THE ROLE OF OBLIQUITY, WATER VAPOR AND TRACE GAS GREENHOUSES ON THE EARLY MARTIAN CLIMATE

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Introduction:

There is substantial geologic and geochemical evidence that points to an early Mars that was substantially warmer and wetter than at present day [e.g. 1,2]. However, the mechanism by which the climate of Mars was maintained in this warm, wet state remains elusive. We present here a review of work in [3] that suggests an interaction between the orbital state of Mars, atmospheric water vapor and other trace gases, which serves as a possible mechanism for producing globally warm temperatures in Mars' past.

There have been a number of approaches to explaining how warm conditions (i.e. >273 K) could be met on early Mars, ranging from simple, thicker, CO_2 atmospheres to more complex mixtures of increasingly 'exotic' trace gases. Nearly all suffer from complications of one form or another that largely preclude the possibility of them achieving warm conditions, further augmented by the reduced solar luminosity of the young Sun [4,5] (resulting in the so-called "faint young Sun" paradox).

Thicker CO_2 atmospheres are warming to an extent, but once above a surface pressure of a few bars, increased Rayleigh scattering reduces the downward shortwave flux at the surface, compensating for the greenhouse warming imparted by the CO_2. Various other gases under consideration suffer, too, from fatal flaws that preclude their ability to act as key components of the early martian climate. Gases such as ammonia and methane [6,7] have short photochemical lifetimes, which require steady replenishment from an indeterminate source in order to maintain any extended greenhouse role. Organic hazes [8] are unlikely to be produced in significant quantities in an oxidizing martian atmosphere, whereas sulfur dioxide [3, 9-11] is highly soluble and may precipitate quickly. More recently, warming contributions from hydrogen gas (H_2) and the corresponding collision-induced absorption occurring in a hydrogen-rich atmosphere (on the order of 5-20% H_2) has been speculated as a possible warming mechanism, especially early in Mars' evolution [12]. More heterogeneous mechanisms have also been employed; the presence of IR-scattering CO_2 ice clouds [13-15] has been proposed, but requires a large fractional cloud cover that may prove difficult to obtain. In [16] it has been shown that strategically placed water ice clouds on early Mars could also provide warming, although only under very specific conditions.

Background:

In the present day, the martian climate is regulated chiefly by planetary obliquity, or axial tilt, which is presently 25°. Obliquity oscillates on timescales of ~10^5 years and, within the past 20 Myr, has ranged between 15°-45° [17]. For periods prior to this, the system is sufficiently chaotic that exact obliquities cannot be determined, although it has been suggested that, statistically, martian obliquity would have had a mean value of ~45°, ranging from nearly 90° down to 0°. The practical consequence of these changes in obliquity on present-day Mars is that the location of thermodynamic stability of water ice on the surface migrates equatorward as obliquity increases. For obliquities above ~45°, ice is stable at the equator. Regardless of the recent obliquity, however, temperatures in a thin CO_2 atmosphere like the present are sufficiently cold that water vapor plays an inconsequential role in setting the planetary temperature.

It should be no surprise, then, that obliquity would have had an influence on climate throughout Mars' history, as far back as the Hesperian and Noachian epochs, when the atmosphere was thicker, and the climate warmer. In general, at higher obliquities, regardless of the underlying atmospheric mass, the atmosphere will be wetter, as polar reservoirs are exposed to increasing summertime insolation [18]. As obliquity approaches zero, the martian poles will serve as dark, perennial cold traps, resulting in the condensation of atmospheric CO_2 to the point of global atmospheric collapse and sharply reduced global temperatures. This periodic collapse serves as something of a temporal control on climate, as we shall see.

