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A reanalysis of water abundances in the Martian atmosphere at high obliquity

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[1] We take a new look at expected atmospheric water vapor abundances on Mars during periods of high obliquity using the Geophysical Fluid Dynamics Laboratory Mars General Circulation Model. For the first time, the sublimation and burial of the present-day residual polar caps beneath a sublimation lag is considered as the planet shifts from lower to high (45°) obliquity periods. Following the elimination of the polar deposits, the only sources for atmospheric water at high obliquity are the low latitude ice deposits emplaced prior to elimination of the polar source. Annual average water vapor abundances are predicted to be only ~20–80 prμm during extended periods of high obliquity, one to two orders of magnitude less than previous estimates. This has implications for the climate history of the planet as it suggests that during extended periods of high obliquity, there is not a significant greenhouse warming effect from elevated atmospheric water vapor. **Citation:** Mischna, M. A., and M. I. Richardson (2005), A reanalysis of water abundances in the Martian atmosphere at high obliquity, *Geophys. Res. Lett.*, *32*, L03201, doi:10.1029/2004GL021865.

1. Introduction

[2] Over periods of tens of thousands to millions of years, the orbital cycles of Mars significantly modify the climate and force the redistribution of surface and near-surface water from the poles to the tropics and back. Models of the obliquity cycle suggest that over the past 10 My, Martian obliquity has ranged from as low as 15° to as high as 50° (the present-day value is ~25°) [*Touma and Wisdom*, 1993; *Laskar and Robutel*, 1993]. Recent work by *Laskar et al.* [2004] indicates that over the past 4 Gy, the most probable obliquity of Mars was 45°, thus the "standard model" for Mars is one significantly different than the present, with cold, icy poles and warm, dry tropics. It is difficult to picture a planet that has gone "through the looking-glass"—in which this paradigm is turned on its head—where it freezes at the equator and bakes at the poles. Our general perception of where ice ought to typically "be" on a planet is shaded by the current presence of ice exclusively in the polar regions of both Earth and Mars.

[3] Attempts have been made to eliminate this "polar bias", first, notably, by *Jakosky and Carr* [1985] who illustrated, using a 1-D model, that water ice would preferentially form in the tropics during periods of high obliquity due to increased cap temperatures at the poles. These elevated temperatures would increase the amount of vapor sublimed off the summer hemisphere cap (up to 5000 prμm at 45° obliquity, compared to ~100 prμm today), which would migrate equatorward to the colder tropics and condense out on the surface as perennial ice deposits.

[4] More recently, *Mischna et al.* [2003] reexamined the problem using the Geophysical Fluid Dynamics Laboratory (GFDL) Mars General Circulation Model (GCM), a 3-D model with the capability to trace the Martian atmospheric water cycle through various orbital states. The results by *Mischna et al.* [2003] generally confirmed those of *Jakosky and Carr* [1985] and found that at high obliquity (>40°), surface ice was preferentially deposited in the tropics at the expense of the polar caps.

[5] Despite clearly demonstrating the formation of ice caps in the tropics while at high obliquity, both models still make the implicit assumption that there will be a perpetual source of water from the polar caps, even after extended periods at high obliquity, when polar ice will be extremely unstable, hence they still retain some measure of the "polar bias". (This bias is not a fault of the models, but of the modelers!) It has been argued that after sustained sublimation, small amounts of dust contained in the ice would accumulate to yield a lag [*Jakosky et al.*, 1993, 1995; *Mischna et al.*, 2003]. If this, indeed, were to happen, the cap would "switch off" as a vapor source. (Given the rates of sublimation estimated from polar sources at high obliquity, in the absence of lag formation they would fully exhaust quite rapidly–of order 10^4 years–also leading to the termination of the source.) The water cycle corresponding to such a state should be examined, as it would likely correspond to much lower atmospheric vapor abundances. Here, we assume the development of such a lag deposit (or, equivalently, ice sheet exhaustion) "shuts off" the polar caps, and reexamine the expected vapor abundance during these conditions.

