CLIMATE SIMULATIONS OF RECENT CLIMATE CHANGES ON MARS

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Introduction: Over the past several years, we have performed a wide array of martian climate simulations studying the state of the high obliquity atmosphere, particularly with respect to atmospheric water. Previous work in this area (Jakosky and Carr, 1985) suggested that in contrast to the dry atmospheric conditions of the present day, the high obliquity atmosphere would have 2-3 orders of magnitude more water vapor, making for a wetter, and therefore warmer, climate. Mischna *et al.* (2003) confirmed the calculations of Jakosky and Carr (1985) by using the GFDL Mars GCM to trace the martian water cycle under a variety of orbital states. The water cycle in this model was basic, and considered water (as either vapor and ice) to be pure, without any contamination by or influence of atmospheric and surface dust. These results, then, described a more idealized Mars, without the strong driving effect of dust in the atmosphere or an active regolith. Here, we wish to present several different investigations we have pursued using the results of Mischna *et al.* (2003) as a springboard, with the ultimate goal of developing a more realistic understanding of the behavior of the martian water cycle.

Subsurface Ice: Based upon simple thermal arguments, it was shown that ice in the martian subsurface is unstable equatorward of ~40° latitude (Leighton and Murray, 1966; Paige, 1992; Mellon *et al.* 2004). The Odyssey GRS instrument observed that the uppermost tropical subsurface is, indeed, quite dry relative to the ice-rich deposits found poleward of 60° (Feldman *et al.* 2002; Boynton *et al.* 2002; Mitrovanov *et al*. 2002), with no more than a few percent water by weight in the lower latitudes. Assuming even a modest porosity (20-40%) and soil properties akin to those inferred by Viking, the regolith has an enormous capacity to trap and store water (as ice, adsorbate and vapor), hence the instantaneous formation of surface ice deposits (seen in Mischna *et al.,* 2003) should be considered as an "end member" case with respect to the speed at which surface deposits will form. More likely, the presence of a large, relatively dry water reservoir will act to slow the development of surface ice deposits. A demonstration of this behavior has been shown numerically with the GFDL Mars GCM plus an additional subsurface diffusion scheme.

The 1-D regolith code we have developed follows the formulation of Mellon and Jakosky (1993) and Houben *et al.* (1997), and allows us to trace the movement of the vapor, solid and adsorbed phases of water through the subsurface as well as their overall abundances. To calculate adsorbate density, we use an isotherm commonly used for basaltic material, which is a simple function of temperature, vapor density and surface composition (Zent *et al.* 1993). Our choice of isotherm was based largely upon the need for an equation that is numerically tractable and a good approximation to the behavior of typical martian soil (see Houben *et al.*, 1997 for further discussion). The primary advantage of this work over that of Mellon and Jakosky (1993, 1995) is our ability to track the subsurface vapor diffusion cycle directly, and for multiple years. The results generally confirm those of previous authors, but also reveal some interesting behavior during the transition between 'low' and 'high' obliquity phases that, for example, the original model in Mischna *et al.* (2003) did not capture.

Given an initially dry regolith at lower latitudes which represents present-day conditions, as obliquity is raised, surface ice deposits become difficult to support (Figure 1). We find that water is very quickly pulled down into the subsurface and stored as ice, particularly in those locations with the lowest conductivity (which will have the lowest mean diurnal temperatures *plus*, most likely, a highly diffusive composition). As long as the regolith has not saturated, the strong temperature gradient is quite efficient at driving water vapor to deeper levels. Figure 1 illustrates the efficiency with which the midlatitude regolith can draw down water vapor. The first three years of the simulation do not contain an active regolith, and show the slow growth of tropical ice at 45° obliquity much in the same way as Mischna *et al.* (2003). At the start of year three, the regolith is introduced, and within a decade, nearly all extant surface ice has been removed and drawn into the subsurface. This can be seen as the opposite "end member" simulation to that in Mischna *et al.* (2003), one with a maximally effective regolith sink. The subsurface is preferred to the surface as the place to store "excess" water from the atmosphere. During the summer season, when the surface is warmer than below, the vapor gradient drives water deeper into the subsurface. During winter, an opposite gradient occurs, which draws water back towards the surface. Because of the non-linearity of vapor pressure with temperature, the wintertime gradient is weaker than its summer counterpart, providing a net annual downward flux.

This behavior is different than what we observe at low obliquity, where a thin layer of surface ice reappears every year as far equatorward as 40° latitude. Under current climate conditions in the polar regions, vapor is not efficiently pulled into the regolith because of the short length of the summer season (when the vapor gradient between surface and depth would be greatest) and the generally cool temperatures, limiting the strength of the vapor gradient and making the entire system rather lethargic. The result is that there is a much slower annual migration of water into the regolith, with much more subsurface water residing close to the surface. Under present-day conditions, there will be an excess of water that cannot penetrate into the regolith, which will be deposited as wintertime surface ice instead.

