Mars at very low obliquity: Atmospheric collapse and the fate of volatiles

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[1] The obliquity of the Martian spin axis is known to undergo quasiperiodic oscillations superposed over chaotic long-term variations. It is probable that within past history there were geologically long periods when the obliquity oscillated around low (10–15°) mean values. During such low obliquity epochs the climate system is controlled by deposition of permanent solid CO_2 deposits in the polar regions. With a simple season-resolved energy balance model, we show that as the atmosphere collapses, surface topography plays a major role in CO_2 condensation and sublimation processes, defining distribution and dynamics of CO_2 deposits. Thick CO_2 deposits are formed at steep pole-facing topographic slopes at moderately high latitudes, not at the poles. The total mass of the deposits is not a function of obliquity, but strongly depends on the pre-history of the climate system. We outline criteria to identify such low-obliquity epochs in Mars history.
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1. Introduction

[2] It has long been understood that the spin axis and orbit of Mars change with time [e.g., *Ward*, 1992], and that these secular variations strongly influence the climate of the planet through variations in the spatial and seasonal insolation pattern [e.g., *Kieffer and Zent*, 1992]. Variable parameters that control the insolation are: spin axis obliquity θ, orbit eccentricity ε, and, for epochs of large eccentricity, season of perihelion, which can be quantified as areocentric longitude of the Sun from the moving equinox at perihelion L_P. Among these three parameters, θ has the strongest impact on the latitudinal distribution of the year-average insolation, and through it, on global climate characteristics. It oscillates quasi-periodically about its mean value with a period of ~0.12 Ma. The amplitude of these oscillations also varies quasi-periodically with a period of ~1.2 Ma and reaches ~±10°. The mean obliquity, in turn, experiences wide variations at the ~5 Ma time scale. In the present epoch, the mean obliquity is ~25° and the oscillation amplitude is in its minimum. The mean obliquity came to the present value from larger values, ~35° 10 Ma ago [e.g., *Laskar et al.*, 2004].

[3] The evolution of the orbit and spin of Mars is dynamically chaotic [*Laskar et al.*, 2004]; it cannot be traced by calculation back in time farther than ~10–20 Ma ago. *Laskar et al.* [2004] performed a series of long-term calculations with slightly different initial conditions and used the results to infer the long-term statistics of obliquity and eccentricity. They found that the typical obliquity was higher in the Martian geological past than the present. On the other hand, in the calculated time series there are numerous examples of geologically long periods (10s or even 100s Ma) when obliquity oscillated about values as low as 10°–15° (low obliquity epochs).

[4] It has long been understood that at low obliquity, collapse of the atmosphere occurs because insolation of polar regions is very low and the atmospheric pressure is buffered by permanent solid CO_2 deposits at the poles. The dependence of pressure on obliquity can be found to a first order from a simple radiative balance model assuming that the year-average surface temperature at the pole is equal to the CO_2 frost point [e.g., *Kieffer and Zent*, 1992]. The formation of permanent CO_2 deposits under different conditions has also been studied with more detailed season-resolved radiative balance models [e.g., *Nakamura and Tajika*, 2003; *Armstrong et al.*, 2004].

[5] It has been recently recognized that periods of high obliquity left recognizable traces in the surface morphology of Mars primarily due to migration of H_2O ice deposits [e.g., *Head et al.*, 2003, and references therein]. In this paper we address possible geological effects during low obliquity epochs. We consider the effect of low atmospheric pressure, and then we analyze the distribution and possible geological effects of permanent CO_2 deposits.

2. Surface Conditions at Low Obliquity

[6] During a low-obliquity epoch Mars spends the low-obliquity phases of the obliquity cycle with the atmosphere collapsed, undergoing geologically long exposure to extremely low-pressure conditions. When almost all atmospheric CO_2 condenses in the polar regions, the residual Ar - N_2 atmosphere has a pressure of 0.25 mbar. Although this pressure is in the domain of a high laboratory vacuum, the atmosphere still has the properties of a real atmosphere rather than an exosphere: the molecular free path is still much smaller than the characteristic atmospheric height. Such an atmosphere still shields the surface from the majority of solar wind protons and high-speed interplanetary dust particles. This means that the processes of regolith formation and maturation typical for atmosphere-free bodies do not occur on Mars during these periods.

