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MODELING THE RECENT (<5 MYRS) MARTIAN ICE AGES

J. Naar[1], F. Forget[1], E. Millour[1], A. Bierjon[1], L. Lange[1], E. Vos[1] and R. Vandemeulebrouck[1]

Abstract. In spite of its present-day arid climate, in which ice is unstable outside polar regions, planet Mars exhibits remnants of glacial landforms dated of a few hundred million years. Numerical Global Climate Models (GCMs) have been used to address the climate conditions in which these glacial structures were formed, driven by variations in orbital forcing. However, GCMs have struggled to explain the recent formation of a water-ice mantle down to the mid latitudes within the last few hundred thousand years. During this period, the obliquity of Mars (the angle between the rotational axis and the plane of revolution around the sun) has risen from its current value of 25.19° to 35° at most.
The previous paleoclimatic studies did not consider the radiative effect of clouds, which dramatically affects the thermal structure and circulation of the atmosphere at higher obliquity. They also did not account for the latent heat of ground ice sublimation/condensation, negligible in today's climate but critical at higher obliquity since the Northern Polar Cap, the main source for atmospheric water, is warmed during summer by the increased insolation. Latent heat cooling is also crucial to the persistence of seasonal mid-latitude ice over the summer and the formation of a thick ice mantle.
With our new state-of-the-art physic, including radiatively active clouds, improved cloud microphysics, and the latent heat of ground ice sublimation, we have performed numerical experiments at 35° obliquity. We find that radiatively active clouds have a mean global positive greenhouse effect of $\sim$ 20 K. But, despite increased summer surface temperatures, the combination of latent heat cooling and thermo-physical parameterizations for ice allows the inter-annual preservation of seasonal frost. The associated accumulation rates are compatible with the formation of a hundreds-of-meters thick latitude-dependent mantle over the duration of recent 35° obliquity excursions.

Keywords: Planet Mars, climate modeling, water cycle, Ice Ages

1 Introduction

Remnants of glaciers are visible at all latitudes on Mars, thought to be of atmospheric origin and deposited during high obliquity excursions (Forget et al. 2006). Finer geomorphological evidences point to the existence of a recent "Latitude-Dependent Mantle" (LDM), a thick layered ice deposit covering Mars from the polar regions down to the tropics (Head et al. 2003).
The climatic scenarios leading to the accumulation of surface ice outside the polar regions in the last hundreds thousand years remained unsatisfactory in previous GCM studies. Only the destabilization of tropical surface water ice reservoirs, deposited millions of years ago at even higher obliquity, allowed for transient high latitude deposition (Levrard et al. 2004; Madeleine et al. 2009).
The subsequent inclusion of radiatively active clouds in the models disrupted our previous understanding of high obliquity climates (Madeleine et al. 2014). Here, we present our new physical package of the Mars Planetary Climate Model (PCM, previously LMD-GCM) with the latent heat of ground ice and improved cloud microphysics, using radiatively active clouds.

The simulated climate at 35° obliquity results in a thicker seasonal frost mantle deposition in the winter hemisphere than present day. We use simple parameterizations for the physical properties of this exotic ice mantle, with increased albedo and thermal inertia. Doing so, we find that the seasonal ice is preserved from sublimation and forms a LDM at 35° of obliquity, which happened for the last time 0.4 Myrs ago.

[1] Laboratoire de Météorologie Dynamique, UMR CNRS 8539, Institut Pierre-Simon Laplace, Sorbonne Universités, UPMC Univ Paris 06, 4 place Jussieu, 75005, Paris, France