What this suggests, then, is that during the migration to high obliquity, it may take substantially longer for surface ice deposits to form in the lower latitudes than suggested in Mischna *et al.* (2003) because of the efficiency with which the regolith can draw-down water. This combined with the results of Mischna and Richardson (2005) found in the next section, suggest that the high obliquity atmosphere may be much drier than initially assumed, and may place constraints on the formation of low-latitude surface ice deposits.

High Obliquity Atmospheric Vapor: The amount of water vapor present in the atmosphere has a significant effect on the rate of surface ice formation in the tropics at high obliquity. Conventional wisdom assumes that exposure of the polar caps to warmer temperatures at high obliquity will drive a more vigorous water cycle and flood the atmosphere with substantially more water vapor than the present-day (up to 10,000 prμm). However this assumption dismisses the role of a polar sublimation till that will likely form after the near-surface—and therefore most mobile—ice has been lost to the atmosphere. Unless the polar cap is composed of pure ice, which, from observations, is doubtful, continued buildup of this lag deposit will shut off the polar caps as a source for atmospheric water, leaving as the only remaining source, that ice which is at or near the surface in the lower latitudes, and which was emplaced prior to the cessation of polar sublimation (Mischna and Richardson, 2005).

Other than a transient period of increased vapor abundance during the initial "loss period", extended high obliquity vapor abundances will be low, perhaps only a few times larger than present-day values (Figure 2). Depending on the amount of polar ice that can get released into the atmosphere, there may be significantly less water to develop tropical ice deposits than previously assumed. This type of inhibition can be countered through aeolian or other erosion of the polar lag deposit, exposing deeper volatile reservoirs.

Clouds and Precipitation: To this point, we have seen two possible ways in which a more realistic representation of the near-surface environment modifies and potentially slows the formation of a wetter global climate at high obliquity. These mechanisms are, to first order, independent of the model being used, and provide insight into questions of the timing of low latitude ice deposit formation. To answer the question of *where* exactly these low latitude deposits might form, we need to tread more delicately into model-dependent behaviors. As has been discussed elsewhere (Mischna *et al.,* 2003), the two primary influences on ice deposition are the surface thermal properties (most importantly, thermal inertia) and topography. The relative proportion of these two influences is dependent upon the local dynamics of the atmosphere and how it controls precipitation. A major uncertainty in model precipitation—and likely a consequential one—is the way in which ice particle size is determined, as this is what controls the rate of precipitation. To explore this uncertainty, we have run a series of identical simulations except for changes to the assumed gravitational settling flux in the model, which we scale across two orders of magnitude. As the model allows cloud particles to sublime as they descend through drier layers below, a decrease in the time for a particle to reach the surface may confine the precipitation to more localized regions on the surface. We follow the method of Haberle *et al.* (1982) and Conrath (1975) for determining the sedimentation rate of spherical atmospheric aerosols following the Stokes-Cunningham relationship.

Results from these simulations (which do not contain a regolith) in Figure 3 show that as the fall speed in increased, the observed distribution of surface ice shifts dramatically. Increases in the fall rate act to enhance the deposition of surface ice on the Tharsis rise at the expense of the high thermal inertia regions. (Note, in the absence of a regolith, surface ice deposits are preferentially formed on *high* thermal inertia regions. See Mischna *et al.*, 2003 for a discussion.) The absence of surface ice on the high thermal inertia regions is a direct result of the Tharsis rise acting as a physical barrier to water vapor and cloud ice. As the fall rate is increased, condensation on Tharsis is sufficiently vigorous that water is essentially "trapped" by the topography. This increased drawdown of water inhibits the occurrence of supersaturated regions elsewhere in the tropics. The water trapping on Tharsis is two-fold: the high precipitation rates gets substantial water onto the surface, but it is the subsequent modification of albedo that locks the water there by greatly reducing the daytime surface temperatures and sublimation rates. We suggest that this mechanism is largely responsible for the differing surface ice distributions between GCMs (*cf.* Mischna *et al.*, 2003; Forget *et al.* 2005), although the formation of ice deposits on Tharsis seems a robust result from all models as well as observations.

Conclusions: Under idealized conditions, the transfer of surface ice from high to low latitudes during obliquity transitions is a quick and tidy process. Unfortunately, the martian surface environment is not quite so simplistic, and the ubiquitous presence of dust (in the atmosphere and comprising the regolith) has the overall effect of slowing down this process in ways that general circulation models have yet to satisfactorily accommodate. Here we have shown three ways in which we can significantly affect the timing and distribution of surface ice in the low latitudes following transitions from lower obliquities. In all cases, a more realistic accounting of surface and atmospheric properties acts to slow down the formation of surface ice deposits. Observational evidence (*e.g.*, Christensen, 2003; Head *et al.* 2005) clearly shows the presence of contemporary surface ice deposits, or convincing evidence that such deposits previously existed, so these retarding mechanisms likely do not completely inhibit the formation of low latitude surface ice, however, by knowing how these mechanisms operate, we can begin to set constraints on the timing and distribution of these surface deposits.

