Thursday, October 16, 2003
Morning Session I
RECENT CLIMATE CHANGE ON MARS: MODELING RESULTS
8:15 a.m. Victoria Room

REVIEW OF THE DAY'S AGENDA

Haberle R. M. * Montmessin F. Forget F. Spiga A. Colaprete A. [INVITED]
Obliquity Driven Climate Change in Mars' Recent Past **[#8060]**

Wilson R. J. * Richardson M. I. Smith M. D.
The Polar Regions and Martian Climate: Studies with a Global Climate Model **[#8123]**

Levrard B. Laskar J. Forget F. * Montmessin F.
A GCM Recent History of the Northern Martian Polar Layered Deposits **[#8096]**

Mischna M. A. * McCleese D. J. Richardson M. I. Vasavada A. R. Wilson R. J.
Polar and Non-Polar Layers on Mars: A Single Mechanism for Formation? **[#8007]**

GENERAL DISCUSSION

10:15 – 10:30 a.m. BREAK

OBLIQUITY DRIVEN CLIMATE CHANGE IN MARS' RECENT PAST.

R.M. Haberle[1], F. Montmessin[1], F. Forget[2], A. Spiga[3], and A. Colaprete[4]. [1]Space Science Division, MS 245-3, NASA/Ames Research Center, Moffett Field CA, 94035, Robert.M.Haberle@nasa.gov. [2]Laboratoire de Météorolgie Dynamique, Universite Paris, 4 pl. Jussieu, 75252 Paris Cedex 05-FRANCE, forget@lmd.jussieu.fr. [3]Ecole Polytechnique, 91128 Palaiseau, Cedex FRANCE, Aymeric.Spiga@polytechnique.org. [4]SETI Institute, Space Science Division, MS 245-3, NASA/Ames Research Center, Moffett Field CA, 94035, tonyc@freeze.arc.nasa.gov.

Introduction: To explain the equatorial valley networks on Mars, Jakosky and Carr [1] suggested that water ice now stored in the north polar region would be mobilized at high obliquity and precipitate out at low latitudes. Extrapolating the present day latitudinal distribution of water vapor to high obliquity conditions, and noting that the low latitude atmosphere would be saturated, they predicted substantial surface ice deposits would accumulate in the tropics at such times.

The first general circulation model simulations to verify this prediction were reported by Haberle et al. [2] who found that while ice can accumulate at low latitudes at high obliquity, it is distributed regionally depending on orbital conditions. Forget [3], Richardson and Wilson [4], and Mischna et al. [5], subsequently obtained similar results with independent models. Thus, obliquity driven climate change may help explain the many tropical landforms thought to be sculpted by water in one form or another (see, for example, refs [6], [7], and [8]).

While low latitude ice accumulations at high obliquity appears to be a robust result, the major challenge now facing models is predicting ice accumulations in the same places where the geological evidence suggests it occurred. This will depend not only on orbital conditions, but also on what physical processes the models include in the hydrological cycle. For example, none of the models mentioned above include the radiative effects of water vapor or clouds, yet both are expected to be in abundance at high obliquity. And none of the models has a very realistic cloud microphysics scheme, which can have a significant effect on how clouds affect the planet's radiation balance.

Here we extend these early modeling results by including a more sophisticated cloud microphysics package, as well as the radiative effects of water vapor and clouds.

Model description: We use the NASA/Ames C-grid Mars general circulation model with an updated radiation code and cloud microphysics scheme. To speed up the simulations, we run the model at fairly coarse resolution (7.5° latitude x 22.5° longitude). Future efforts will examine the effect of resolution on the results.

Radiation Code Fluxes and heating rates are calculated from a radiation code based on the two-stream solution to radiative transfer that fully accounts for multiple scattering in the presence of gaseous absorption. The model has 12 spectral intervals. Dust and water ice scattering properties are included. For dust, we use the Ockert-Bell [9] values in the visible, and Forget [10] values in the infrared. For ice, we can either compute them online as the cloud evolves, or we can specify them. Gaseous opacities for water vapor and CO_2 are calculated from correlated k-distributions taken from full line-by-line models.

Cloud Microphysics Our cloud scheme is based on a moment/order scheme in which the mass mixing ratio and number density of the cloud ensemble are the advected species. From these we obtain a mean particle size and an estimate or the particle size distribution (assuming a variance) which we then divide into 8 bins. Cloud microphysics is performed in each of these bins and includes nucleation, condensation, and gravitational settling. Dust is treated as a tracer and serves as condensation nuclei. The altered size distribution is then converted back into a mean size, a mixing ratio, and a particle number density.

