Ancient Mars Climate with a Polar Ocean and Ice Sheet Dynamics

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Introduction:

The possibility of an ocean on Mars has been proposed since the 1990's (e.g. Parker, 1989, Baker, 1991) with a lot of controversy. Several reviews of the hypothesis of an ancient northern ocean on Mars have been proposed in recent years. These studies point to an episodic presence of an ocean in the early Hesperian to the early Amazonian (about 3.6-2.5 giga years ago, Ga). This hypothesis has been relaunched by the discovery of potential tsunami deposits (Rodriguez, 2016; Costard, 2017) with at least two impact events. In addition, the Lomonosov crater morphology is coherent with an impact in shallow water, at the very same age of the tsunami deposits (Costard, 2019), around 3 Ga, that could be the source of the tsunami. A detailed geological analysis identified similarities between Olympus Mons and other edifices with oceanic island on Earth (Hildenbrand, 2023). In previous work, the long-term stability of an ocean in a cold and wet Martian climate seemed impossible in three-dimensional General Circulation Models (3D-GCM) (e.g. Forget et al., 2013; Wordsworth, 2013; Turbet, 2017; Turbet & Forget, 2019; Kite, 2021). These studies found that the water tends to accumulate in the form of ice in the southern highlands. This view changes when ice sheet processes and ocean circulation are included (Schmidt, 2022). In this study, a fully equilibrated water cycle has been proposed with a simplistic ice sheet model. This contribution aims at improving it.

Following up on Schmidt (2022) with improved surface modeling, the aims of this article are to estimate the coupled ice sheet/climate processes, including the strong bi-directional coupling between ice sheet, albedo and topography. To our knowledge, this is the first instance where a 3D-GCM was coupled to a detailed ice sheet model on Mars to estimate the equilibrium water cycle. We use asynchronous coupling, with alternative equilibrium climate and equilibrium ice sheet modeling. This article aims at studying the potential distribution of ice, including ice sheet flow, on Mars at 3 Ga and at estimating the water cycle at this time. The results of this numerical study can be extended to Earth-like climate conditions on Mars, that are also foreseen earlier than 3 Ga. An extension to the Noachian is more challenging because of the unknown topographic change of the Tharsis bulge.

Model and method:

The work is here based on 2 models : ROCKE-3D a 3D-GCM that is used for terrestrial planet climate studies (Way et al., 2017) and GRISLI (Quiquet, et al. 2018) a 3D thermo-mechanical ice sheet model. The typical timescale for ROCKE-3D to reach equilibrium is ~200 Martians years, but the ice sheet requires a modeling timescale around 10 000 y. It is therefore impossible to compute both at the same time. Instead, we propose the standard scenario: an asynchronous coupling. It consists of:

R compute the equilibrium climate using ROCKE-3D

RG compute the equilibrium ice sheet using GRISLI using input from R

RGR compute ROCKE-3D using input from RG

And so on..

Results:

Figure 1 shows the main output field of ROCKE-3D after 3 alternative couplings (step RGRGR): rain precipitation, snow and ice fraction at the surface, snowfall, and sea/land surface temperature. The general results are comparable to those in Schmidt (2022) except that due to the ice-albedo feedback the snow fraction tends to accumulate more on the Tharsis bulge.

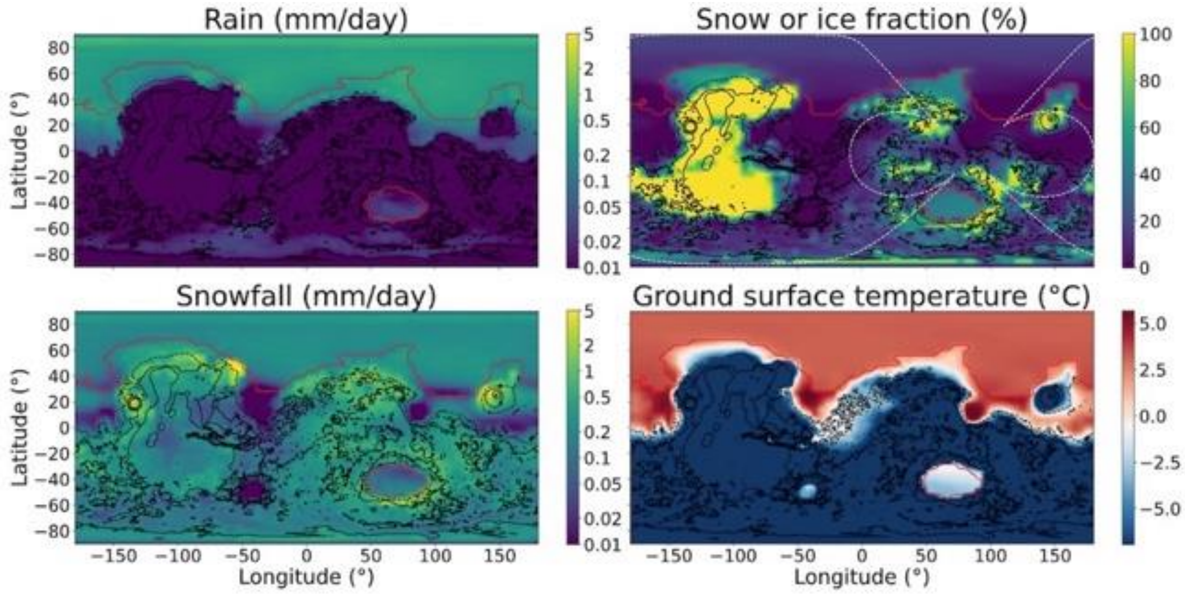

Figure 1: Main fields outputs from the RGRGR simulation for the rain precipitation, ice fraction, snowfall, surface temperature. Black contour lines represent the Martian topography. The dashed white contour line represents the domain of the GRISLI ice sheet simulation area, centered in the major snow accumulation area around the Tharsis plateau.