2 Improved physics of the Mars PCM

2.1 Latent heat of ground water ice sublimation/condensation

In present-day Mars GCMs, ground water ice is sublimed/condensed either on top of the Northern Polar Cap or as diurnal and seasonal frost. In both cases, the associated latent heat flux is low, respectively because the ice deposits are cold or the mass budget is small. This is why latent heat of ground ice deposits has been neglected in the Mars PCM until now, as well as in other GCMs (Haberle et al. 2019). At 35° obliquity high latitude summer insolation is increased, the surface of the Northern Polar Cap is warmer and sublimes further, and the latent heat associated with sublimation becomes relevant.
Figure 1 depicts a validation experiment conducted under typical Martian conditions at the Phoenix Lander location (Lat=70°N), during the Norther summer solstice. In this experiment, latent heat release cools the martian surface by 8 K, with a corresponding decrease in the diurnal ice surface variation of 40%. Exposed water ice does not exist at this latitude and time of year in present-day climate but the insolation is comparable to the one received at the edge of the Northern Polar Cap at 35° obliquity at this time of year.

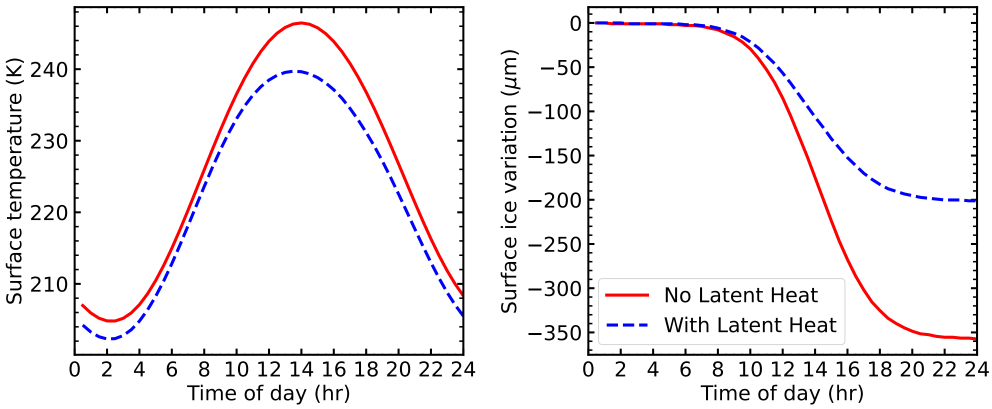

Fig. 1. Influence of latent heat on surface temperature and instantaneous sublimation rate with exposed surface ice in the model (for present-day conditions), at Phoenix lander location (Lat=70°N) at summer solstice (L_S=90°), with a prescribed integrated atmospheric water vapor of 10 precipitable microns. Extracted from Naar et al. (2023b)

2.2 Cloud microphysics

The radiative effect of clouds was implemented in the PCM and investigated in Madeleine et al. (2012). The global water cycle was tuned to match the Thermal Emission Spectrometer (TES) retrievals of seasonal water vapor and ice behavior Navarro et al. (2014). However, the model still was still biased in the representation of clouds. We implement a temperature-dependent contact parameter which improves our modeled water ice cloud cycle, especially in the polar regions (Naar et al. 2023b).
In addition, we identified that the numerical scheme of cloud microphysics was not well-resolved in the model. This is especially relevant at high obliquity where cloud activity is enhanced with the intensification of the global water cycle. We have developed an adaptive scheme to address this issue.
Using the new physical package, we tune the global water cycle in the model against TES observations. Our best simulation is presented in figure 2

3 High obliquity climate

Starting from the reference simulation presented in figure 2, we conduct 35° obliquity experiments.

3.1 Greenhouse effect of clouds

At 35° of obliquity, the insolation is increased in the high latitudes during the summer. The surface temperatures over the Northern Polar Cap (NPC) rise, and along with the sublimation rates of surface water ice. The increased