Results: We have conducted simulations for a variety of different obliquities, all at present solar luminosity. In each case the model is spun up from dry initial conditions with a residual ice cap at the north pole. After several years, depending on obliquity, the atmosphere equilibrates and repeats from year-to-year. A sample result for the 60° obliquity simulation, without the radiative effects of clouds or water vapor, is shown in Fig. 1. The top panel in Fig. 1 is the zonally averaged column water vapor as a function of time for 7 Mars years. The middle and bottom panels are similar, but for cloud mass and surface ice, respectively.

Water ice subliming from the north residual cap during summer is rapidly transported southward. Clouds form in low northern latitudes and ice precipitates to the surface. The remainder is transported into the southern hemisphere and condenses onto the south seasonal CO_2 ice cap which extends almost to the equator at the solstice. When the south cap retreats, water is released into the atmosphere where some precipitates back to the surface and the remainder is transported north. Again clouds form in the low latitudes and ice precipitates to the surface. At equilibrium, thousands of precipitable microns of water vapor appear in the summer polar regions. There is more water in the south than the north because the south cap is a better trap for water, and because the Southern Hemisphere is warmer during summer than in the north. Cloud abundances also reach the thousand precipitable micron mark with model predicted particle sizes in the 20-30 micron range. These particles are much bigger, and subsequently fall out faster, than those for present obliquity.

Eventually, permanent deposits form (i.e., ice remains on the ground all year long) in the low latitudes of each hemisphere. These deposits are concentrated along the northern flanks of the Tharsis region and to the northeast of the Hellas basin. Topography plays a key role on where the deposits form through its influence on the circulation. The deposits do not necessarily form in locations where the mean annual surface temperatures are a minimum. They form where the saturation state of the atmosphere is highest. This, in turn, is influenced not only by the thermal structure of the atmosphere, but also by the transport characteristics of the atmosphere.

Simulations which include the radiative effects of water vapor show similar results, but with (a) an increase in the amount of surface ice, (b) a slight shift in the location of the deposits, (c) a cooler and cloudier atmosphere, and (d) slightly warmer surface temperatures. We are presently undertaking simulations with the radiative effects of clouds included and will report the results at the meeting. However, off line 1-D simulations using the predicted cloud abundances indicate they will have a much greater influence on the results than water vapor alone. Their abundances (~ 1000 pr-µm), particle sizes (20-30 µm), widespread occurrence, and impact on the solar and infrared radiation fluxes give clouds a much greater role in determining the climate at high obliquity than for present day conditions.

Conclusions: Mars has a natural mechanism for experiencing significant climate change and redistributing surface ice. Obliquity changes alone are quite capable of moving ice into low latitudes and may provide an explanation for the many geological landforms that strongly indicate recent climate change.

References: [1] Jakosky, B.M. and Carr, H.H. (1985) *Nature, 315*, 559-561. [2] Haberle, R.M., et al. (2000) *LPS XXX1*, Abstract #1509. [3] F. Forget (2001), personal communication. [4] Richardson, M.I., and Wilson R.J., *JGR, 107,* 5031-5049. [5] Mischna, et al. (2003) *JGR*, In press. [6] Cabrol, N.A. and Grin, E.A. (2001). Icarus, 149, 291-328. [7] Kargel, J. (2001) DPS Abstract # 48.12. [8] Head, J.W. and Marchant, D.R. (2003) 6th International Mars Conference, Abstract #3807. [9] Ockert-Bell, M.E. et al. (1997). *JGR*, *102*, 9039-9050. [10] Forget, F. (1998). *GRL*, *25*, 1105-1108.