[7] Another effect of very low atmospheric pressure is the increased susceptibility of the surface to small meteorites. *Hörz et al.* [1999] described a 25-cm impact crater on a rock at the Pathfinder landing site and estimated that this is

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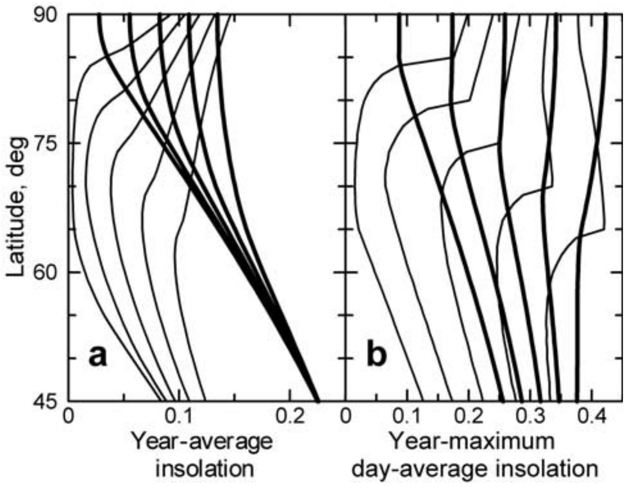

Figure 1. The year average insolation (a) and the year-maximum day-average insolation (b) relative to the Martian solar constant as a function of latitude. Bold curves correspond to a horizontal surface; thin curves correspond to 30° steep pole-facing slopes. Curves, left to right, correspond to obliquity θ = 5, 10, 15, 20, 25°. Eccentricity ε = 0 is assumed.

about the smallest crater that can be formed with the present atmosphere. Geologically long exposure to low atmospheric pressure would lead to formation of a population of 10-cm-size and smaller craters.

3. Distribution and Dynamics of Perennial CO_2 Deposits

3.1. The Role of Surface Topography

[8] Surface slopes strongly affect the local insolation regime; their effect is especially significant at low obliquity and high latitudes because the Sun is always low, and insolation is very sensitive to the tilt of the surface. For example, Figure 1 compares the latitudinal profiles of the year-average and year-maximum day-average insolation for a horizontal surface and steep pole-facing slopes. Calculations show that at low obliquity the steep pole-facing slopes at moderately high latitudes are the coldest places on the planet. We therefore expect that when atmospheric collapse occurs the most massive solid CO_2 deposits should reside in these places.

[9] To check and assess this idea and to understand better the nature and distribution of solid CO_2 deposits at low obliquity, we constructed a simple energy balance model tracking condensation and sublimation of CO_2. Similar models were applied for the martian climate system in a number of studies, e.g., *Nakamura and Tajika* [2003] and *Armstrong et al.* [2004]. Our main advance relative to these models is that we consider surface slopes. Although our model is less accurate than the global climate models, it allows us to understand the principal effects, provides an overview of the influence of the principal parameters, and produces calculations for long time spans on modest computers.

3.2. Model

[10] Our model considers only two CO_2 reservoirs: the atmosphere and solid deposits at the surface. The model resolves seasons, latitudes, and surface slopes. For each time step, each latitude, and each surface tilt and its orientation, we calculate the rate of condensation ($dM/dt > 0$) or sublimation ($dM/dt < 0$) from the energy balance, which involves release or consumption of sublimation latent heat, thermal radiation, and insolation:

$$\frac{dM}{dt}L = E\sigma_{SB}T^4_{CO_2} - (1 - A)S, \qquad (1)$$

where M is the column mass of solid CO_2 per unit area, t is time, T_{CO2} is the CO_2 frost point at a given pressure, S is the day-average insolation, E is effective thermal infrared emissivity, A is the visible albedo, L is the sublimation latent heat, and σ_{SB} is the Stefan-Boltzmann constant. We track the column mass M of solid CO_2 in time; of course, M cannot be negative, and no further sublimation occurs when there is no solid CO_2 on the surface.

