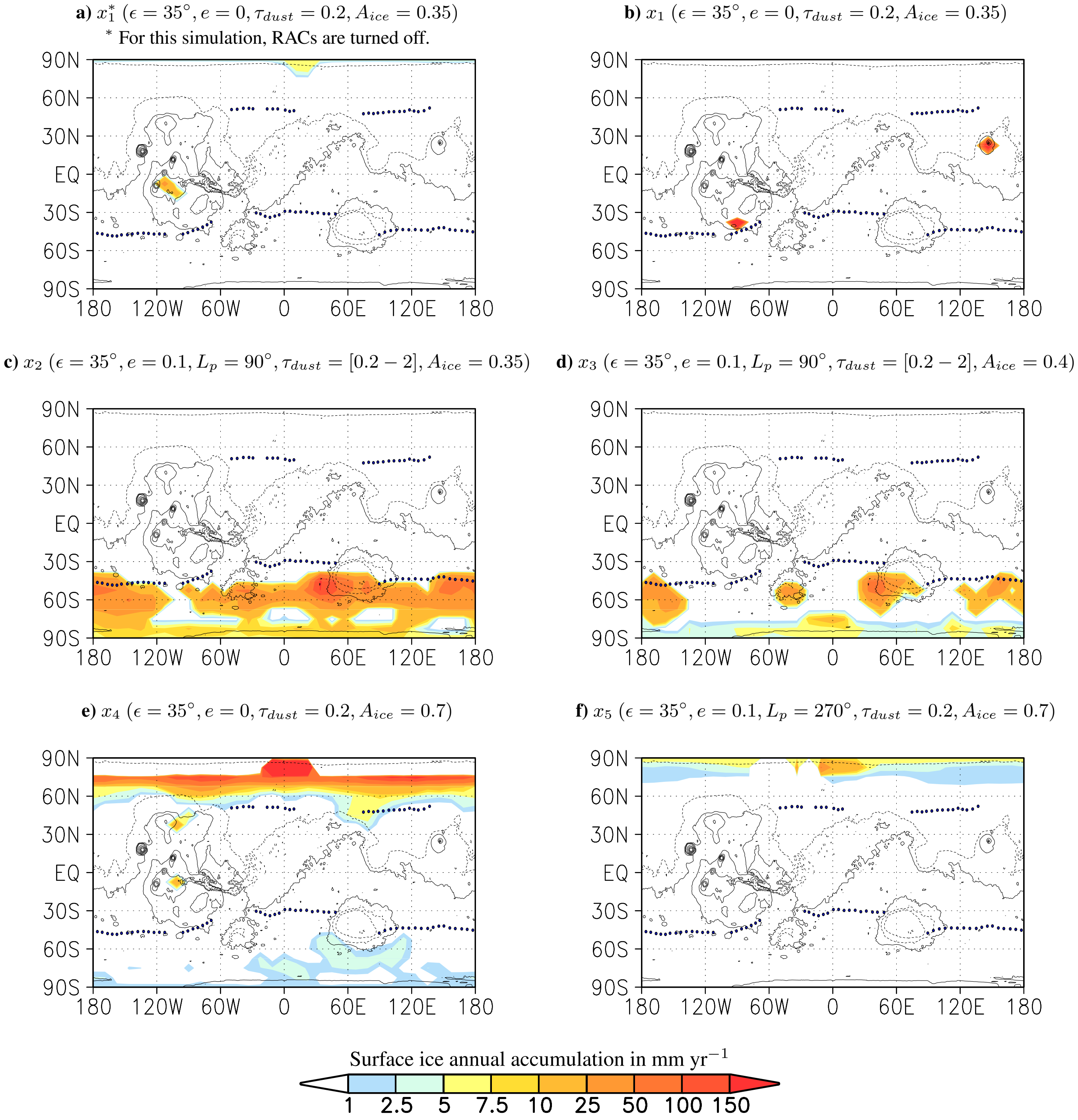

a) x_1^* ($\epsilon = 35°, e = 0, \tau_{dust} = 0.2, A_{ice} = 0.35$)
* For this simulation, RACs are turned off.

b) x_1 ($\epsilon = 35°, e = 0, \tau_{dust} = 0.2, A_{ice} = 0.35$)

c) x_2 ($\epsilon = 35°, e = 0.1, L_p = 90°, \tau_{dust} = [0.2 - 2], A_{ice} = 0.35$)

d) x_3 ($\epsilon = 35°, e = 0.1, L_p = 90°, \tau_{dust} = [0.2 - 2], A_{ice} = 0.4$)

e) x_4 ($\epsilon = 35°, e = 0, \tau_{dust} = 0.2, A_{ice} = 0.7$)

f) x_5 ($\epsilon = 35°, e = 0.1, L_p = 270°, \tau_{dust} = 0.2, A_{ice} = 0.7$)

Figure 1: Net gain of surface ice over a year (mm yr^{-1}, see the color bar) for each sensitivity experiment. The boundary of the Latitude Dependent Mantle (LDM) is also indicated by the blue dotted line, based on the roughness map of [11]. A north polar cap is always prescribed. Notation: Obliquity ϵ, eccentricity e, solar longitude of perihelion L_p, dust optical depth τ_{dust}, ice albedo A_{ice}. RACs stands for Radiatively Active Clouds.