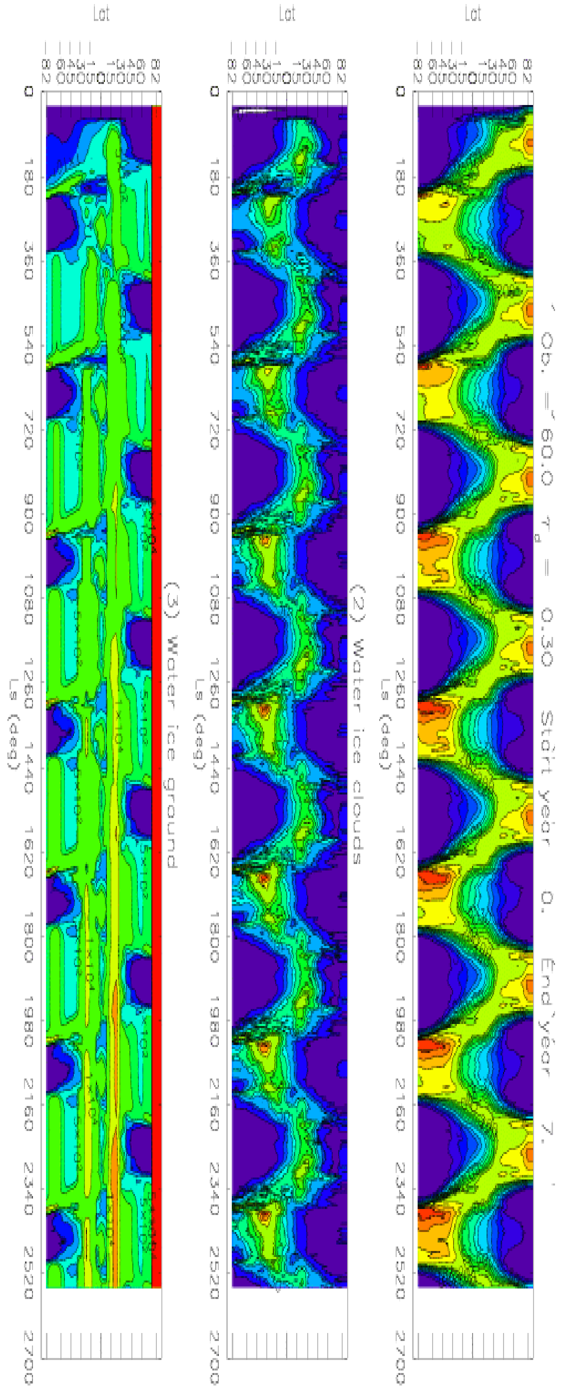

Figure 1

THE POLAR REGIONS AND MARTIAN CLIMATE: STUDIES WITH A GLOBAL CLIMATE MODEL.

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Introduction: Much of the interest in the polar regions centers on the fact that they likely contain the best record of Martian climate change on time scales from years to eons. This expectation is based upon the observed occurrence of weathering product deposits and volatile reservoirs that are coupled to the climate. Interpretation and understanding of these records requires understanding of the mechanisms that involve the exchange of dust, water, and carbon dioxide between the surface and atmosphere, and the atmospheric redistribution of these species. We will summarize our use of the GFDL Mars general circulation model (MGCM), to exploration aspects of the interaction between the global climate and the polar regions. For example, our studies [1] have shown that while the northern polar cap is the dominant seasonal source for water, it can act as a net annual source or sink for water, depending upon the cap temperatures and the bulk humidity of the atmosphere. This behavior regulates the annual and global average humidity of the atmosphere, as the cap acts as a sink if the atmosphere is too wet and a source if it is too dry. We will then focus our presentation on the ability of the MGCM to simulate the observed diurnal variations of surface temperature. We are particularly interested in assessing the influence of dust aerosol and water ice clouds on simulated surface temperature and the comparison with observations. Surface thermal inertia and albedo are critical boundary inputs for MGCM simulations. Thermal inertia is also of intrinsic interest as it may be related to properties of the surface such as particle size and surface character.

Model: The GFDL Mars general circulation model simulates the circulation of the Martian atmosphere from the surface to roughly 90 km [2]. The MGCM includes parameterizations for radiative transfer associated with CO_2 gas and for aerosols. An arbitrary number of aerosol populations can be transported by the simulated circulation. Dust may be injected at the surface using a prescribed rate and spatial distribution. We have recently added a dust source scheme that associates injection with resolved wind stresses and parameterized dust devil activity. This scheme allows the seasonal cycle of air temperatures and dust to match observations well at times when large-scale dust storms are not occurring. The model has also proven capable of simulating global dust storms with interannual variability in size and timing of occurrence. A potential source of memory for interannual variability is the spatial distribution of dust on the surface, as suggested by spacecraft and telescopic observations of interannual albedo variations. An ongoing line of research is considering the coupling of injection and sedimentation to the surface budgets of dust to investigate their role in interannual variability and assess net transport of dust onto the polar caps.

The water cycle is represented by surface ice and regolith water reservoirs, atmospheric transport and ice cloud formation [1,3]. The optical properties of predicted ice clouds can be passed to the radiative heating codes, allowing cloud radiative feedbacks and dust-water ice interactions to be examined.