2. The Model and Initial Conditions

[6] Details of the GFDL Mars GCM have been published elsewhere [*Wilson and Hamilton*, 1996; *Wilson*, 1997; *Wilson and Richardson*, 2000; *Richardson and Wilson*, 2002; *Richardson et al.*, 2002; *Mischna et al.*, 2003]. Briefly, the model includes full CO_2 and H_2O cycles and has radiatively active, seasonally varying atmospheric dust. Water is treated as a passive tracer in the model except when

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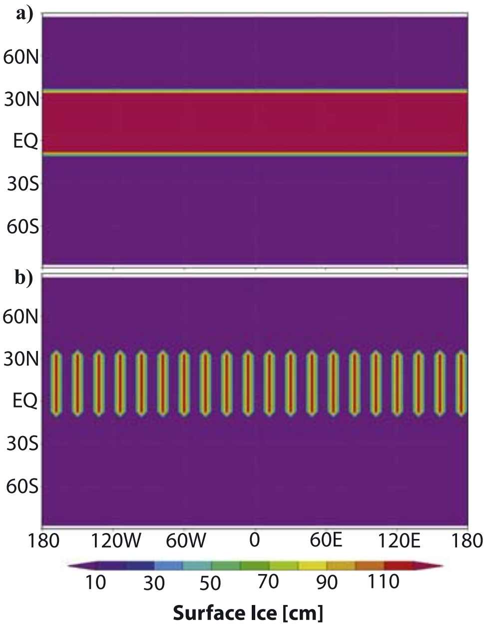

Figure 1. (a) Initial distribution of surface ice (in cm) for simulation TI. (b) Same as (a) but for simulation PI.

it condenses on the surface as ice, when the surface albedo is modified accordingly. For contemporary conditions, we generally need not worry about heating by water vapor, as the radiative and latent heating effects on the atmosphere are negligible. There is concern, however, that under high obliquity conditions, the atmospheric vapor content can be sufficiently large to have a noticeable warming influence [*Jakosky and Carr*, 1985; *Jakosky et al.*, 1995; *Mischna et al.*, 2003]. We show here that this may not be as large of an issue as once believed.

[7] As an initial condition, we establish a single, uniform ice band of arbitrary (but essentially infinite) thickness spanning 10°S to 40°N (Figure 1a). The ice-covered surface is modified to exhibit the thermal properties of thick ice cover (high thermal inertia, high albedo). The residual polar caps have been removed, and replaced with soil having typical circumpolar surface properties. Seasonal caps are still permitted to form. The choice of latitude band is based on results for present-day eccentricity ($\varepsilon = 0.096$) and perihelion ($L_s = 251°$) from Figure 7a of *Mischna et al.* [2003], which indicate this to be the preferred region for surface ice to form. Over the full precession cycle, the ice band will more evenly straddle the equator, but will not affect the overall results. Our choice of a circumferential ice band is an extreme scenario, and provides us with the greatest exposed surface area for subsequent vapor sublimation.

[8] The model is initialized to start from the end of the 34-year simulation s45 [*Mischna et al.*, 2003, Figure 7b], which is in steady state. The polar caps are removed and the tropical ice belt introduced. The model is then run out until a new steady state is reached.

3. Results

[9] Simulation TI (“total ice”) was run for 7 Martian years, by which point it had achieved a steady-state atmospheric vapor abundance. We simultaneously ran simulation PI (“partial ice”), with most of the tropical ice belt removed, leaving a periodic ice deposit covering only one-third of the surface (Figure 1b). Simulation PI represents, in a very coarse way, the type of patchy ice deposits found by *Mischna et al.* [2003], and the conditions we would find first in the transition from lower to high obliquity.

[10] Figure 2 shows the last few years of simulation s45 along with the results from simulation TI (Figure 2a) and PI (Figure 2b). We see that the steady-state obtained in TI has substantially lower water vapor abundance than s45. Water vapor peaks in the northern polar region at 600 prμm, while tropical vapor peaks at about 80 prμm. Both values are a factor of 5–6 lower than found in s45. Over the course of the year, the global mean average is 50 prμm, one-quarter the value determined from *Mischna et al.* [2003] and nearly a factor of 100 lower than *Jakosky et al.* [1993, 1995]. These values agree with the modeled summertime temperatures in the high obliquity source region. Under present-day conditions, polar vapor peaks at ~100 prμm for a diurnally averaged polar temperature of about 220 K. At high obliquity, tropical vapor peaks at ~80 prμm for a somewhat lower average temperature of 205 K. This is significant, as it suggests that high obliquity periods in Mars' past may not be as “warm and wet” as previously expected if a protective lag forms on the polar residual ice cap or the cap is fully exhausted.