Conceptually, the control of obliquity on temperatures during the three martian epochs is illustrated in Figure 1. The top row shows a portion of an (identical) obliquity cycle, from high to low obliquity, for each epoch. The bottom row shows temperature as a function of the aforementioned obliquity, reflecting, qualitatively, the influence of increased levels of water vapor at high obliquity on surface temperatures, and the consequent drop in temperatures as obliquity evolves to lower values. For comparison, in red, the temperature cycle from a purely CO_2 atmosphere is indicated (temperatures are lower at high obliquity in this case because of the increased surface area covered by tropical bright ice at high obliquity). Presently, in the Amazonian, mean temperatures are always too cold for liquid water, regardless of obliquity state. The role of water vapor is always inconsequential. As one moves back in time into the Hesperian, and assumes a thicker CO_2 atmosphere, the 'baseline' global mean temperature would be somewhat higher, as would the peak amount of radiatively active atmospheric water vapor, resulting in periods at high obliquity where temperatures, augmented by both CO_2 and H_2O, could be considered 'warm'. When obliquity drops below some critical threshold, most H_2O is lost from the atmosphere and the climate returns to a 'cool' state. Even further back in time, during the Noachian, 'baseline' temperatures may have been at or near the melting point for nearly the entire obliquity cycle, regardless of the vapor content of the atmosphere.

So obliquity plays a key role in regulating temperatures, and especially so during the Hesperian, when mean average temperatures were neither "too warm" as in the Noachian (resulting in perpetual liquid water), nor "too cold" as in the Amazonian (resulting in perpetual ice); when epochal conditions were "just right", migration through an obliquity cycle could effectively switch on and off the ability to generate a 'warm' atmosphere.

This obliquity-driven mechanism can be augmented further by the injection of additional greenhouse trace gases in the atmosphere. The most obvious source of these gases would be from periodic volcanic activity, which could release an assortment of radiatively active greenhouse gases, including CH_4, SO_2, H_2S, and H_2. The incremental warming introduced by these gas releases would further increase surface temperatures beyond the influence of water vapor alone. However, their influence, as with water vapor, is ultimately controlled by the obliquity state. As we shall see, the influence of the aforementioned trace gases is modest, at best, under concentrations plausibly introduced by large-scale volcanic activity. Therefore, it may be only a few, periodic, very significant volcanic events that can actually have a substantive influence on global temperatures. Periodic spikes in global surface temperature indicate those short periods where these processes are all 'in phase' causing temperatures to increase above their background levels. Once one or more of these factors becomes out of phase, temperatures return to their previous values. As the level of volcanism has been steadily decreasing with time, the magnitude of these warming events has been correspondingly decreasing, as there is less and less in the way of radiatively active greenhouse gases being introduced into the more recent Mars atmosphere. This idea runs somewhat counter to the widely held notion that Mars, as a whole, has been experiencing a steady, secular decrease in global temperatures, with perhaps only regional increases in temperature due to local subsurface heating.

Model Results:

Simple Greenhouse Models: To perform the tests in this study, the MarsWRF general circulation model (GCM) [19] was used, incorporating an improved radiative transfer code that can accommodate multiple absorbing gases, and which uses a *k*-distribution radiative transfer method. Details of this scheme are found in [20]. The choice of atmospheric composition to represent putative early Mars conditions is based on prior work by [21], which investigated the warming influence of sulfur species (SO_2 and H_2S) in thick CO_2 atmospheres. To replicate the most significant warming atmospheres, a CO_2 atmosphere of 500 mb was used, with a fixed, uniform SO_2 mixing ratio of 2.45×10^{-4}. To reflect the reduced solar luminosity earlier in Mars history, we use a 'faint young Sun' parameter of 0.75. The MarsWRF GCM is then run forward for two martian years, with surface temperatures determined from the second year.

Results of the basic simulations trend as expected. For a 500 mb CO_2-only atmosphere, the global/annual mean surface temperature is ~218 K (Figure 2a), which is, coincidentally, near the present-day mean temperature. The level of greenhouse warming nearly exactly offsets the reduction in solar luminosity. The warming influence of water vapor is small if the water cycle is allowed to evolve naturally using the internal model physics and dynamics (the 'standard' case)—only about 3 K (Fig. 2b). If one prescribes a globally and perpetually saturated atmosphere in the model (an extreme situation, indeed), the warming by H_2O is increased to about 10 K (Fig 2c).

