Climate Simulations of Mars at Low Obliquity

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Introduction:
In some high latitude craters, intriguing moraines are interpreted to have been formed by CO_2 ice glacier flows [1]. These glaciers might have formed when Mars's obliquity was low and the local climate was colder [1,2]. The obliquity of Mars reached values ~15° nearly 800,000 years ago, and probably less than a few degrees during the Amazonian era [3]. The climate of Mars at such low obliquities has been little studied. [2,4] suggested that the atmosphere could totally collapse into CO_2 glaciers, leaving behind a residual atmosphere of only Ar and N_2 that is 20 times less dense than today. We present here preliminary results of our climate simulations of Mars at low obliquity using the LMD Mars Global Climate Model [5] and a new model for long-timescale surface and subsurface evolution.

Planetary Evolution Model:
Low obliquity periods last generally tens of thousands of years [3]. It is thus impossible to study for such long-period with the classic GCM. We therefore built a new tool called « Planetary Evolution Model » to simulate the evolution of the climate over long time steps. This model has been validated by comparing its results with the ones of LMD GCM long-runs made at low obliquity (e.g., Fig. 1a, b). A complete review of the PEM validation will be provided in [6].

Slope parametrization in the GCM:
The LMD GCM used for the current Mars climate study [5] cannot be used directly to study the formation and evolution of CO_2 glaciers on sloping terrain. Indeed, the typical resolution is about 300 km in longitude and 220 km in latitude at equator. However, the moraines observed in [1] are rather of the order of one km. We introduced in the LMD GCM a detailed parametrization of the topography distribution at kilometer scale. This parameterization enables to model the microclimate on local slopes and thus the formation of CO_2/H_2O glaciers. This parametrization has been tested and validated using the current observations of ice deposits on pole-facing slopes [7,8].

Simulation parameters:
Two sets of simulations are presented below. In the first one, the opacity of the atmosphere is fixed, and we only consider two tracers in the atmosphere: CO_2 and Ar/N_2. Water is not modeled here. Based on the work of [9,10], we assume that the CO_2 ice thickness can not exceed 10 m on slopes, and must flow if this thickness is reached. This simulation is noted S_1.

In the second simulation S_2, the opacity of the atmosphere follows the present-day dust scenario provided with the MCD [11,12]. The main tracers are CO_2, dust, and water. The same conditions for glacial flow as those described for S_1 are used.

Values of albedo, emissivity for CO_2 and H_2O ices, as well as ice tables are set to the current values used in the LMD GCM. The obliquity of the simulations is set to 5°. Other orbital parameters than the obliquity are kept at their current value. If not explicitly specified, slope parameterization is set off. The resolution is 3.75° latitude, 5.625° longitude, with 26 levels for vertical resolution. The initial state is the current martian climate at Ls = 0°.

Atmospheric collapse:
At low obliquity, the martian poles receive less insolation and are cold most of the year. As such, a significant part of the atmosphere is expected to collapse, forming permanent polar caps [2, 4]. We studied this collapse with the simulation S_1, with both the GCM and the PEM (Fig. 1). A dramatic collapse first occurs within the first fifty years (Fig. 1A), as a consequence of the violent shift of obliquity. Massive (> 10 m thick) deposits form at the poles. High latitudes regions tend to be depleted with CO_2, and enriched with non-condensable gases (Fig. 1B), similar to what is observed during the formation of seasonal ice caps today [13,14]. This depletion is however not observed at such magnitude in equatorial regions. After a fast condensation of the atmosphere, a slower regime appears: ice at high latitudes is transferred to the poles (Fig. 1D). Finally, the ice from the South Pole (S.P) is transferred to the North Pole (Fig. 1E). This is actually expected as the Northern hemisphere has a lower altitude: ice will be thus more stable. This behavior was already observed with Pluto for instance [15]. After 650 martian years of simulations, we reach an equilibrium, i.e., the massif ice deposit (> 63 m of thickness) is in equilibrium with the atmosphere. Low-obliquity occurrences could have lasted thousand of years according to [3], meaning that a complete atmospheric collapse is possible.