[11] For simulation PI, ice covers only one-third of the surface, yielding zonally averaged values of albedo and thermal inertia lower than in TI (influenced specifically by the ice-free locations). The reduction in these values allows daytime near-surface air temperatures to be warmer, resulting in a slightly greater daytime atmospheric abundance

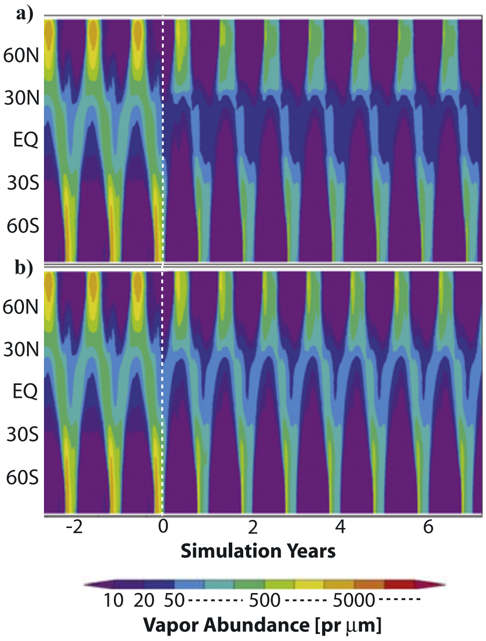

Figure 2. (a) Time evolution of zonally-averaged atmospheric vapor abundance (in prμm) for 3 years of simulation s45, followed by 7 years of simulation TI. Surface ice is instantaneously removed from poles and added to tropics at time 0. (b) Same as (a) but for simulation PI.

relative to TI, but not substantially. The global mean average is ~75 prμm, still significantly lower than previous estimates of the tropical vapor abundance.

4. Discussion

[12] The arguments in this paper relate to a state in which the polar water ice sheets are inactive at high obliquity. This may involve complete sublimation or the formation of a protective sublimation dust lag that forestalls such exhaustion. The latter may occur substantially earlier than the former, and would allow buried, and potentially layered, ice deposits to remain protected at the poles for a very long time. Would sublimation lags form? Such behavior is seen on Earth [*Johnson and Lorenz*, 2000; *Marchant et al.*, 2002] and has been hypothesized to occur on Mars as well [*Toon et al.*, 1980; *Hofstadter and Murray*, 1990; *Mischna et al.*, 2003; *Head et al.*, 2003]. Observations of the polar caps and circumpolar deposits show the presence of dust. Indeed, by their very nature, the polar layered deposits (PLD) are comprised of layers of varying dust concentration. The abundance of dust, however, is uncertain, and hence an uncertainty exists as to how quickly or even whether a lag would form. Elsewhere on the planet, indurated, dusty layers in the mid-latitudes are believed to be the remnants of once ice-rich deposits formed during high obliquity periods [*Mustard et al.*, 2001]. There is some reason, then, to expect that as the polar caps sublimate, they would leave behind a dusty residue. However, we cannot discount the possibility that all of the residual dust will be carried away by aeolian processes.

[13] In order to obtain a diffusively insulated sublimation lag, the thickness of the dust needs to be on the order of 1 m [*Hofstadter and Murray*, 1990]. The amount of ice required to build a lag deposit of this thickness depends on the dust fraction of the ice. If we were to assume a 10% dust concentration [*Toon et al.*, 1980; *Hofstadter and Murray*, 1990] this requires the sublimation of 10 m of polar ice to develop the necessary dust lag (or 100 m for 1% dust; 1 km for 0.1% dust). The length of time required to build such a deposit is uncertain, and depends not only on the dust fraction, but the geometry of the dust material as well, yet we can establish bounds based upon sublimation and diffusion models of the polar caps. Both *Toon et al.* [1980] and *Mischna et al.* [2003] estimate that at high obliquity (45°), it would take ~30–50 years to sublimate 10 m of dust-free polar ice (or ~10^2 years and ~10^3 years for 100 m and 1 km, respectively). All of these times are short compared with orbital cycles. Indeed, the formation time for a 1 m lag from a 10% dust content ice may be too rapid–concentrations of 0.1–1% dust are more consistent with the removal of a sufficient thickness of ice from the north polar cap during the last high obliquity excursion to satisfy the low crater retention ages of the north polar cap [*Herkenhoff and Plaut*, 2000].

[14] Best-guess estimates as to the pore size and geometry of Martian soil provide a diffusion coefficient of order 10^{-4} m^2/s [*Zent et al.*, 1993; *Mellon and Jakosky*, 1993]. Such values suggest that even for an overly cold assumption of the high obliquity polar summertime surface temperature (200 K), a dust lag of 1 m thickness will form within 5 × 10^4 years [*Toon et al.*, 1980]. Considering that the high obliquity mean summertime polar temperature is ~50 K greater than this, the dust lag likely forms on the order of several 10^3 years. In addition, the contribution to warming made by the initially increased vapor abundance in the atmosphere will serve to accelerate the rate of sublimation, and reduce the time to create the lag deposit.