Surface Temperature:

The daily and seasonal variation in surface temperature is a central element in the description of the martian climate. In the case of an optically thin atmosphere, surface temperature provides the bottom boundary condition that fundamentally influences the profile of overlying atmospheric temperature. The low thermal inertia of the Mars surface allows for the large seasonal variation in diurnal-mean surface temperature that reflects the seasonal migration of the subsolar latitude and the annual variation in insolation due to the eccentric orbit. We have used MGS TES surface temperatures and thermal inertia estimates [4,5] to derive thermal inertia and albedo maps suitable for use in the MGCM. It is important to note that estimates of thermal inertia must account for atmospheric opacity due to dust and water and CO_2 ice clouds. These effects are significant in the polar regions and will influence the characterization of the polar surfaces. By using relatively coarse spatial resolution compared to [4], we can more readily trade off spatial resolution for temporal resolution and relate the evolution of observed morning and afternoon temperatures (and thermal inertia estimates) to variations in atmospheric opacity.

Figure 1 shows the seasonal evolution of zonally-averaged daytime (2pm) surface temperature (contoured) from a reference simulation representing relatively clear sky conditions. There is a large seasonal variation in temperature that reflects the seasonal migration of the subsolar latitude and the annual variation in insolation due to the eccentric orbit. The advance and retreat of the polar CO_2 ice caps approximately follows the 150 K isotherm. It is apparent that very strong temperature gradients develop along the retreating edge of the polar caps as spring advances into summer in each hemisphere. These gradients likely give rise to strong local thermal wind systems that evidently are associated with observed local dust storm activity along the cap boundaries [*6*].

Figure 1 also shows the difference between zonally-averaged TES surface temperatures and those from a reference MGCM simulation. This figure clearly highlights the seasonal changes of observed temperatures that may largely be attributed to variations in atmospheric opacity. Temperature differences are minimal during the relatively clear NH spring/summer season when the atmospheric opacity assumed in the simulation most closely approximates that of the actual Mars atmosphere. The effects of a regional scale dust storm at $L_s=225^\circ$ in the first mapping year and a major, planet-encircling dust storm at $L_s=185^\circ$ in the second year are evident. A dusty atmosphere leads to an increase in morning temperature and a decrease in afternoon temperature.

There are systematic temperature differences in the vicinity of the polar caps. These are due, in part, to errors in simulating the polar cap latitude. Significant temperature differences are also due to the presence of dust and polar hood clouds in the vicinity of the polar caps. The aphelion season tropical water ice cloud has a clear influence on apparent tropical nighttime temperatures. We will show how simulated temperatures depend on atmospheric opacity. In a related manner, we consider how atmospheric opacity affects the determination of surface thermal inertia.

References: [1] Richardson, M. I. and Wilson, R. J. (2002) *JGR 107(E5)*. [2] Wilson, R. J. and Hamilton, K. (1996) *J. Atmos. Sci., 53*, 1290-1326. [3] Richardson, M. I., Wilson, R. J. and Rodin, A.V. (2002) *JGR 107(E9)*, 5064. [4] Mellon et al., (2000), *Icarus, 148*, 437-455. [5] Christensen et al. (2001) *JGR 106*(E10), 23823-23872. [6] *Cantor et al*. (2001), JGR 106, 23653-23687.

