Mars's environment during low obliquity epochs : toward a quantitative study of CO_2 deposits and atmospheric composition

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Abstract

We have built a new 3D climate Model to simulate Mars during low obliquity epochs. The model is derived from LMD's global climate model (GCM), taking all key physical processes into account, including long and short wavelength radiations (direct and scattered), thermal inertia in the ground, CO_2 condensation and sublimation on the ground. This model computes the influence of local slopes on the insolation as well as CO_2 glaciers flow on slopes. It uses simplified calculations for atmospheric transport so that we could simulate long enough to obtain an equilibrium that do not depend on the initial state. As we expected, lowering obliquity causes Mars' atmosphere to collapse, condensing its CO_2 onto the ground to form glaciers. The influence of slopes and the flow of CO_2 glaciers both affect the localisation of perennial CO_2 glaciers with CO_2 condensing and flowing on steep facing-poles slopes, at relatively low latitudes, in agreement with today's observations of moraines on Mars' ground. Although our long-timescale-simulations do not account for diurnal phenomena, they show interesting seasonal changes in atmospheric composition that are amplified during low obliquity epochs. The atmosphere near the ground is depleted during seasons of condensation and enriched during seasons of sublimation, with CO_2 mixing ratio oscillating between x and y percent. Not only this phenomenon acts as a feedback on sublimation and condensation themselves, but it creates large gradients in atmospheric composition that have an impact on dynamic processes.

Keywords:
Mars, Atmospheres, Obliquity,

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1. Introduction

Presently, Mars' obliquity is 25.2°, ressembling the Earth's. However, contrary to the terrestrial obliquity, Mars' is chaotic and may have oscillated around values as low as 10° during the past 250 Million years (Laskar et al., 2004). Low obliquity epochs have had an important impact on Mars' climate system, causing the atmospheric CO_2 to condense. While permanent solid deposits of CO_2 were formed, the atmosphere was depleted and became much thinner. This evolution is often described as an atmospheric collapse. Some features that can presently be found on Mars are thought to be evidences for such low obliquity epochs. Kreslavsky and Head (Kreslavsky and Head, 2011) found ridges at relatively low latitudes (70°N) that they related to drop moraines that are left by episodes of advance and retreat of cold-based glaciers. They showed that those features were significantly different from landforms resulting from water-ice flow and rather interpreted these as the consequence of CO_2 ice flow during recent periods of very low obliquity.

In this paper, we quantitatively address the effect of low obliquity epochs on Mars' environment. We study the resulting depletion of atmospheric CO_2 in term of drop of pressure and seasonal local changes in atmospheric composition that are at stake in such conditions. We focus on CO_2 ice deposition in term of total mass, localization and flow in order to discuss the link between those conditions and geological evidence.

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2. Model description

2.1. Generalities

The model we used is derived from the LMD Mars GCM (Forget et al., 1999). This model is made of a physical core computing physical processes and a dynamic core that performs temporal and spatial integration of the equations of hydrodynamics. We choosed to drop the dynamic core of the initial model and replaced it with a simpler redistribution scheme detailled below in order to ensure quicker simulations.

In this paper, we present simulations with a horizontal grid of 32×48, that is a grid-point spacing of 11.25° in longitude by 3.75° in latitude. This configuration allowed us to obtain accurate estimates of the latitudes where solid CO_2 can be deposited. In term of vertical resolution, the model uses the terrain-following "sigma" coordinate system in finite difference form (i.e. each layer is defined by a constant value of the ratio pressure devided by surface pressure). As we worked in conditions where the atmosphere is much thinner than presently, we choosed to divide the vertical coordinate in only 3 layers, with the pressure for the upper layer of which corresponds to a spatial resolution of about for the case of 10° obliquity.

We simulated the evolution of the planet during timescales ranging between 1000 and 20000 martian years. As we did not need to resolve diurnal climate variations, we choosed timesteps of 10 martian days each for simulations. We found that these timesteps were sufficiently short to provide interresting insights on seasonal evolutions of the climate over a year.

2.2. Model for dynamics

We replaced the dynamic core of the original GCM by a newtonian return to the mean, that was already used by Bertrand et al. to simulate the climate on Pluto on large timescales (**?**). We applied this redistribution scheme to potential temperature, surface pressure and CO_2 mixing ratio. For any mesh i, in any vertical layer l between times t and $t + \delta t$, we apply:

$$\theta_{(i,l)}(t+\delta t) = \theta_{(i,l)}(t) + \left(\overline{\theta_l}(t) - \theta_{(i,l)}(t)\right)\left(1 - e^{\frac{\delta t}{\tau_\theta}}\right) \tag{1}$$