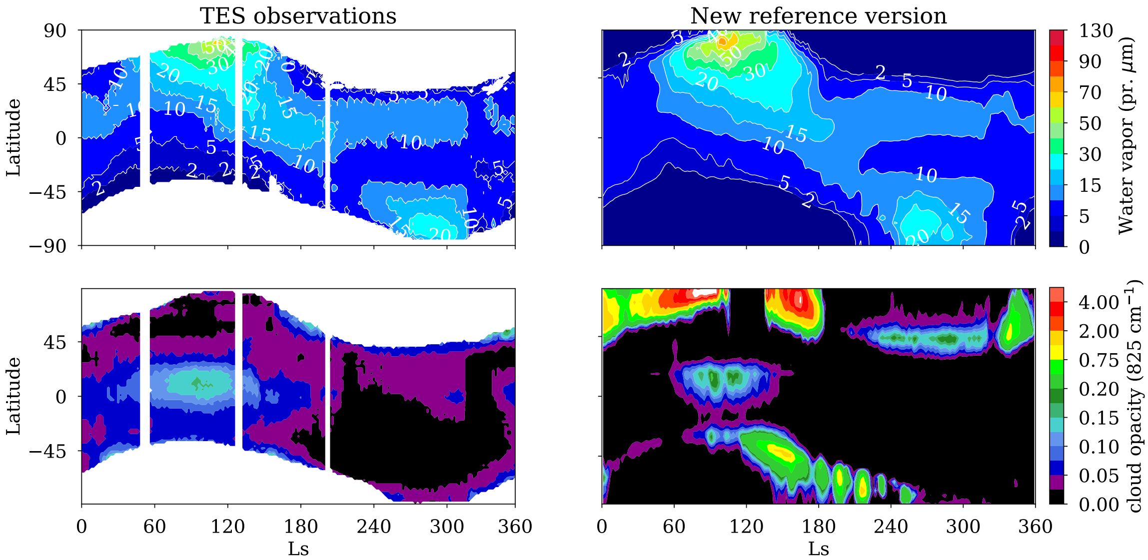

Fig. 2. Column-integrated water vapor (top panels) and cloud opacity (bottom panels) at 2 pm local time for TES observations (left panels) and our best numerical simulation of present-day Martian climate (right panels), corresponding to Martian year 26. Adapted from Naar et al. (2023a).

amount of water vapor in the atmosphere leads to the formation of water-ice cloud. In turn, their net radiative effect is to warm both the atmosphere and the surface. Clouds initiate a positive feedback via their greenhouse effect, further warming the surface and enhancing summertime sublimation of the NPC.

However, this positive feedback is dampened by the latent heat cooling associated with sublimation of the Northern Polar Cap. The corresponding energy flux reaches over 10 $W.m^{-2}$, more than an order of magnitude higher than in present-day climate.

The combination of these two effects leads to a climate regime approximately two order of magnitude wetter than today, with the mean atmospheric water vapor column reaching over 1000 precipitable microns when orbital configuration favors extended sublimation of the NPC. The resulting thick water-ice cloud coverage has a net greenhouse effect of about 20 K on global average.

3.2 Entering the Ice Age phase

In our present-day simulations, the seasonal frost in the winter hemisphere of Mars is formed via direct sublimation of atmospheric humidity on the surface. In our high obliquity simulations, the increased cloud activity leads to intense snowfall in the winter hemisphere, and thus a seasonal ice mantle several millimeters thick. The latent heat cooling of this seasonal ice sublimation reaches up to 30 $W.m^{-2}$ but it still is not sufficient to preserve any ice from disappearing completely.

However, the thermo-physical properties of the seasonal ice mantle at high obliquity should be very different than the present-day winter frost. Specifically, snowy precipitations may have a high albedo, and millimeters-thick ice may have a higher thermal inertia than present-day microns-thick frost.

We conduct additional simulations, using conservative parameterizations for these two possible feedbacks. In those experiments, the seasonal frost albedo and thermal inertia feedbacks diminish the summertime temperature increase. The resulting water cycle is less intense than in the high obliquity simulation described above, as NPC sublimation is decreased. The latitudinal extent of the seasonal ground ice mantle is reduced, but the summer temperature decrease allows for the inter-annual accumulation of high-latitude ice, at tens of millimeters per year (figure 3).