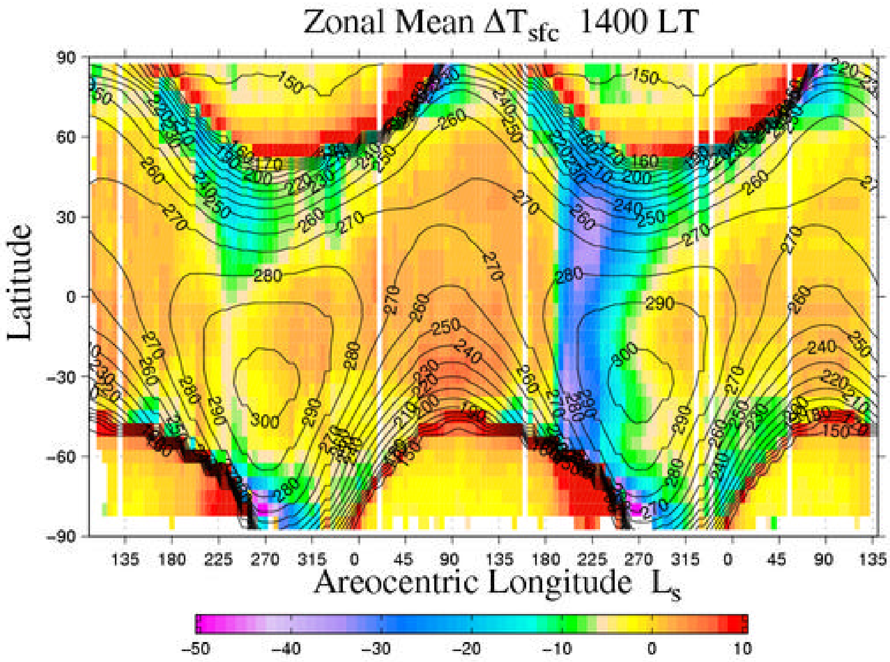

Figure 1. The seasonal evolution of zonally-averaged afternoon surface temperature anomaly derived from TES spectra. Afternoon temperatures nominally correspond to 1400 LT. Predicted surface temperatures from a MGCM simulation employing a low (τ=0.1) atmospheric dust column have been subtracted from the observed surface temperatures to highlight changes in surface temperature due to atmospheric opacity. The simulated surface temperature is contoured. A dusty and/or cloudy atmosphere leads to a decrease in observed afternoon temperature (and an increase in observed morning temperature) relative to the reference simulation. The effects of a regional scale dust storm in the first year ($L_s=225^\circ$) and a major, planet-encircling dust storm in the second year ($L_s=185^\circ$) are evident.

A GCM RECENT HISTORY OF THE NORTHERN MARTIAN POLAR LAYERED DEPOSITS.

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Introduction: The polar layered deposits are thought to contain alternate layers of water and dust in different proportions resulting from the astronomical forcing of the martian climate. In particular, long-term variations in the orbital and axial elements of Mars are presumed to generate variations of the latitudes of surface water ice stability and of the amount of water exchanged in the polar areas.

At high obliquity, simplified climate models [1] and independent general circulation simulations suggest a transfer of water ice from the north polar region to tropical areas [2, 3], whereas at lower and present obliquities, water ice is expected to be stable only at the poles. If so, over obliquity cycles, water ice may be redistributed between the surface water reservoirs leading to their incremental building or disintegration depending on the rates of water transfer. If only a relative limited amount of the available water is exchanged on orbital timescales, this may provide an efficient mechanism for the formation of the observed polar deposits.

Within this context, GCM simulations of the martian water cycle have been performed for various obliquities ranging from 15° to 45° and for a large set of initial water ice locations to determine the rate of water exchange between the surface water reservoirs as a function of the obliquity. Propagating these rates over the last 10 Ma orbital history gives a possible recent evolution of these reservoirs.

Recent obliquity history: The martian obliquity is chaotic between 0° and 60° [4] but regarding the uncertainties on the present precessional martian parameters, the chaotic behaviour is only significant beyond $\sim$ 10 Ma. Over the last 10 Ma, a new accurate obliquity solution has been recently computed (Figure 1) [5]. It shows the presence of a low mean obliquity regime ($\sim 25^\circ$) during the recent 0-5 Ma interval before a marked transition toward a higher mean obliquity regime $\sim 35^\circ$ with frequent excursions beyond 40°. Since it may represent a critical obliquity for the stability of a northern pure water cap [2], the dissymetric behaviour of the obliquity between the two regimes may have had a large impact on the recent northern terrains history.

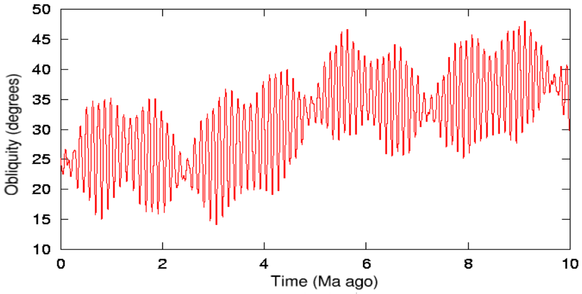

Figure 1: **Evolution of the martian obliquity over the last 10 Ma. From [5].**

Model description: We used the GCM developped in the French laboratory (LMD) for terrestrial climate simulations, which has been modified to incorporate physical parameters consistent with Martian processes and constants [6]. The model resolution is 48 longitudinal points-32 latitudinal points and 25 vertical levels. It provides a full simulation of the martian water cycle which includes the transport and seasonal exchange between surface water ice, atmospheric vapor and water cloud ice [6, 7]. The local albedo is set to 0.4 wherever an ice layer thicker than 5 μm is predicted by the model, which permits ice-albedo feedback process. In all the simulations, the eccentricity has been set to zero and the total available amount of CO_2 is kept constant with obliquity changes with respect to the present value. No permanent CO_2 ice cap or south water reservoir are initially present. All the runs start with a dessicated water vapor and cloud ice reservoir and surface water ice is thus the only initial water source. The stability of water-ice and the rate of movement of water are determined when the water cycle reaches an apparent steady state. In that case, the water vapour and cloud ice budgets comes to an interannually repeatable state. Radiative effects of vapor and clouds that might be important at high obliquity are not considered and largely unknown processes in other orbital conditions (dust storm frequency, cap albedo, atmospheric pressure) may affect the present results.