[11] Atmospheric pressure P is necessary to obtain the frost point. We calculated P for each time step from the net mass balance:

$$a\frac{P}{g} + \int_{\mathrm{Mars}} M\,\mathrm{d}a = M_{total}, \qquad (2)$$

where g is gravity, a is total area of the planetary surface, integration is over the surface area where solid CO_2 may reside, and M_{total} is the total inventory of CO_2. We take M_{total} to be equivalent to 8 mbar pressure, close to the present-day atmosphere plus seasonal caps. We accounted approximately for the frost point difference due to the altitudinal pressure lapse by making the pressure 30% higher than the "nominal" P from (2) for the northern polar region, and 30% lower for the southern.

[12] The quantities that depend on slope are insolation S and effective emissivity E. The day-average insolation S for a tilted surface for a given season, latitude and obliquity was calculated by simple numerical integration. The effective emissivity E of a surface tilted at angle γ is lower than for a horizontal surface by a factor of $\cos^2(\gamma/2)$, accounting for a part of the "cold" sky shielded by the "warm" surface.

[13] For the choice of slope distribution, the model results strongly depend on the proportion of steeply tilted surfaces, which in turn, strongly depend on scale. The meter-scale topography would be strongly modified by seasonal CO_2 frost, and even larger scale roughness will be smoothed by multi-year accumulation. Because of this, the best scales are decameters and hectometers. There are no systematic slope data at the decameter scale. For hectometer scale, we used MOLA data at ~200 m resolution for 67.7–86.5° latitudinal zones in both hemispheres. Outside these zones the resolution of MOLA data is not as good, and we assumed flat horizontal surfaces, which does not noticeably influence the results. Steep hectometer-scale slopes are generally rare at high latitudes, however, there are 20–25° steep walls in several large craters and some other features, as well as numerous 10–20° steep slopes on dunes and many other objects.

[14] Since our model is intentionally simplified, and our aim is to evaluate the effect of topography qualitatively rather than to model climate quantitatively, we did not adjust parameters to best reproduce the present climate. Our model, however, correctly reproduces the amplitude of

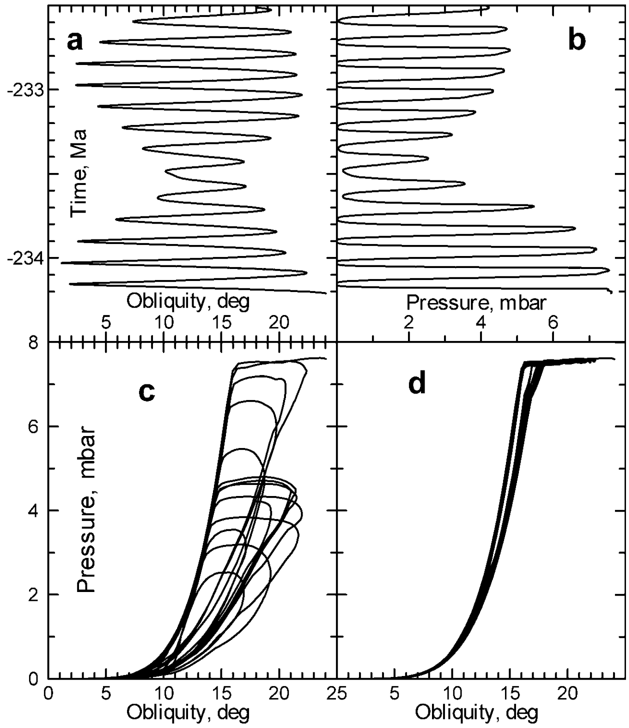

Figure 2. (a) An example of the ~2 Ma long history of obliquity oscillations during a low-obliquity epoch. The data are taken from one of the calculation series from [*Laskar et al.*, 2004]. (b) Modeled history of year-maximum atmospheric pressure for the same obliquity history as in (a). Model calculations for a "rough" planet were done for a total CO_2 inventory equivalent to 8 mbar, albedo A = 0.65 and emissivity of horizontal surface E = 0.95. (c) Pressure from (b) plotted against obliquity from (a). (d) The same as (c), but for a "smooth" planet.

seasonal pressure variations, the extent of the seasonal polar caps and their thickness. The model results, especially the onset obliquity of perennial CO_2 deposit formation, depend on the choice of albedo A and solid CO_2 emissivity. This dependence has been analyzed in detail by *Armstrong et al.* [2004] and our results show complete qualitative agreement and quantitative similarity.