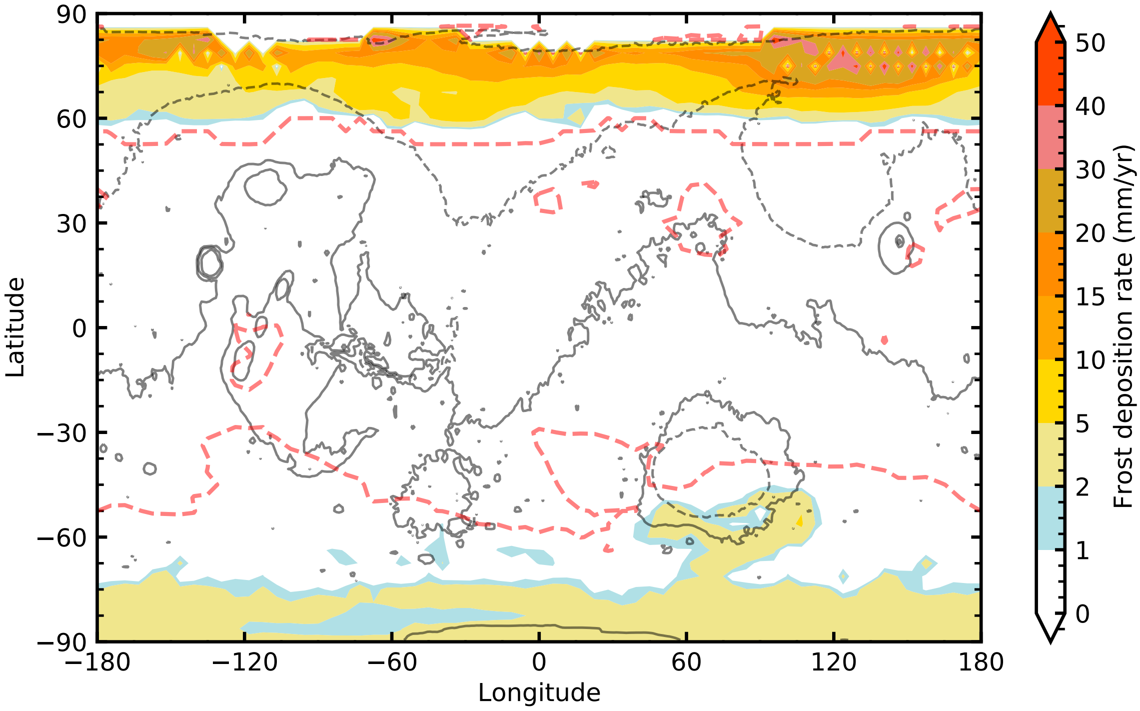

Fig. 3. Year by year accumulation of frost outside the Northern Polar Cap in a 35° obliquity numerical simulation, with the solar longitude of perihelion corresponding to the Northern summer solstice (L_S=90°) and with a ground ice albedo of 0.7 and a thermal inertia of 1200 $J.m^2.K^{-1}.s^{-1/2}$. The red dashed line is the extension of the seasonal ice mantle (1 mm thickness).

4 Conclusions

The 35° obliquity excursions of Mars occurred about 30 times in the last 5 million years, for tens of thousands of years at a time. The accumulation rates that we find with our conservative hypothesis provide a climatic explanation for the formation of the "Latitude-Dependent Mantle" in the recent past of Mars, during the high obliquity excursions, in agreement with geological observations. The climate regime corresponding to the emplacement of such "Ice Ages" is driven by the feedbacks of radiatively active clouds on the whole climate system and is one of a warmer and more cloudy planet.
Future work includes the development of an asynchronous "Planetary Evolution Model" which would allow for a self-consistent evolution of the water cycle with the location of surface water-ice deposits and the atmospheric pressure cycle. In addition, the interaction of atmospheric water with the regolith will be accounted for and may play a key role in the stability of surface water ice outside the polar regions.

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