The addition of SO_2 to an otherwise dry CO_2-only model increases temperatures by about 18 K (Fig. 2d), indicating that SO_2 is a significant warming agent in the atmosphere. This warming influence is compounded by the inclusion of water vapor (both 'standard' and saturated), as the two gases do not have significant overlap in their absorption spectra. Warming above the CO_2-only baseline for these two simulations is 20 K and 28 K, respectively (Figs. 2e,f). However, even in the most warming scenario, the globally averaged temperature still only reaches ~247 K, well below the nominal melting point of water ice. This is further seen in Figure 3, which shows the percentage of the year for which temperatures exceed 273 K for each of the same six simulations. Under nearly every plausible condition, one generally finds 'warm' temperatures for <10% of the year, and, in most locations, for <1%. Only in the most extreme case of CO_2, SO_2 and a saturated atmosphere do we find any regions with warm temperatures approaching 40% of the year. At the warmest location on Mars, the annual average temperature approaches 270 K, suggesting that localized melting, rather than global, may be possible for simply the right combination of atmospheric gases.

A Peculiar Behavior: During the analysis of results for thick CO_2 atmospheres with and without trace gases, an interesting observation was noted. Panels 'b' of Figures 2 and 3 represent conditions for a 500-mb CO_2 atmosphere with the 'standard' water cycle. Panels 'c' of these same figures represent conditions for the 'saturated' simulation. It was assumed that, by maximizing the levels of radiatively active water vapor in the atmosphere, resultant surface temperatures would be greatest, and the likelihood of obtaining temperatures conducive to liquid water would be maximized.

As seen before, the first of these two assumptions does bear out—by increasing the water vapor abundance in the atmosphere, annually averaged temperatures do increase. However, a comparison of panels b and c in Figure 3 show that, while, on an annual basis, temperatures increase, the overall fraction of time for which temperatures exceed 273 K actually *decreases* with an increase in atmospheric water vapor. For the 'standard' water cycle, only portions of the southern hemisphere exceed 273 K, generally for <5% of the year, although the base of Hellas may reach these 'warm' temperatures for as much as 15% of the year. When the atmosphere is saturated, however, this fraction drops to <1% over nearly all of the planet—only at the bottoms of the Hellas and Argyre Basins are there any appreciable durations with temperatures above 273 K.

The consequences of this for generating and sustaining liquid water are notable. While it is difficult to do so under any circumstances, the assumption that maximizing the quantity of water vapor in the atmosphere will yield the greatest likelihood of producing liquid water is a faulty one and should be avoided.

What causes this behavior? One can clearly see in Figure 4a that the amount of shortwave flux reaching the southern hemisphere (summer) surface in the saturated case (dashed line) is markedly less than for the 'standard' case (solid line); therefore, this flux must be lost from the downwelling stream prior to reaching the surface. One can plot the zonally averaged temperature difference between the two cases as a function of height for each latitude band (there are 36) from the GCM (Figure 4b). Here, positive values represent where the saturated case is warmer than the 'standard' case. Solid curves represent profiles in the southern hemisphere and dashed curves, the northern hemisphere. In both hemispheres, down to about the 10 mb level, there is little difference between the two atmospheric states—both provide the same level of warming. However, as one proceeds deeper into the atmosphere, values in the southern hemisphere turn negative, indicating a cooler saturated atmosphere compared to the 'standard' one. Below ~200 mb, this trend reverses (in both hemispheres), however the higher elevation in the south intersects the southern hemisphere curves before they swing back positive, resulting in a near-surface atmosphere that is colder in the saturated case than non-saturated. In the north, which is in winter at this time, the level of water vapor is low and it is ineffective as a greenhouse agent. It becomes clear, then, that "too much" water vapor in the atmosphere scatters increasing amounts of the downwelling shortwave stream, preventing it from reaching and warming the surface. (As this behavior only manifests itself below the ~10 mb level, it is inconsequential in the present-day atmosphere).