[15] Our model runs start from the initial condition where all available CO_2 is in the atmosphere. We trace its condensation and sublimation with a time step of ~4 martian days, season by season, year by year. We took a 1.7 Ma long sample evolution of θ, ε, and L_P from a low-mean-obliquity segment of one of the spin/orbit evolution calculation runs from *Laskar et al.* [2004]. The obliquity history for these calculations is shown in Figure 2a. The history of year-maximum atmospheric pressure in one of our model runs is plotted in Figures 2b and 2c. The pressure simultaneously characterizes the total amount of perennial CO_2 at the surface. For comparison, Figure 2d shows the same results for a "smooth" planet, without surface slopes.

3.3. Model Results

[16] After a few simulated years a steady seasonal cycle is established; the year-maximum pressure is a little smaller than the total CO_2 reservoir because of the lifetime overlap of seasonal caps in the two hemispheres. When decreasing obliquity reaches a certain onset value (16° for the run in Figure 2), the lifetime of one of the seasonal caps reaches the entire year, and accumulation of perennial CO_2 deposits starts. With further obliquity decrease, the accumulation progresses until finally total atmospheric collapse occurs. This decreasing branch of the evolution is similar for a "smooth" and a "rough" planet (Figures 2c and 2d). On the "smooth" planet, two compact (~200 km across) thick polar caps are formed. On the "rough" planet, however, the spatial distribution of CO_2 deposits is very different: the major mass is concentrated at pole-facing slopes in rough terrains, the northern cap is much thinner, and the southern cap is absent. The latter is not a universal result; by changing model parameters and/or ε and L_P history, we can obtain either two thin caps or no caps.

[17] When obliquity increases, the restoration of the atmosphere goes much slower for a "rough" planet than in the "smooth" case; the characteristic time scale is a few thousand years in comparison to a hundred years for the "smooth" case. Two factors cause this. First, at the early net sublimation phase, the topography-related cold traps are still very cold, and along with net CO_2 sublimation from weakly tilted surfaces there is ongoing condensation in the deep cold traps, which does not occur on the "smooth" planet. Second, at a later stage of obliquity increase, when perennial CO_2 on weakly tilted surfaces completely disappears, the residual solid CO_2 is concentrated in thick deposits in the former cold traps that have a small total area; the net rate of sublimation, being proportional to the area, is still low. These factors lead to a wide hysteresis of pressure seen in Figure 2c and absent in Figure 2d, when the pressure is almost a function of obliquity.

[18] In the second obliquity cycle in our model run, the maximal obliquity was somewhat lower than in the first one; the high-obliquity phase of the cycle was too short for complete sublimation of the deposits at the steepest pole-facing slopes at 70–75° latitude, and a small but noticeable part of the CO_2 inventory survived the obliquity maximum in solid state. These deposits were thickened in the next oscillation. The total mass trapped became significant, and no perennial deposits were formed at the poles even at the obliquity minimum. When the model went through several small-amplitude obliquity cycles, the CO_2 deposits progressively migrated from less effective to more effective cold traps, and huge thicknesses of solid CO_2 accumulated in the most effective cold traps. Later in the simulation, when the amplitude of obliquity oscillations and the maximal obliquity increase, almost half of the total CO_2 inventory remained in solid state at the obliquity maximum, and the initial situation with no perennial deposits was not restored.

3.4. Model Applicability

[19] The model does not consider the regolith reservoir of adsorbed CO_2; however, *Armstrong et al.* [2004] showed that it has no effect on perennial CO_2 cap formation. The model does not deal with any albedo variations and as noted by *Armstrong et al.* [2004], varying albedo alone can lead to a wide pressure hysteresis. Thus, although we have strong confidence in the qualitative conclusions, the model should not be considered a quantitative prediction.

