THE PERSISTENCE OF MID-LATITUDE GROUND ICE ON MARS (PAST 1 MYR). J. Bapst[1,*], S. E. Wood[1] and S. Griffiths[2], [1]Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195. [2]Department of Applied Mathematics, University of Leeds, U. K. (*jnbapst@uw.edu)

Introduction: Observations from the Mars Odyssey Neutron Spectrometer (MONS) suggest substantial water ice exists beneath the Martian surface from the polar regions to mid-latitudes in both hemispheres [1,2; Figure 1].

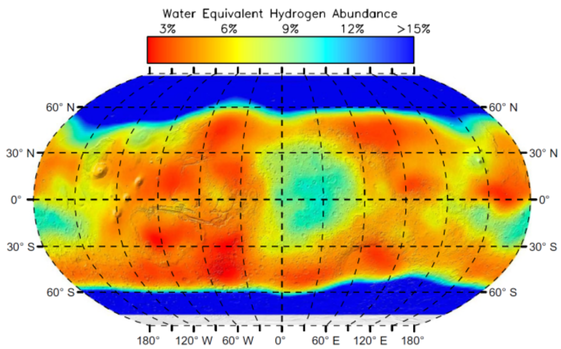

Figure 1. Global water equivalent hydrogen map clearly showing the presence of near-surface hydrogen (water ice) in both hemispheres. [3]

This instrument is only sensitive to depths of <1 m so subsurface ice below that would likely remain undetected. Equilibrium estimates for the present Martian climate provide a strong agreement with the observations [4]. Is it true that ice below the upper meter is close to equilibrium as well?

Recently, HiRISE images of fresh, shallow (~1-2 m excavation) impact craters indicate mid-latitude ground ice that resides outside the theoretical stability boundary (i.e. prone to sublimation and removal; [5]). Theoretical models have shown near-surface ice equilibrates with climate relatively quickly (and is backed up by the MONS observations) and the location where these craters lie is expected to be mostly dessicated [6]. This inconsistency needs investigation. The survivability of subsurface ice is important for understanding past and present distribution of water ice on Mars.

Theoretical studies [6-8] predict that the behavior of ground ice is sensitive to changes in climate, most notably the atmospheric water abundance. Furthermore, previous studies have shown that changes in Mars' orbit, primarily obliquity, lead to variation in atmospheric water abundance due to fluctuating levels of insolation at the water-rich polar caps [9,10]. Due to the cyclical nature of orbital variation, the stable regions of ground ice will advance and retreat at high and low obliquity, respectively. The goal is to understand how ground ice responds to this forcing.

Methodology: This work aims to is to better understand and quantify the long-term (>100 kyr) behavior of ground ice on Mars. We incorporate a 1-D, time-dependent, coupled heat and vapor diffusion model for this investigation. Particular attention is given to the mid-latitudes as this region experiences constant shifts in ground ice stability. We also focus on the last 1 Myr of Mars' history (after the orbital solutions of [11]) to make predictions for present-day Mars in response to recent climate change.

The computational time for our 1-D model is about 1 minute ≈ 1 Mars year. This makes long-term (~kyr) simulations time intensive or unfeasible. Fortunately, the growth of ground ice for a particular Mars' climate scenario (as we denote as "epoch") converges after about ~10-20 Mars years of simulation (Figures 2 and 3).

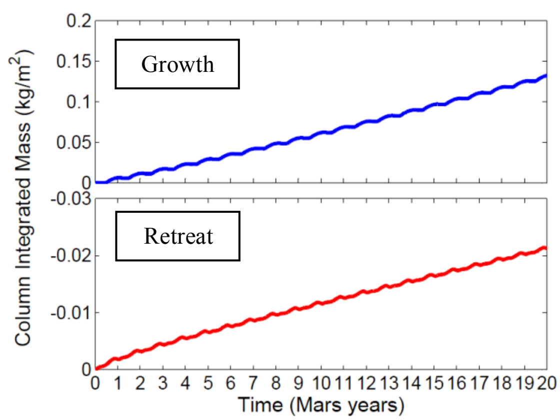

Figure 2. Growth (blue) and retreat (red) examples for 20 Mars years. As time increases the curves become approximately linear, i.e. the slope becomes constant.

