THE EFFECT OF GROUND ICE MIGRATION ON THE MARTIAN PALEO-CARBON DIOXIDE BUDGET

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Introduction:

The mass and distribution of the CO_2 and H_2O ground ice (GI) reservoirs on Mars evolve in response to the evolving orbit of Mars, which is characterized by oscillations in eccentricity (e), longitude of perihelion (L_p) and obliquity (ε) [1]. The seasonal condensation/sublimation CO_2 cycle intensifies with rising obliquity, as more CO_2 mass exchanges seasonally between surface and atmosphere; it considerably subdues as obliquity decreases, at low enough obliquity reaching atmospheric collapse and the formation of massive CO_2 deposits [2,3]. Similarly, ground ice extends equatorward at high obliquity, as mid-latitudes become more humid and receive less insolation, and recedes back poleward with decreasing obliquity [4,5].

In addition to the individual evolution of the two reservoirs, they also interact with each other: due to the high thermal conductivity of water ice, ground ice on Mars acts as a heat sink during the spring/summer months and as a heat source during autumn/winter, thereby inhibiting the accumulation of CO_2 and increasing atmospheric pressure [6]. In this work, we seek to provide a systematic analysis of the coupling of these two phenomena, *i.e.*, the effect of the orbitally-forced redistribution of ground ice on the evolution of the CO_2 budget.

Methods:

We use the Global Climate Model developed by the Laboratoire de M'et'eorologie Dynamique, CNRS, Paris (LMD-GCM) [7] in order to simulate the paleoclimate with different orbital parameters and ground ice distributions of choice. The model operates on a three-dimensional 64x64x29 grid (resolution of 2.8125º latitude and 5.625º longitude) and calculates the temporal evolution of variables such as temperature, atmospheric pressure, and various tracers. We run the GCM for an array of orbital parameters within the range of the past 1.5 Ma ($0 \leq e \leq 0.12$, $0º \leq L_p \leq 360º$, $15º \leq \varepsilon \leq 35º$) [1] for two cases (Figure 1): (1) a study case where ground ice distribution changes according to the orbital configuration (Equilibrium GI scenario, or EqGI) and (2) a control case where ground ice distribution is constant regardless of orbital configuration (Static GI scenario, or StGI). Comparing the two scenarios underlines the contribution of ground ice redistribution to the CO_2 evolution.

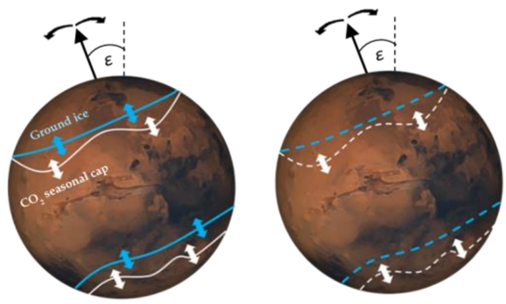

Figure 1: Schematic illustration of the equilibrium ground ice (EqGI; left) and the static ground ice (StGI; right) scenarios

To calculate the equilibrium ground ice distribution at each orbital configuration for the EqGI scenario, we use the Mars Subsurface Ice Model (MSIM), a one-dimensional equilibrium ground ice model, developed by Schorghofer & Aharonson [8]. The model calculates the depth of an ice table at ice-vapor equilibrium with the atmosphere under a dry regolith layer. Mean annual daytime water vapor pressure, a critical parameter for MSIM, is derived from GCM simulations (after a spin-up time of 15 Mars-years). MSIM ice table depths are interpolated to the GCM subsurface grid consisting of 18 grid points of exponentially growing depth from 0.14 mm to 18 m. GCM ground ice is represented in terms of thermal inertia (I) with the relation between pore fill fraction and thermal inertia following previous formulation [8]. Pore space ($\Phi = 0.4$) is completely filled with ice under the ice table, as expected in a state of full ice-vapor equilibrium. At this stage of the study, we calculate the zonal mean ground ice distribution and expand it for all longitudes. For the StGI scenario, we use a ground ice distribution based on MONS observations [9] (this distribution has been previously incorporated in the LMD-GCM and has been calibrated to reproduce Viking seasonal surface pressure [10]).