Figure 2 shows the ice sheet topography, computed by GRISLI (step RGRGRG). The ice sheet is up to 4300 meter thick but the flow is relatively limited with 300 m/y at maximum, compared to Earth where it can reach several km/y. This is mainly due to the low gravity. The typical basal melting values are in cm/y, and are highly correlated to the ice sheet velocity reaching locally maximum values at 30 cm/y. One interesting point to note is that the ice sheet reaches the ocean in two points in the North East and North West edges, demonstrating that a glacier can flow through the wetland and reach the ocean to potentially produce icebergs. In addition, the relative low velocity would prevent the ice from massively eroding the substratum. The isostasic effect can reach up to 800 m.

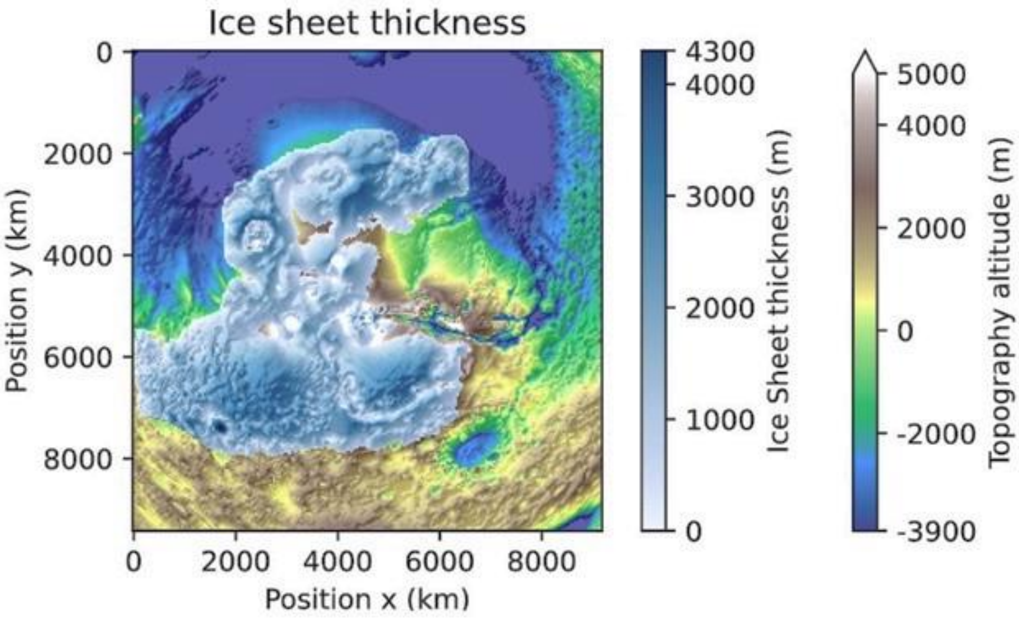

Figure 2: Ice sheet topography computed by GRISLI ice sheet model (step RGRGRG). For this particular simulation, the ice sheet reaches the ocean in the North-East region and could potentially produce icebergs. The ice tends to accumulate in the flattest regions near the topographic peaks.

Table 1 presents the same integrated results as in Schmidt (2022). The first part of the results table clearly demonstrates that the climate is getting colder when coupling with the ice sheet model due to the ice-albedo feedback. The Icy Highland surface is increasing due to the decreasing altitude of the 0°C isotherm. The corresponding wet lowland is shrinking by a factor of 1.5. The thickness of sea ice and its fraction of the total ocean surface is also significantly increasing.

Parameter	R	RGR	RGRGR
Altitude of the ocean (meter)	-3900	-3900	-3900
Altitude of the 0°C isotherm (meter)	-2070	-2990	-2920
Mean temperature (°C)	-7.2	-10.5	-12.0
Mean ocean temperature (°C)	7.1	3.8	2.8
Mean land temperature (°C)	-10.0	-13.2	-14.8
Surface of Icy highland (%)	62.4	71.0	73.8
Surface of Wet lowland (%)	21.9	14.5	11.9
Surface of Ocean (%)	16.2	16.2	16.2
Mean thickness of sea ice (meter)	0.04	0.25	0.48
Mean fraction of sea ice (%)	1.3	4.7	11.5

Table 1: Table of the main climatic parameters from ROCKE-3D. The ocean could be either liquid water or iceberg. All quantities are averaged over the last 10 years of the simulations.

Conclusion:

We found that the total volume of water to reach the coupled equilibrium water cycle is ~700 m GEL (340 m for the ocean and the same amount for the ice sheet). This budget is plausible, if a significant amount of water has been removed from the atmosphere/hydrosphere/cryosphere in the last 3 Gy, for instance by chemical alteration (Scheller et al., 2021). A recent analysis of seismological data proposes that the current mid-crust porosity is filled by liquid water (Wright, 2024) a reservoir representing ~1700 m GEL. The global inventory proposed here would imply that this deep reservoir was filled after the wet climate proposed herein at 3 Ga, since atmospheric escape does not appear efficient enough to remove so much water (Jakosky & Treiman, 2023). This study is presented in more detail in Schmidt et al, 2025.

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