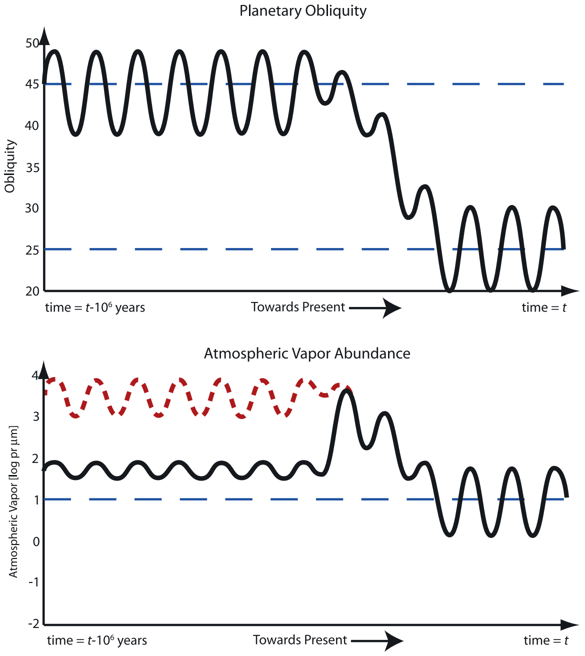

Figure 3. (top) Cartoon illustrating evolution of Martian obliquity to time *t* from a point ~10^6 years prior. Time approaches present going towards the right. This approximates the recent trend, but not the exact obliquity behavior of Mars. (bottom) Cartoon of globally-averaged atmospheric vapor abundance (black line) corresponding to obliquity value above. Present-day value is ~10 prμm. Dashed red line approximates the behavior with a dust-free, limitless polar supply of ice found in previous models. Atmospheric vapor abundance does not fall off with time.

[15] This has implications for obliquity cycles during which high obliquity periods are reached for only short periods of time. Presently, and for the past 4 My, periods of high obliquity are reached only fleetingly (thousands of years). Under these conditions, a sublimation lag does not have sufficient time to fully insulate the polar cap, and throughout this period there will be a steady release of vapor from the polar caps to the atmosphere. These are the conditions where the water cycle is at its most vigorous—water ice is stable in the tropics, but also resides (albeit unstably) at the poles. Such behavior would be expected to last for a few thousand years at most, until such point as the obliquity decreases once again.

[16] What, then, of Mars' more ancient past, when obliquities were as large as 80°, and persistently 'high'? Prior to 5 Ma, the mean Martian obliquity was 35°, with excursions as high as 50°. Though the orbital parameters of Mars become chaotic beyond ~20 Ma, analysis by *Laskar et al.* [2004] find that the obliquity may very well have been even higher for much of Mars' past, with a most likely value of 45°. In this case, with an extended period of high polar summertime temperatures, when either a sublimation lag

forms permanently or the residual ice cap is completely sublimated, the only source of atmospheric water will be the tropical deposits. This is the situation modeled in Figure 2, where atmospheric water is low and the polar caps are absent. There is little to prevent this situation from happening on long time scales with high mean obliquity.

[17] What this means is that the atmospheric vapor distribution will evolve even while fixed in a particular obliquity regime. In the case presented here, for the first several thousand years (at most) of high or increasing obliquity, the atmosphere will have very high water abundance, as the unstable polar caps sublime. As time progresses, the amount of water available in the atmosphere will steadily decrease as the polar source dries up, until it reaches a value only marginally higher than we find for contemporary conditions (Figure 3), being fully supported by the tropical ice belt.

5. Conclusions

[18] We show that the current assumption that high obliquity means high atmospheric vapor abundance is not always correct and for extended periods of high obliquity cannot be correct. Under more recent conditions, when obliquity only flirts with higher values, large vapor densities could be expected. While the residual ice cap remains an active vapor source, atmospheric vapor abundances can be as high as predicted by previous models. However, the polar caps should not be expected to remain indefinitely active, which lowers estimates of atmospheric vapor by as much as two orders of magnitude. Because of the reduced influence of water vapor in the high obliquity atmosphere, climate models of ancient Mars might not require substantial modifications (of water vapor radiative and latent heating effects) to provide valid predictions. This is independent of greenhouse warming caused by a thicker CO_2 atmosphere, which *will* increase the atmospheric vapor density through increased global temperatures.

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