The speed of the atmospheric collapse and the amount of CO_2 ice that condensed are mainly controlled by the obliquity values [16]. Low obliquities favor a greater amount of condensed ice and a faster atmospheric collapse. For instance, at an obliquity of 5°, we found that the quasi-steady state was reached

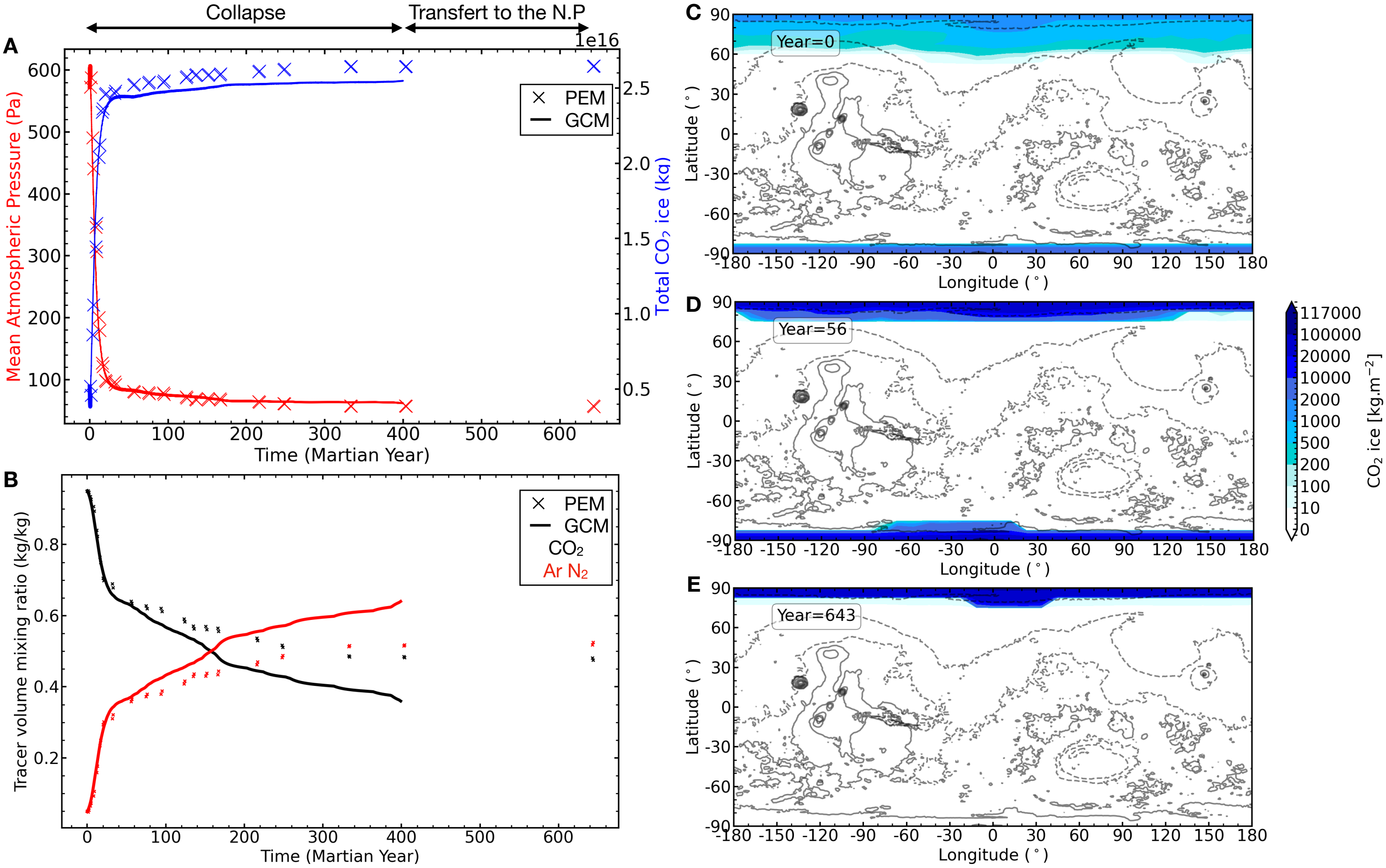

Fig. 1: a) Evolution of the global averaged atmospheric surface pressure (red) and the total amount of surface CO_2 ice (blue) predicted during the atmospheric collapse with the simulation S_1. Plain curves are the outputs of the GCM, whereas crosses are for the PEM. b) Same but for the volume mixing ratio of CO_2 (red) and ArN_2 (black). d) Initial state for the distribution of CO_2 ice. Black curves are elevation levels from MOLA. d) Same but after 56 years of the simulation with the PEM. e) Steady-state obtained by the PEM after 643 years of simulations with the PEM.

within 40 years, whereas at an obliquity of 15°, the simulations have not converged yet after 100 years of simulations. Furthermore, the final pressure reached at an obliquity of 5° is ~60 Pa, with an atmosphere equitably composed of CO_2 and non-condensable gases, whereas at 15° of obliquity, the residual atmosphere tends to be within ~200 Pa, and an atmosphere still mostly composed of CO_2. These values might be upper limits as we have not modeled here the adsorption of the regolith that might trap CO_2, and helps to reduce the CO_2 left in the atmosphere. Modeling ground response to an atmospheric collapse as well as adsorption will be part of future works. Interestingly, [2] have noted that 'the total mass of the deposits is not a function of obliquity, but strongly depends on the pre-history of the climate system'. However, preliminary results [16] with a no-GCM model have suggested that this assumption might be false, as the steady-state was not dependent on the initial state. Several simulations are ongoing to test this hypothesis.