$$q_{(i,l)}(t+\delta t) = q_{(i,l)}(t) + \left(\overline{q_l}(t) - q_i(t)\right)\left(1 - e^{\frac{\delta t}{\tau_q}}\right) \tag{2}$$

$$Ps_i(t+\delta t) = Ps_i(t) + \left(P_0 k_i(t) - Ps_i(t)\right)\left(1 - e^{\frac{\delta t}{\tau_P}}\right) \tag{3}$$

where $\theta_{(i,l)}$ and $q_{(i,l)}$ are respectively the potential temperature and the CO_2 mixing ratio of mesh i in layer l, Ps_i is the surface pressure of mesh i. The return is made toward the mean values $\overline{\theta_l}$, $\overline{q_l}$ and $P_0 k_i$ where $k_i = e^{-\frac{z_i g}{RT}}$ with z_i the elevation of the ground. Time constants for the return are τ_θ, τ_q and τ_P. The constraints of total mass and energy conservation lead to:

$$\overline{\theta_l} = \frac{< \theta_{.,l} \Delta P_l >}{< \Delta P_l >} \tag{4}$$

$$\overline{q_l} = \frac{< \Delta P_l q >}{< \Delta P_l >} \tag{5}$$

$$P_0 = \frac{< Ps >}{< k >} \tag{6}$$

where ΔP_l is the pressure loss in layer l and $f \rightarrow < f >$ is the surface-average operator. We compared test simulations between our model and the original GCM to tune the value of the three time constants τ_θ, τ_q and τ_P, so that our model gives a good account of the evolution of the climate in average. In our simulations, we use $\tau_\theta = 10^{-7}$s, $\tau_q = 10^{-5}$s and $\tau_P = 1$s

2.3. Insolation on slopes

Kreslavsky and Head studied with a simple energy balanced model the atmospheric collapse and deposition of solid CO_2 in low obliquity conditions (Kreslavsky and Head, 2005). They insisted in their article on the role of topographic slopes on the insolation regime. Regarding their results, we found important to take local slopes into account. Given the extension of the mesh grid (more than 100 km large), associating each grid area to a singe slope would not be relevant. To characterize the slopes on a mesh, we binned its local slopes extracted from MOLA observations (with ˜300 m resolution) into 7 characteristic slopes, based on their value of $\mu = \theta\, cos(\psi)$ where θ and ψ are the local inclination and orientation of the slope, meaning that μ is the projection of the orientation on the south-north axis. We found that slopes having close parameters μ also receive close mean daily insolation.

Computation of the insolation on each of the characteristic slopes is done accordingly to Spiga and Forget article on estimations of the solar irradiance on Martian slopes using 3D Monte-Carlo calculations (Spiga and Forget, 2008). Using this method, the mean daily insolation is estimated on the first day of the timestep, assuming that it approximately remains the same during the 10-days timestep. Similarly, surface temperature, soil temperature and mass of CO_2 ice deposits are computed separately on each characteristic slope.

2.4. CO_2 glaciers flow

(**?**) used models of rheology to compute maximum thickness and velocity of CO_2 ice in the conditions of sloppy topography. They showed that, even on tiny slopes, the CO_2 ice sheet is very thin and has high velocity: looking at the maximum inclination of 0.1° they studied, we find that the related maximum thickness remains under 100m. Among the 7 characteristic slopes we choosed to describe the topography, the 6 that are not flat have inclinations ranging between 6° and 31.5°, being much steeper than the ones studied by (**?**). We thus expect the CO_2 ice layer upon those slopes to be very thin and of high velocity, meaning they would not impact quantitatively the geographic deposition of CO_2 while they would errode and shape the ground on which they are moving fast. Also, we expect that the steeper the slope, the more likely CO_2 deposition is to occur.

Those preliminary observations lead us to designing a very simple model to simulate the flow of CO_2. We arbitrary defined a maximum thickness of 10m on every characteristic slopes that are not flat. When the CO_2 mantle reach this thickness on one of those characteristic slopes, all further deposition will be directly transmitted to the slope of neighboring inclination. This phenomenon account for the flow of CO_2 ice from the slopiest ground to the flat ground. We found during that taking into account the CO_2 flow has an important impact on simulations concerning the time needed to reach an equilibrium when changing the obliquity.

3. Initial parameters and simulations

Although we have accurate models and observations of the present Mars' environment, estimating it for very different obliquities remains a difficult task. To obtain rough estimates of what Mars looks like with a certain obliquity, we carried out preliminary simulations with constant values of orbital parameters. Those simulations provided us with initial states for further simulations in which we took into account the variation of orbital parameters.

3.1. Preliminary simulations

As a first step, we ran our model without excentricity and with constant obliquities ranging between 0° and 15° for 10000 years. The initial state for those simulations corresponds to present Mars, with obliquity 25.2° and excentricity 0.05.

3.2. Reference simulations

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