Results:

Effect of ground ice equilibrium distribution at low and high obliquities: Figure 2 shows the seasonal evolution of CO_2 ice accumulation at EqGI and StGI. In EqGI, the extent of the equilibrium ground ice roughly matches the extent of the seasonal CO_2 cap. At obliquity 20º the seasonal cap is mainly restricted

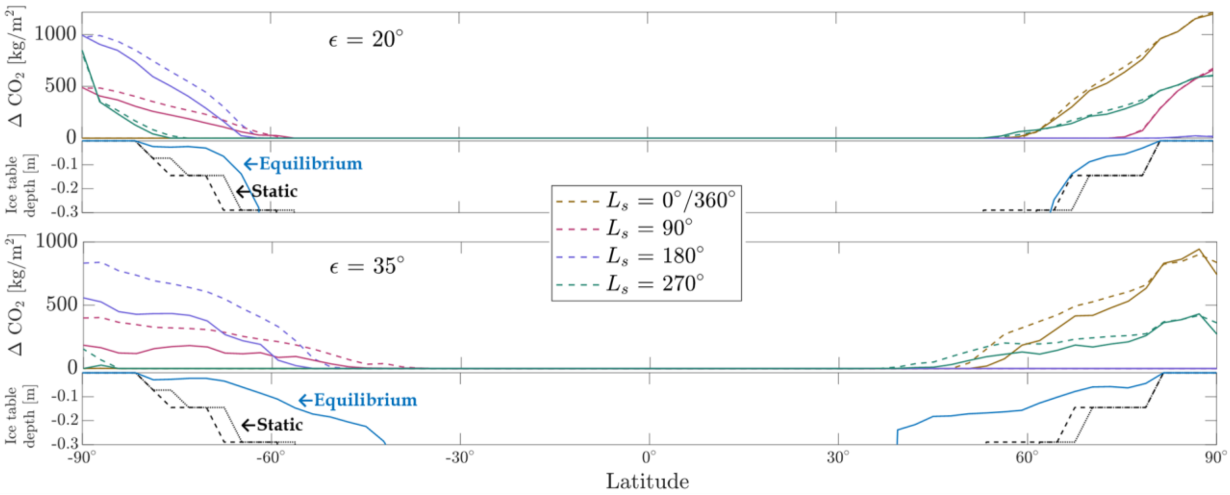

Figure 2: Seasonal evolution of zonal mean CO_2 accumulation at Mars year 7, *e* = 0, *ε* = 20º (top) and *ε* = 35º (bottom); dashed/solid CO_2 mass correspond to StGI/EqGI scenarios; dashed/dotted ground ice profiles (black) correspond to static ground ice at longitude -151º/135º.

to latitudes >60º at both poles, and the effect of ground ice migration on accumulation is small. The small decrease in accumulation in EqGI can be attributed to shallower burial depth of the equilibrium ground ice relative to the static case. At obliquity 35º, the seasonal cap extends toward the equator as a greater range of latitudes experiences sub-CO_2 frost point temperatures. Ground ice now not only extends to latitudes where it was previously absent, but also becomes shallower at higher latitudes. It therefore has a more substantial effect on the CO_2 accumulation at all latitudes.

Seasonal CO_2 accumulation over the orbital parameters space: Total seasonal accumulation from all simulations is summarized in Figure 3. This perspective allows us to look not only at the exchangeable mass at individual orbital configurations (which is lower for EqGI, as expected), but also the rate of change of exchangeable CO_2 mass with orbital parameters, which decreases due to ground ice migration. The difference between scenarios increases with obliquity, as exchangeable CO_2 mass grows without the inhibiting effect of ground ice. Exchangeable mass is larger when L_p coincides with winter (aphelion winters are longer), yet interestingly, ground ice has a particularly larger effect at the same L_p (perihelion summer is warmer, leading to higher humidity and more extensive ground ice). Rise/decline in eccentricity increases/decreases the magnitude of the L_p effects mentioned above (not shown in the figure).

Interpolation of seasonal CO_2 accumulation for the past 1.5 Ma: Exchangeable mass values are interpolated for Laskar et al. historical orbital parameters values for the last 1.5 Ma (Figure 4, top and middle plots; obliquity 15º is extrapolated, modeled exchangeable mass is expected to be much lower around this obliquity, due to atmospheric collapse). The same effects of ground ice migration discussed above can be seen from the perspective of volatile budget evolution: decrease in the seasonally accumulating mass and attenuation of the orbitally-forced intensive oscillations in volatile budget. Finally, the bottom plot of Figure 4 shows the evolution of seasonal surface pressure variations (global mean), with ground ice migration considerably decreasing the seasonal amplitude