Several factors can influence the amount of CO_2 that condenses during the atmospheric collapse. First, the ice-albedo could enhance the deposition of CO_2 ice. Second, the reduction of the greenhouse effect as less CO_2 is sublimated could cold the atmosphere and promote atmospheric condensation. Third, heat transport could also affect the CO_2 budget. Finally, as polar regions are depleted of CO_2, condensation temperature will be reduced (Clapeyron law). Other tracers could also influence the radiative budget reaching the surface, and increases CO_2 atmospheric condensation (e.g., dust bringing elements for nucleation, water cycle, …). These feedbacks, especially the dynamic one, are considered here compared to 1D/3D radiative models. Investigations are still ongoing to better understand the processes that control atmospheric collapse in the recent past history of Mars. Interestingly, we find that when we modeled the dust (assumed to be the same as the one observed today) and the water cycle, more CO_2 is condensing (Fig. 2). This point is still

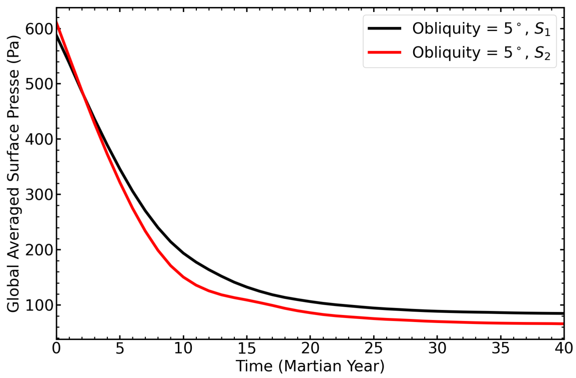

Fig. 2: Comparison of the evolution of the global averaged atmospheric surface pressure during the first 40 years of simulation for S_1 (black) and S_2 (red).

under investigation.

CO_2 and Water glaciers:

We then tested the influence of the slope parametrization on atmospheric collapse. Pole-facing slopes at high latitudes can receive similar insolation to terrains close to the poles, and can potentially host a significant amount of ice. However, the work of [9,10] have shown that CO_2 ice is a weak material compared to water ice. Therefore, a vast majority of ice that condenses on steep slopes must flow to flatter terrains where it can sublimate. This glacier flow was not modeled by [2] which found that a consequent amount of CO_2 can condense at high latitudes, not only at the poles, during the collapse. Here, we find again that high latitude north pole facing slopes can be cold traps and form CO_2 glaciers that become quickly saturated (within ~15-20 years of collapse). The excess ice flows to flatter terrains where it sublimates. Yet, we still find that some geological features induced by glacial flows could be evidence of atmospheric collapse.

[1] have documented some geomorphological features that have been interpreted as CO_2 moraines, even if their origins have been controversial, and potentially related to water ice [17]. If the link with CO_2 ice is proved, these moraines might be direct proof of the low obliquity periods that Mars has experienced in its last millions of years. We used our slope parameterization and the simulation S_2, with this time an obliquity of 15° to check if the CO_2 origin of these moraines is plausible. We made this simulation with the GCM only and for 25 years. We found that within the band 75°N- 82.5°N, steep slopes (i.e., 30° slopes) can host a significant quantity of CO_2 ice that enables glacial flows. Moraines found by [1] are located between 68°N and 75°N (Fig. 3a). We can therefore suggest that these moraines are created by a CO_2 glacial flows. Longer simulations with a finer resolution are however needed to conclude.