Results: In a first set of simulations, the stability of a north polar ice cap is studied for obliquities ranging from 15° to 45° with a 5° step. As in [2], we found that the residual nature of the north polar cap is lost between 35° and 40°. The annual loss rate of the northern polar water enhances with the obliquity due to increasing summer sublimation. It reaches $\sim$ 2.7 cm/yr for 40° and $\sim$ 6.9 cm/yr for 45°. We found that water ice mainly accumulates in the equatorial areas of the Tharsis Montes (Arsia, Pavonis, Ascraeus and Olympus Mons) where it becomes stable. However, unlike [2], no accumulation of water has been found in the northern high latitudes for an obliquity equal to 35°. Moderate changes in the initial cap size do not significantly affect these results. At lower obliquities, formerly stable low-latitude deposits become unstable with respect to the poles. In a second set of simulations, the water ice cap has been removed and the stability of an initial water source located on Arsia and Pavonis Mons has been investigated for the same range of obliquities. No change to polar albedo and thermal inertia has been made. Interestingly, we found an increasing accumulation of water in the latitudes higher than $\sim 60^\circ$ both in the north and south polar areas. This may be correlated with the existence of massive water deposits inferred in the near-sub surface by the Mars Odyssey

Gamma-Ray Spectrometer (GRS) at these latitudes [8]. At the lowest obliquity 15°, the maximum accumulation rate is close to 0.15 cm/yr at the north pole, whereas it reaches ~ 0.05 cm/yr at the south pole. Note that these rates are one order of magnitude smaller than the previous opposite situation. It may illustrates an important dissymetric evolution of the northern cap during the two obliquity regimes. We are presently undertaking additional simulations to estimate the speed of water exchange for other initial water-ice locations and final results will be reported at the meeting.

Conclusion: Considering the present evolution of the water reservoirs on the $15^\circ - 45^\circ$ recent obliquity excursion, our results suggest two significant conclusions. First, we found that for obliquities higher than 40°, the annual loss rates of the northern polar cap towards tropical areas are about one order of magnitude higher than the opposite situation (only tropical sources at obliquities lower than 40°). If no interaction with the dust cycle (possible formation of a residual lag deposit which inhibits the sublimation of water ice from the surface) is considered, the model thus predicts (1) a possible quick disintegration of a $\sim$ 3-km thickness polar cap during the high obliquity excursion of the 5-10 Ma recent time interval (2) a recent averaged accumulation of the northern cap during the lower mean obliquity regime ($\sim 25^\circ$) of the 0-5 Ma interval from equatorial areas and also probably at the expense of the south polar area. Second, the slow rates of water accumulation in south and north polar areas on orbital timescales may provide, coupled with dust accumulation, a possible mechanism for the formation of $\sim$ 10-50 m thickness polar layers.

References: [1] Jakosky, B.M. and Carr, H.H. (1985) *Nature*, *315*, 559-561. [2] Mischna, M.A. et al., 2003, *JGR*, in press. [3] Haberle, R.M. et al., 2003, this issue. [4] Laskar, J. and Robutel, P. (1993) *Nature*, *361*, 608-612. [5] Laskar, J., Levrard, B. and Mustard, J.F., (2002) *Nature*, *419*, 375-377. [6] Forget F. et al. (1999), *JGR*, *104*, 24155-24179. [7] Montmessin, F., Ph.D dissertation, 2002, Université Paris VI.[8] Boyton, W.V. et al., 2003, *Science*, *297*, 81-85.

POLAR AND NON-POLAR LAYERS ON MARS: A SINGLE MECHANISM FOR FORMATION?

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Introduction: The recent discovery of vast quantities of near-subsurface ice in both polar regions of Mars by the Mars Odyssey Gamma Ray Spectrometer (GRS) [1-4] has presented us with an interesting quandary. On one hand, these deposits, found poleward of 60° in both hemispheres, are consistent with thermal models suggesting ice will be best protected in these regions during periods of high obliquity [5-7]. On the other hand, the current paradigm regarding the placement of these deposits, *i.e.*, diffusive deposition of water vapor, appears to be inconsistent with the large volume mixing ratios (~90%) inferred from the GRS data. This incongruity argues that diffusion alone cannot be the primary mechanism for the creation of these reservoirs, and that an alternate, large-scale process should be considered.