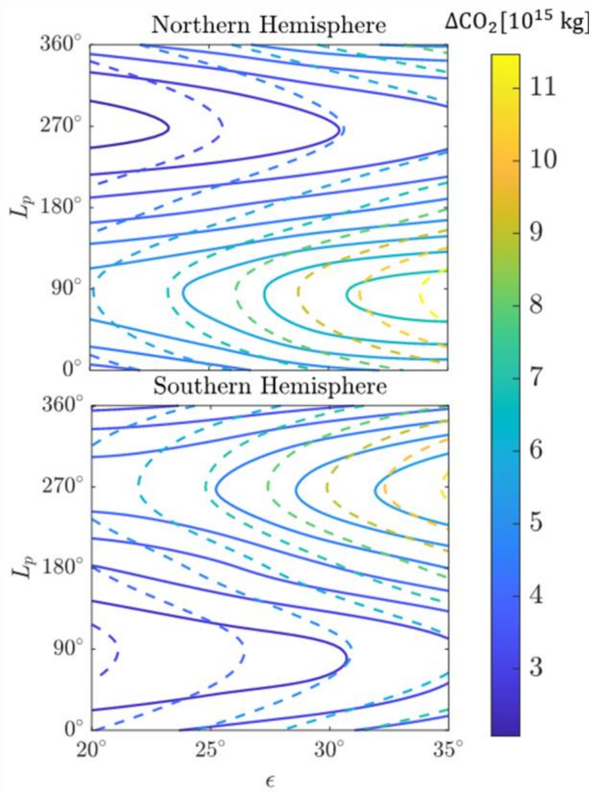

Figure 3: Total seasonal CO_2 exchangeable mass, *e* = 0.12, at northern (top) and southern (bottom) hemispheres; dashed/solid contours correspond to StGI/EqGI scenarios, respectively. Results for *ε* =15º are not included here because these simulations did not reach steady state.

at epochs of high obliquity. At its maximal effect, ground ice migration decreases the seasonal surface pressure variations by 42% relative to the non-migrating ground ice scenario.

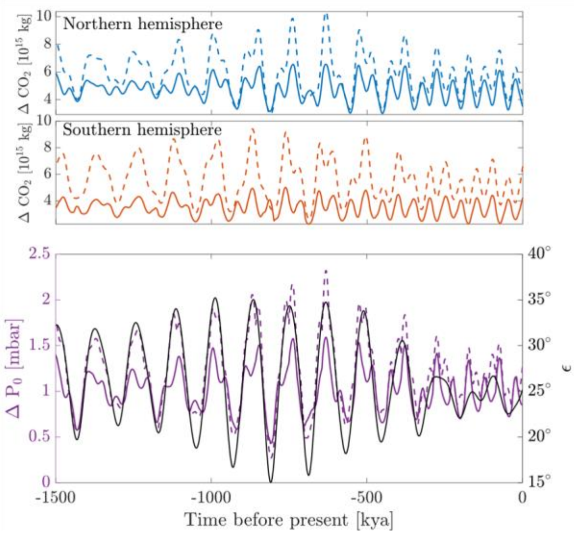

Figure 4: Historic evolution of seasonal exchangeable CO_2 mass in the northern (top) and southern (middle) hemispheres); historic evolution of seasonal surface pressure variations (bottom; in purple, left vertical axis) overlayed with obliquity (in black, right vertical axis); dashed/solid lines correspond to StGI/EqGI scenarios, respectively.

Discussion:

Ground ice is redistributed due to orbital evolution, and much like the seasonal CO_2 cap it extends towards the equator at high obliquity and recedes at low obliquity. It acts as an adapting heat reservoir that inhibits the seasonal accumulation of CO_2 and attenuates the more extreme orbitally-forced oscillations in the secular evolution of the seasonally-exchangeable CO_2 budget. Our work emphasizes the notion that ground ice redistribution is non-negligible and has potentially significant implications on the reconstruction of the Martian paleoclimate. Particularly, surface pressure variations and CO_2 ice accumulation are relevant to questions of liquid water stability [11] and the interpretation of the enigmatic polar layered deposits [12], the massive south polar CO_2 deposits [13] and other climate records.

Further work will advance the current analysis of secular CO_2 evolution (e.g., including the steady state seasonal CO_2 accumulation at low obliquity) and improve our understanding of the effect of ground ice distribution on the seasonal cycle. Finally, we must consider more complex scenarios, such as non-equilibrium ground ice, ground ice in the presence of an equatorial humidity source, and others.

Acknowledgments:

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