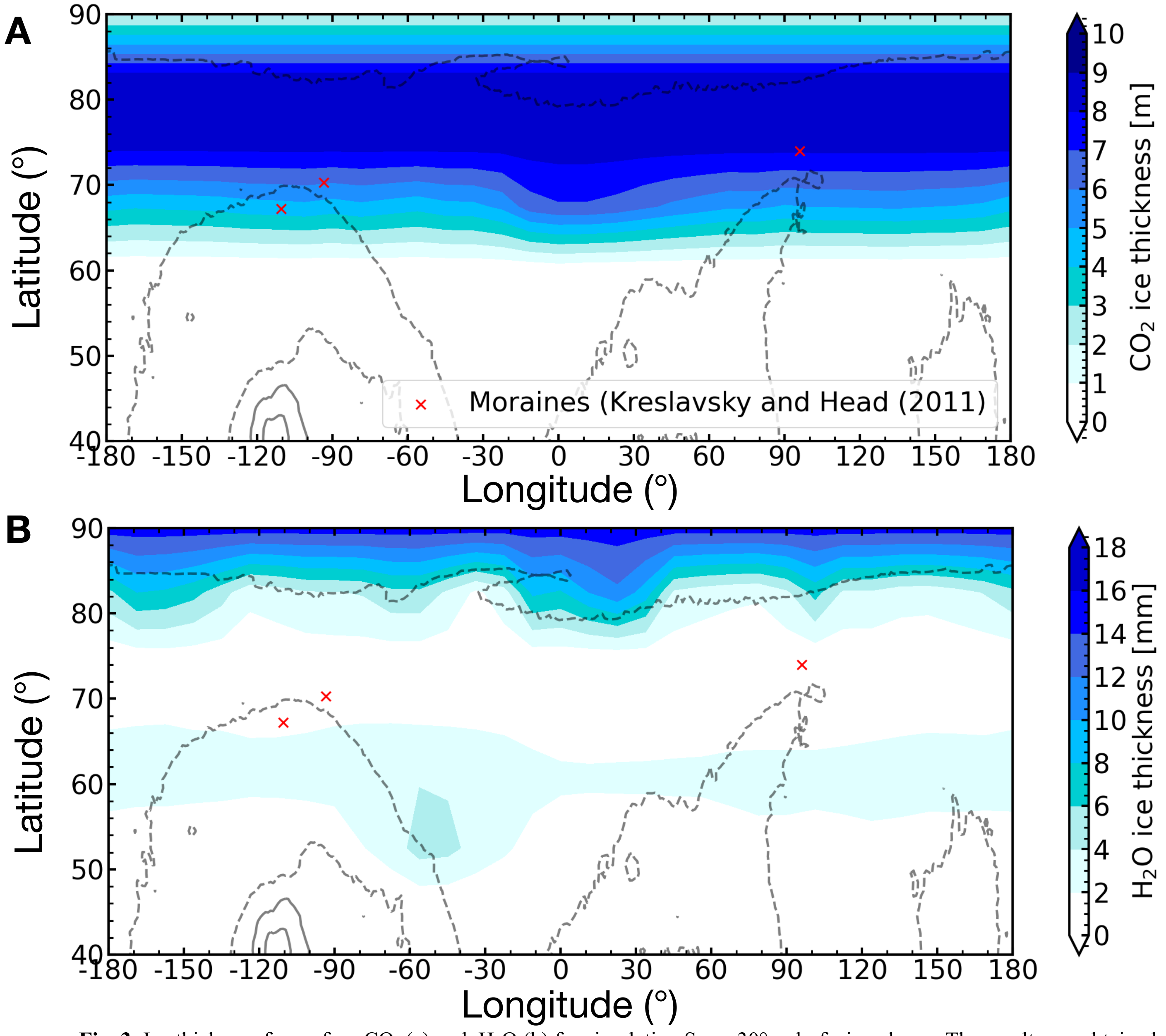

Fig. 3: Ice thickness for surface CO_2 (a) and H_2O (b) for simulation S_2 on 30° pole-facing slopes. The results are obtained after 25 years of simulation, and are given at Ls = 0°.

Water ice glaciers can also be formed at high latitudes. Our simulations (Fig. 3b) show that mm-thick glaciers can be formed on 30° pole-facing slopes in the band 50°N-70°N. Their latitude is not low enough to be correlated with the glacier-like form evidenced by [18], suggesting that these features are indeed products of high obliquity periods as already assumed [19]. Netherveless, these glaciers grow at a rate of ~0.3 mm/year, suggesting that they can form ~meters glaciers on steep slopes. Longer simulations with a finer resolution will help to conclude on the maximum thickness they can reach, their spatial extent, and their correlation with geological glacial features.

Perspectives and Future works:

The Planetary Evolution Model opens the way to future complete climate simulations of Mars at low obliquity. While the basic implementation of the PEM has been validated [6], we still need to improve the physics of the model to consider the effect of atmospheric collapse on the soil and geothermal fluxes as well. An atmospheric collapse could indeed strongly influence the temperature profile within the soil, the geology of the shallow surface, and at least the adsorption of the ground [20]. Future models for the glacier flows will be developed.

At last, this new tool will help us to better understand the influence and contribution of atmospheric parameters during the collapse, the water cycle and the structure of the atmosphere during low obliquity periods. Finally, a complete simulation of a low-obliquity oscillation will help us to better understand the impact of obliquity variations on the development of glacier-like landforms.

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