[20] The model does not include a feedback between CO_2 deposition and topography and implicitly assumes infinite capacity of the cold traps. The cold traps associated with small features would be filled quickly, and the steep slopes would disappear. The most effective traps, however, turned out to be associated with high (>1 km) pole-facing walls of large impact craters. Accumulation of CO_2 at these walls might lead to progressive fill of the craters reproducing the steep slopes of the deposits. Special local-scale models will be necessary in order to assess whether deposition progresses in this way.

[21] The principal qualitative results we obtained are that during low-obliquity epochs (1) massive solid CO_2 deposits are formed on steep pole-facing slopes at moderately high latitudes rather than at the poles, and (2) the distribution of these deposits and atmospheric pressure are not simple functions of obliquity, but crucially depend on the geologically long pre-history of these deposits and climate variations.

4. Discussion

[22] Epochs of low mean obliquity could produce two types of geological evidence. The first is decimeter and smaller impact craters. Detection of such crater populations would identify geologically long periods of atmospheric collapse in the past. Documented absence of small craters together with a good understanding of resurfacing processes may put a lower age limit on the most recent low obliquity epoch.

[23] A second type of geological evidence would be produced by solid CO_2 preferentially deposited at cold traps. The seasonal few- meter-thick solid CO_2 deposits leave no apparent traces. The deposits on steep pole-facing slopes, however, could be much more massive. Dry ice is mechanically weaker than water ice; for very thick deposits the liquid CO_2 phase can play some role; density contrasts between liquid and solid phases are very different for CO_2 and H_2O; all these factors may make geological evidence left by CO_2 deposits very different from terrestrial and martian H_2O glaciers.

[24] Thus, morphologic traces of CO_2 deposits will not necessarily be easy to recognize. One possible indication of their presence may be systematic differences between the morphology of slopes of different orientation. At 75–80° latitude, the insolation patterns of pole- and equator-facing slopes are significantly different only at low obliquity. Thus, if a north-south asymmetry of morphology of crater slopes at high latitudes were found, this would indicate a process operating at low obliquity.

[25] Our model shows that thick solid CO_2 deposits associated with steep slopes can survive until obliquity increases to rather high values, up to an obliquity similar to the present value. At the present obliquity summer-time sublimation of H_2O from the icy polar caps occurs, as on the present-day Mars. Solid CO_2 deposits under these conditions, being at the CO_2 frost point temperature, will work as effective traps for water vapor. This would lead to the formation of H_2O ice deposits in association with sublimating CO_2 deposits. High-albedo H_2O frost would decrease the CO_2 sublimation rate and the CO_2 deposits would last longer, accumulating more H_2O ice. Layers of CO_2 buried by H_2O ice could metamorphose to form clathrate hydrates. These hypothetical deposits of H_2O ice and clathrates would be more thermally stable than CO_2, might survive epochs of high obliquity, and could leave more well-expressed morphological traces. Solid CO_2 deposits themselves could not survive the recent high-obliquity epoch that ended 5 Ma ago.

[26] Several large craters at high latitudes have very specific dome-shaped deposits in their interiors. These craters are located in exactly the same latitudes where our model predicts maximal accumulation of solid CO_2 during low-obliquity epochs. The largest deposit of this kind is in Korolev crater in the northern high-latitude region. Similar deposits in a number of craters in the south polar region are smaller. Typically these domes are not in the crater centers, but closer to their pole-facing walls. The morphology of these deposits suggests icy material, and they were interpreted as remnants of formerly larger polar caps [*Russell and Head*, 2005]. Alternatively, we can suggest that these deposits are the strongly modified H_2O-rich deposits formed in association with solid CO_2 accumulation at low obliquity. *Russell et al.* [2004] presented a local-scale model of the sublimation dynamics of such deposits and showed that the absence of icy material from the crater walls is a natural consequence of the local thermal regime at the present obliquity. Further advances in modeling of this kind might help to distinguish between these two modes of origin for these deposits. If these deposits indeed originated during the last low-obliquity epoch, they could be the place where the oldest ices on the planet can be found relatively close to the surface.

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