This convergence is also seen in the depth profile of the ice. This can be tested by comparing the growth and retreat profiles between each year (Figure 3). This result in the model allows us to extrapolate through Mars epochs (1000 year/531 Mars year periods) with only solving the vapor diffusion model for a small fraction of that time.

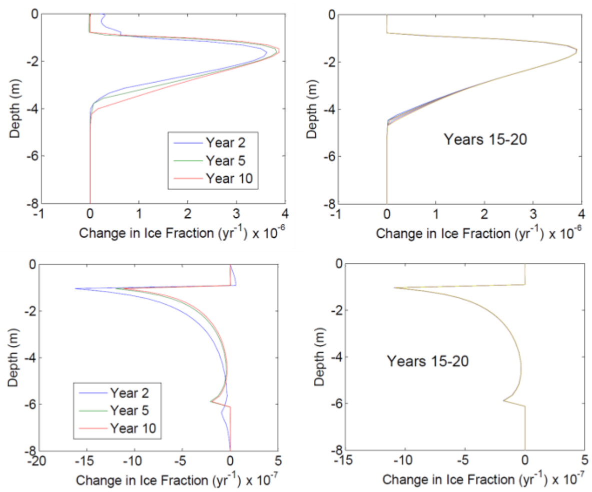

Figure 3. Growth (above row) and retreat (lower row) in ice fraction between Mars years. The profiles for >10 Mars years show good consistency.

The result is the ability to approximate the long-term behavior of subsurface ice at a relatively low computational cost.

Results: Figure 4 shows the result for 1 Myr of evolution at a simulated location, 45°N. Surface albedo is 0.27, dry porosity of 0.4, constant tortuosity of 3, dry thermal conductivity is .0625 W m^{-1} K^{-1}, icy regolith conductivity follows a linear additive approach, thermal inertia of 282 J m^{-2} K^{-1} s$^{-1/2}$, CO_2 frost albedo is set to 0.10 to limit its effect and geothermal heat flux is 0.028 W m^{-2}. Past atmospheric water abundance for the last 1 Myr is a function of obliquity only and is determined after [12].

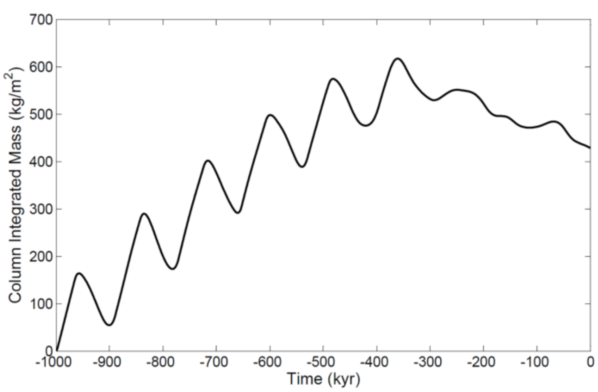

Figure 4. Column integrated mass of ice in the subsurface for the past 1 Myr at 45°N.

The results of this run are most similar to [7]. Most notable is that our retreat rate is comparable to growth rate (dissimilar to [8]).

The most important parameter in our model simulation is the atmospheric water abundance. Figure 5 shows two possible approaches [12,13]. The column integrated mass difference is significant between the two cases (the model was run at a slightly coarser temporal resolution which explains the difference between Figure 4). By plotting the rate of change and atmospheric water abundance together, it is noticeable that the growth/retreat of ground ice is dominated by the humidity prescription.