Surface Properties: The aforementioned simulations all assume present-day surface properties, but is this assumption a good one? While it is plausible that bright, dusty conditions have been present on Mars since the earliest epoch, it is at least equally plausible that early conditions were sharply different. For one, the shorter period of time over which aeolian erosion would have taken place suggests that the surface was less physically weathered and, consequently, less bright than today. Further, it is unclear what the level of chemical weathering on early Mars would have been. Were the atmosphere to be less oxidizing, oxidative weathering would have been suppressed. Additionally, many end products of chemical weathering tend to be brighter than their source materials. Together, this points to a darker early Mars surface.

There is compelling observational evidence that surface liquid water and precipitation occurred earlier in Mars history, through at least the Noachian/Hesperian boundary, if not later. In order to sustain precipitation would require a surface source of liquid water. It has been suggested that a large northern ocean may have existed in the northern lowlands for indeterminate periods [22,23]. If this is the case, it should be noted that liquid water, too, has a low albedo and would yield an apparently darker surface, with perhaps a stronger influence on water vapor in the atmosphere. Figure 5 shows surface temperatures obtained for simulations that assume a darker northern hemisphere. The results show that simply by reducing surface brightness, it becomes possible to sustain temperatures above 273 K throughout most of the northern hemisphere for 50-100% of the Mars year. Were this the case, the presence of a large body of surface water might be self-sustaining and resist freezing, at least until the next drop in obliquity.

Conclusions:

It is, indeed, difficult to obtain warm temperatures on Mars with only atmospheric greenhouse warming, but it is not impossible. Several factors can improve the likelihood of such conditions. First, obliquity needs to be sufficiently high so as to provide areas on the surface that can reach initially high temperatures and allow for a substantial amount of water vapor into the atmosphere. Second, the presence of a radiatively active trace gas can enhance the warming conditions. Third, darker surfaces, which will reflect less incoming sunlight, can also enhance the likelihood of warm temperatures. When two or more of these conditions overlap in time, Mars may experience brief but intense periods of atmospheric warming, chiefly regulated by the 100,000-year obliquity cycle. So long as obliquity is sufficiently high, this mechanism will operate. Once it drops below a threshold value, the warming will cease. The reduction in volcanic activity over time on Mars has reduced the injection of greenhouse gases into the atmosphere, making the frequency and intensity of occurrence less and less as we approach the present day.

References: [1] Craddock and Howard, JGR, 107, 2002; [2] Hoke and Hynek, JGR, 114, 2009; Mischna et al., JGR, 118, 2013; [4] Gough, Solar Phys., 74, 1981; [5] Sackmann and Boothroyd, Ap. J., 583, 2003; [6] Kuhn and Atreya, Icarus, 37, 1979; [7] Kasting, JGR, 87, 1982; [8] Sagan and Chyba, Science, 276, 1997; [9] Postawko and Kuhn, JGR, 91, 1986; [10] Yung et al., Icarus, 130, 1997; [11] Tian et al., Earth Planet. Sci. Lett., 295, 2010; [12] J. Kasting, personal comm.; [13] Forget and Pierrehumbert, Science, 278, 1997; [14] Mischna et al., Icarus, 145, 2000; [15] Forget et al., Icarus, 222, 2013; [16] Urata and Toon, Icarus, 226, 2013; [17] Laskar et al., Icarus, 170, 2004; [18] Jakosky and Carr, Nature, 315, 1985; [19] Richardson et al., JGR, 112, 2007; [20] Mischna et al., JGR, 117, 2012; [21] Johnson et al., JGR, 113, 2008; [22] Parker et al., Icarus, 82, 1989; [23] DiBiase et al., JGR, 118, 2013.

Figures:

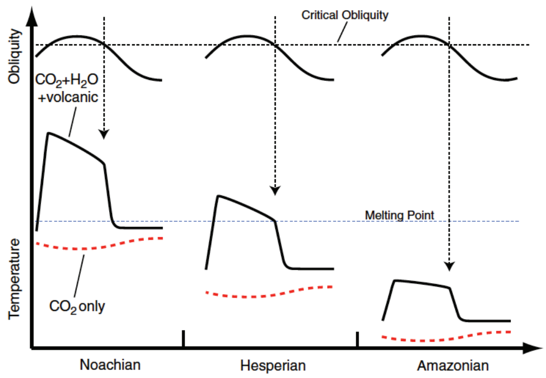

Figure 1: The role of water vapor in each of the three martian epochs for the same portion of an obliquity cycle. When obliquity is high, water vapor levels can increase, resulting in warmer conditions until obliquity again drops below a critical level. Closer to present, baseline temperatures are too cold to allow water vapor-induced warming at any obliquity. Early in Mars history, such warming may have been persistent regardless of obliquity.