Spacecraft Observations: Maps generated by the Mars Odyssey GRS team reveal the presence of massive ice deposits ubiquitously poleward of 60º in both the north and south, well beyond the extent of the observable surface polar layered terrain. We can infer from the GRS data that such deposits may be found only a few to a few tens of centimeters below the surface, and are likely covered by a desiccated surface layer [1].

The GRS results show a distribution of near-surface ice quite similar to the results of [5-7], based on the physical and thermophysical properties of the regolith. One key assumption of these models is the porosity of the soil, which, even for poorly-consolidated regolith, never exceeds ~40%. In other words, the available volume for water vapor within the pore space is limited to 40%. The GRS data, however, yields abundances that are extremely high—as much as 90% by volume, and therefore emplacement via diffusion does not seem wholly consistent with GRS observations.

Further, MGS images of mantled, fretted and otherwise disaggregated, layered terrain are restricted to latitudes just equatorward of these subsurface ice deposits. The suggestion has been made [8] that this distinct "latitude-dependent" morphology is a result of sublimation-driven cementation of the surface material, and hence that these regions, too, must have, at one time, been quite volatile-rich.

Ice Deposition Model: We propose that these observed deposits result from dusty ice sheets formed at the surface, with diffusion into the subsurface being of only secondary importance. Results from a full general circulation model (GCM) [9] support this contention. Whereas presently ice is stable year-round only at the poles (Figure 1a), under periods of higher obliquity, the latitudes of stable, perennial ice change. An increase in obliquity to 35º—approximately that reached at the last obliquity maximum—shifts this zone of stable water ice towards the mid-latitudes, between 50º and 70ºN (Figure 1b). Ice will be deposited in large, localized sheets, predominantly during the wintertime, and in locations of favorable surface properties (*i.e.* high thermal inertia) and favorable atmospheric dynamics. This ice, deposited at a rate of several millimeters to a centimeter per year, will survive through the summer. Over time, ice in such regions may accumulate to potentially significant depths—model results indicate up to several tens of meters may be deposited locally over the course of a single high obliquity excursion.

Increasing obliquity to 45º, which is representative of the high obliquity excursions of 5-10 million years ago, will push this region of stable water ice into the tropics, equatorward of 30º latitude. Under such extreme conditions, the deposition and accumulation of ice is even more substantial, and may, in fact, be limited by the amount of volatiles available for sublimation and transport towards the tropics.

Based upon these model results, it seems possible that the GRS signature we are observing outside the present-day polar deposits is not the present-day diffusion and freezing of water ice in pore space below a preexisting surface, but rather the remnant of a deposited ice sheet(s) during past high obliquity phases, covered by a sublimation lag.

We have developed a simple mechanism to explain the global distribution of water ice by invoking only orbital parameters and the thermophysical conditions of the surface, which is illustrated in Figure 2. The deposition of a layer of dusty ice at a given location will commence once ice at that latitude becomes thermally stable (b). The period of time for which ice will be deposited is clearly dependent on the length of time that obliquity is above some "critical" value, which is different for each latitude. Once Mars' obliquity drops below this "critical" value, ice at lower latitudes is thermally unstable, and will quickly sublime (c), leaving behind the residual lag deposit. For the remainder of the obliquity cycle, ice beneath this lag is quasi-stable and will remain at least until the following obliquity cycle (d). At this point, we argue that one of two processes may occur. If obliquity again rises above the “critical” value, a new layer of ice and dust may form on the new surface. Such behavior may already be seen in the PLD, for which exposed layers of alternating ice and dust are readily apparent. If, however, obliquity does not again rise above the “critical” value, subsequent mechanisms may act to modify the surface and near surface, including the deposition or removal of dust or sand, and other processes responsible for creating the surface morphology observed in these regions. Such behavior may possibly be observed in the latitude-dependent layer.

Discussion: The advantage of the layering mechanism discussed above is its simplicity. A single mechanism for ice distribution can be used to explain both layered volatile and layered sedimentary deposits presently observed in both the polar and non-polar regions of Mars [10]. This argument is consistent with the observed latitudinal distribution of the dissected terrain being the result of mid-latitude ice deposition at a once higher (~35°) obliquity. It requires no *ad hoc* assumptions about the properties of the surface, or the presence of liquid water. Indeed, the only assumption we must make (which is well grounded) is that dust must be present along with the water ice during deposition.