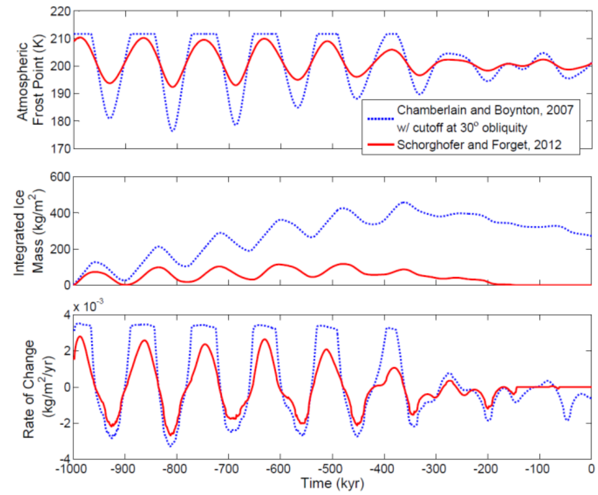

Figure 5. Top: Two schemes for atmospheric water abundance [12,13]; Middle: Column integrated mass for both humidity approaches; Simulations at 45°N with same parameters as Figure 4; Bottom: Rate of change for both simulations.

We make note of our model's result (Figure 4) showing ice persisting (though mainly in a disequilibrium state) for the past ~350 kyr. Major changes in integrated mass follow the obliquity (i.e. humidity) cycles but not entirely. To study this more closely it is convenient to plot, in a 3-D sense, the ice fraction at depth for 1 Myr (Figure 6).

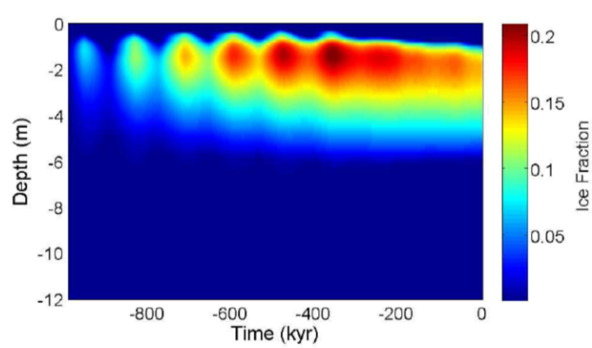

Figure 6. A contour-style plot with colors representing various levels of ice-filling-pore fractions (data from Figure 4 simulation).

Pore ice reaches a maximum at depths ~1.5-2 m. It then is slowly removed during the last ~350 kyr. Our results suggest ice can remain in an unstable state for this time or longer. It also implies that obliquity cycles determine the state of ice at <~1 m depths. At depths of 2 m it is possible to "defy" the obliquity forcing. The long-term behavior is then dependent on the amplitude of obliquity variations. This has strong implications for the state and distribution of ground ice on Mars today.

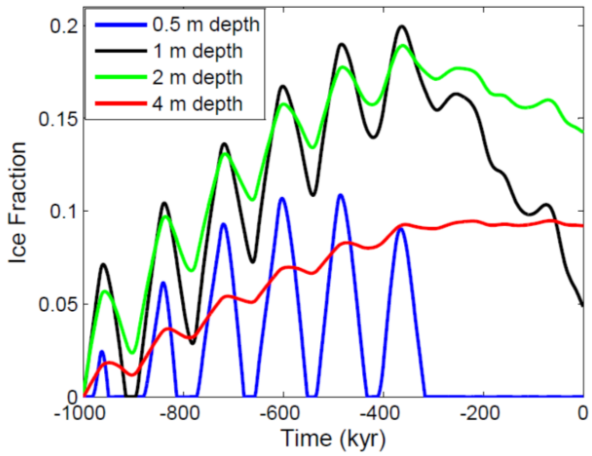

Figure 7. Ice fraction values at four depths in our simulation. The blue curve (0.5 m depth) responds quickly to climate changes. At 1 m depth the response is slowed but ice is almost completely removed at present. At the 2 and 4 m depths a different trend is seen. The fraction does not vary as much (relatively) due to the ~120 kyr period obliquity cycles. It also persists much longer (e.g. the 4 m depth curve has an approximately zero slope for the last ~350 kyr).