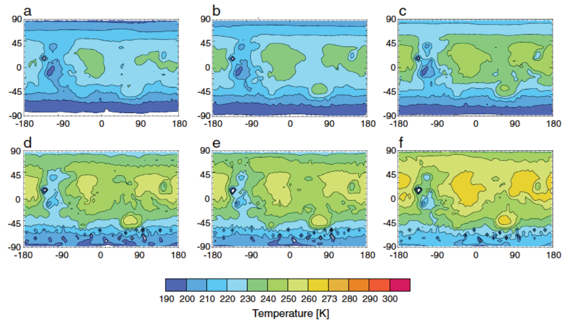

Figure 2: Mean annual surface temperatures for a 500 mb CO_2 atmosphere (panel a), with a 'standard' water cycle (b), saturated atmosphere (c), with SO_2 (d), with SO_2 and a 'standard' water cycle (e) and with SO_2 and a saturated atmosphere (f).

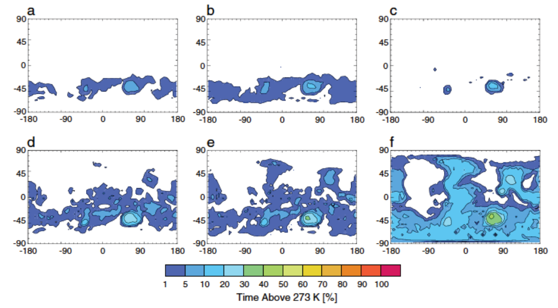

Figure 3: Fraction of the year for which surface temperatures exceed 273 K. As in Figure 2.

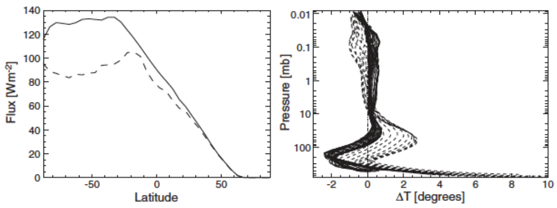

Figure 4: (left) Zonally averaged downward visible solar flux during southern summer solstice for 'standard' (solid) and saturated (dashed) cases. (right) Zonally averaged temperature difference between the 'standard' and saturated cases. Positive values indicate where the saturated atmosphere is warmer than the 'standard' water cycle. There are 36 profiles corresponding to the 36 latitude bands in the GCM. Solid lines (18) are profiles in southern hemisphere, dashed lines (18) in the northern hemisphere.

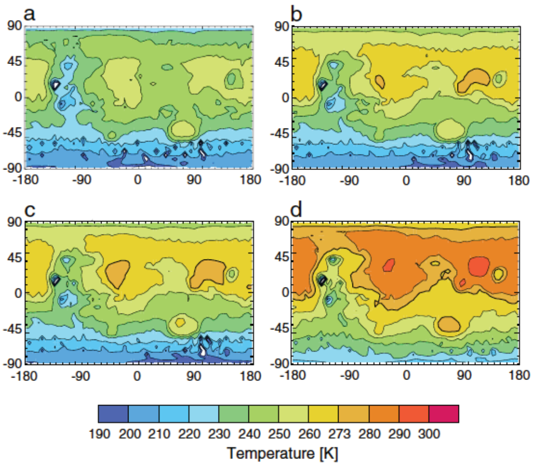

Figure 5: Mean annual surface temperature for a 500 mb CO_2 atmosphere with 'standard' water cycle and SO_2 (a). With northern hemisphere albedo fixed at 0.12 (b), and 0.08 (c), 0.08 with saturated atmosphere (d). Thicker contour represents the 273 K isotherm.