References: Boynton *et al., Science*, 297, 81-85, (2002); Christensen, *Nature*, 422, 45-48, (2003); Conrath, *Icarus*, 24, 36-46, (1975); Feldman *et al.*, *Science*, 297, 75-78 (2002); Forget *et al., Science, in press,* (2005); Fu and Liou, *J. Atmos. Sci.*, 49, 2139-2156 (1992); Haberle *et al., Icarus*, 50, 322-367, (1982); Head *et al.*, *Nature*, 434, 346-351, (2005); Houben *et al.*, *J. Geophys. Res.*, 102, 9069-9084, (1997); Humlicek, *JQSRT*, 27, 437-444, (1982); Jakosky and Carr, *Nature*, 315, 559-561, (1985); Lacis and Oinas, *J. Geophys. Res.*, 96, 9027-9063, (1991); Leighton and Murray, *Science,* 153, 136-144, (1966); Mellon and Jakosky, *J. Geophys. Res.*, 98, 3345-3364, (1993); Mellon and Jakoksy, *J. Geophys. Res.*, 100, 11,781-11,799, (1995); Mellon *et al., Icarus,* 169, 324-340, (2004); Mischna and Richardson, *Geophys. Res. Lett.* 32, L03201, doi:10.1029/2004GL021865 (2005); Mischna *et al., J. Geophys. Res.*, 108(E6), 5062, doi:10.1029/2003JE002051, (2003); Mitrofanov *et al., Science*, 297, 78-81, 2002; Paige, *Nature*, 356, 43-45, (1992); Zent *et al., J. Geophys. Res.*, 98, 3319-3337, (1993)

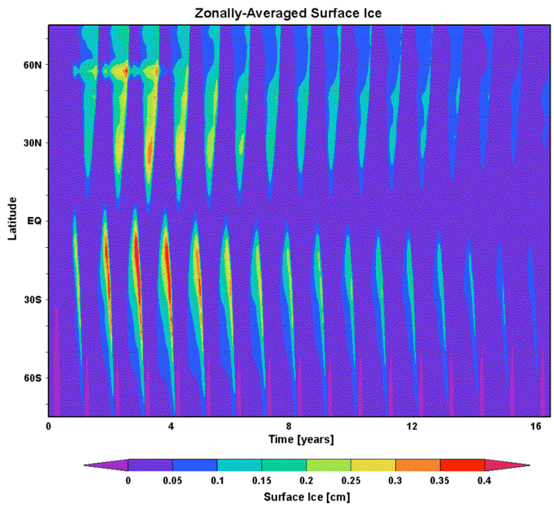

Figure 1: Seasonal growth and recession of zonally averaged surface water ice deposits for 16 Mars years at high obliquity (45°). After year three, the previously inert regolith is activated and surface ice is quickly drawn down into the subsurface, removing previously emplaced surface ice deposits.

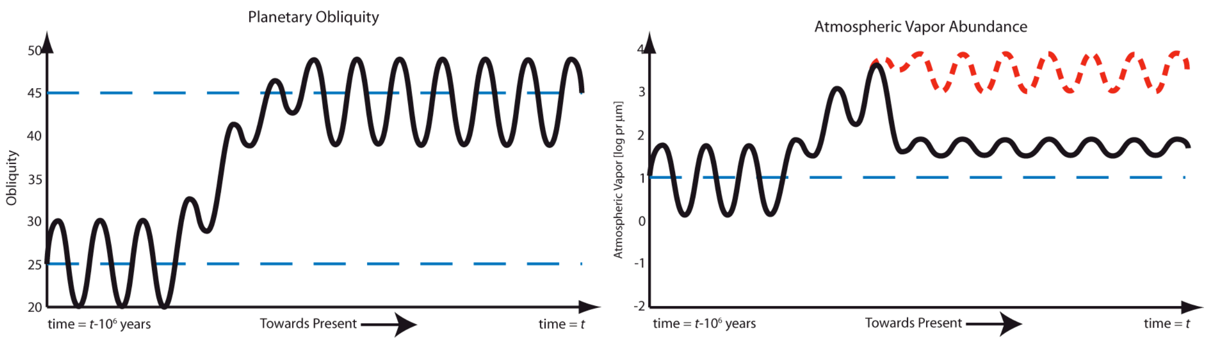

Figure 2: (Left) Cartoon illustrating evolution of martian obliquity to time *t* from a point ~10^6 years prior. Time approaches present going towards the right. This approximates the type of periodic obliquity shift we might expect during Mars' history. (Right) Cartoon of globally-averaged atmospheric vapor abundance (black line) corresponding to the obliquity value at left. Present-day value is ~10 prμm. After an initial spike in atmospheric vapor, the abundance falls off to near-present day values. 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.