References: [1] Boynton, W.V. *et al.* (2002) *Science, 297,* 81-85. [2] Feldman, W.C. *et al.* (2002) *Science, 297,* 75-78. [3] Mitrofanov, I. *et al.* (2002) *Science, 297,* 78-81. [4] Mitrofanov, I. *et al.* (2003) *Science, 300,* 2081-2084. [5] Mellon, M.T. and Jakosky, B.M. (1993) *JGR, 98,* 3345-3364. [6] Mellon, M.T. and Jakosky, B.M. (1995) *JGR, 100*, 11,781-11,799. [7] Mellon, M.T. (2003) LPSC XXXIV Abstract #1916. [8] Mustard *et al.* (2001) *Nature, 412,* 411-414. [9] Mischna, M.A. *et al.* (2003) *JGR, 108(E6),* 5062. [10] Malin, M.C. and Edgett, K.S. (2001) *JGR, 106,* 23,429-23,570.

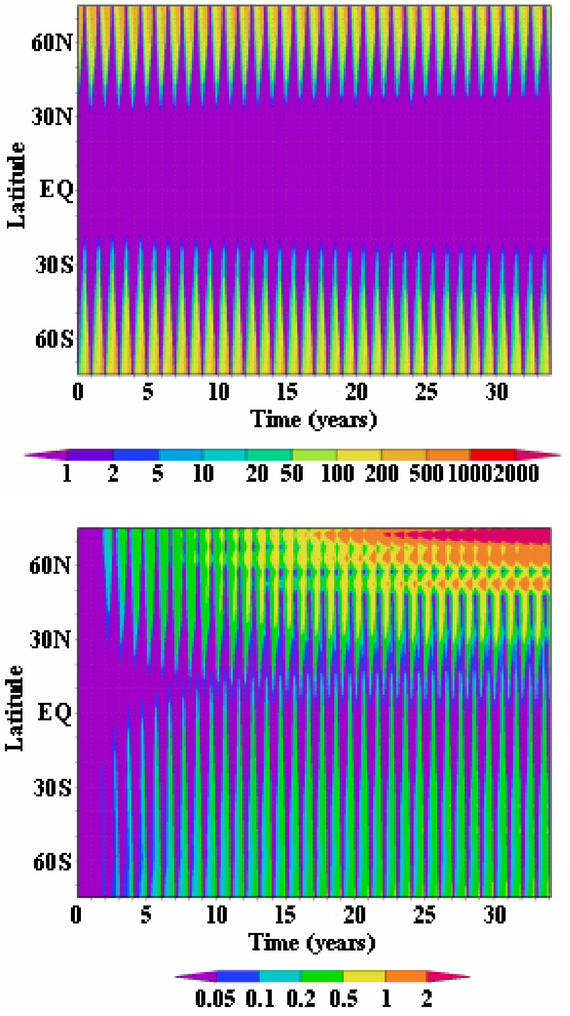

Figure 1: (a) Zonally-averaged surface ice (±75° latitude) at 25° obliquity run for 34 simulated martian years. Ice abundance is in µm. **(b)** Same as (a) but for 35° obliquity. Ice abundance is in cm. Surface ice predominantly located in high mid-latitudes, between 50°-70°N latitude.

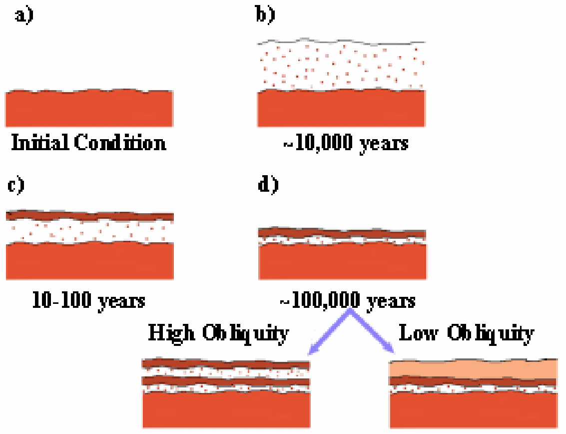

Figure 2: Timeline of surface layering mechanism over obliquity timescales (indicated times are phase durations, not accumulated time during process). **a)** initial exposed regolith **b)** becomes site for residual ice deposition due to variation in astronomical elements. Accumulation goes on for ~10^4 years before **c)** elements change again, area becomes unstable for water ice and net sublimation occurs. However, dust in ice accumulates during sublimation, and generates an isolating lag within 10^1-10^2 years that can **d)** greatly reduce ice loss over an astronomical cycle. The cycle can continue, developing layers, or area may become buried in unconsolidated dust.