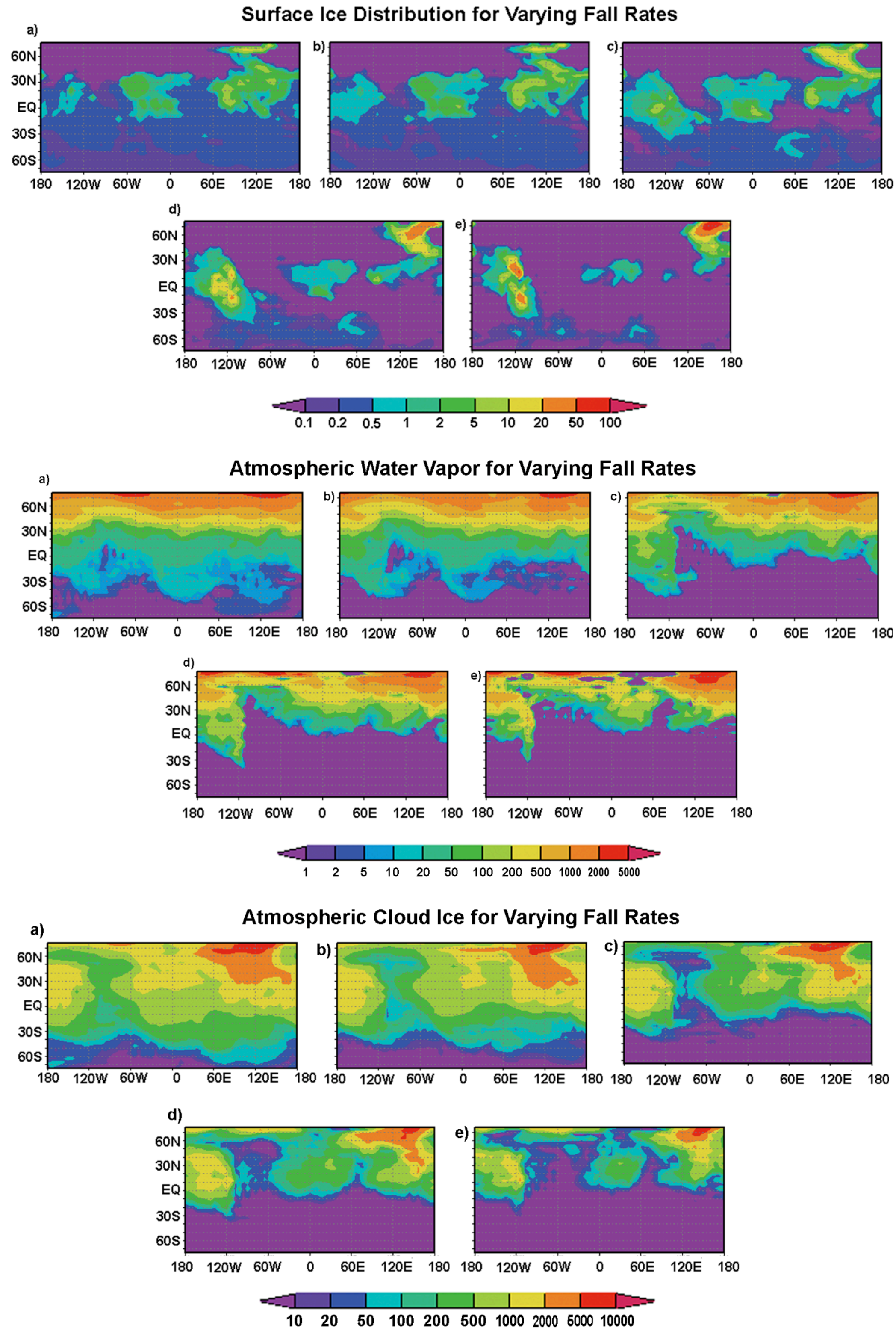

Figure 3: (Top) Surface ice distribution for high obliquity (45°) GCM simulation without a regolith and with increasing atmospheric fall rate (a to e). Difference in fall rate from a to e is ~20x. (Middle, Bottom) Corresponding atmospheric water vapor abundance and cloud ice distribution for the fall rates in top panels. As the fall rate increases, the topographic influence of Tharsis is more clearly seen, with the large mountains "squeezing" water from the atmosphere, leaving generally drier conditions on the leeward side, and reducing the amount of surface ice that is deposited in these locations at the expense of the windward side of the volcanoes. Note the "wall" of vapor that is formed at ~120°W as a response to Tharsis.