Discussion: If ice is able to persist and meters depths beneath the surface of Mars through "dry" periods, it may explain some of the features observed (e.g. mid-latitude icy impacts [5]).

Perhaps what is more important is understanding how growth and retreat behave. Figure 8 sheds some light on this issue.

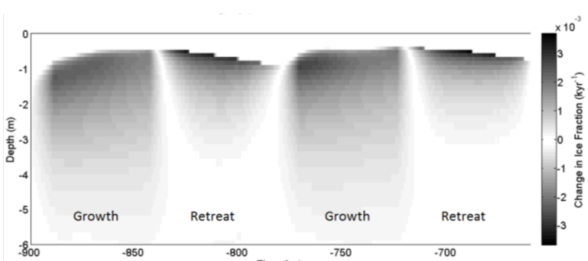

Figure 8. Contour-style plot showing the change in ice fraction for ~2 obliquity periods. The colorbar has been made equal for both growth (positive) and retreat (negative) to isolate differences.

Growth and retreat are both largest in magnitude near the ice-dry regolith interface. However, ice beneath this point will grow even when the interface is in retreat (density gradient follows the saturation vapor density when ice is present). Because of this ice will tend to accumulate beneath the interface. This can be seen in Figure 8; during growth the ice rates appear more distributed throughout depth.

Retreat, on the other hand, is more concentrated at the interface. Rates are larger than growth and are relatively small at depths >1 m (Figure 8). This growth/retreat asymmetry requires more investigation but our results thus far suggest that ice will preferentially be preserved at greater depths. We then would expect present ice that lays outside the equilibrium boundary on Mars today to be at these depths (consistent with [7]). It should be noted that this ice should not be detected by MONS and therefore is consistent with present observational data [1,2].

These results may have greater meaning for deeper in Mars' past. Today's Mars is somewhat anomalous in terms of obliquity variations (Figure 9).

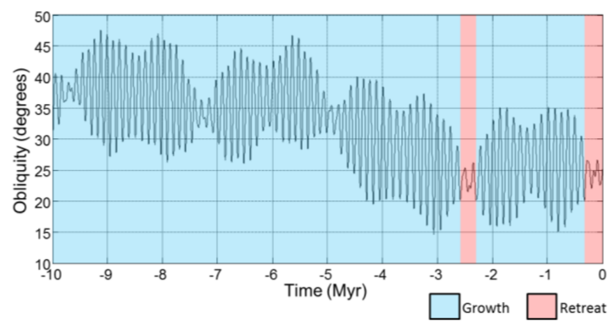

Figure 9. Obliquity variation of Mars for the past 10 Ma. Overlaid is our best guess of the growth/retreat phases of ground ice for our conditions at 45°N.

If our results are realistic and ground ice at this latitude undergoes net growth through the obliquity changes 0.4>t>1 Ma then it is probable that have been stable and growing for much of the past 10 Myr. If this is the case then it would likely be near pore-filling capacity ~1 Ma.

Although this explains the occurrence of ice at lower latitudes than expected it does not solve all problems. Pore-filling ground ice, as described here, cannot exceed the initial dry porosity of the regolith (here, 0.4). Observations by Byrne *et al.* (2009) are most consistent with nearly pure or excess ice beneath the surface. Snowfall is the most obvious choice for emplacing such ice. However, there are problems with observational evidence for this mechanism, such as boulders on the surface.

Other suggestions, altering pore-filling ice to excess ice, have been suggested [14-16]. These would likely take a lot of time on a recent Mars (~Myr), which our model appears to be consistent with. Future work and observations may help constrain formation mechanisms for the observed mid-latitude ground ice.

References: [1] Feldman, W.C. et al. (2002) *Science,* 297, 75. [2] Boynton, W. V. et al. (2002) *Science,* 297, 81. [3] Mouginot, J. et al. (2010) *Icarus*, 210, 612. [4] Mellon, M. et al. (2004) *Icarus*, 169, 324. [5] Byrne, S. et al. (2009) *Science,* 325, 1674. [6] Schorghofer, N. (2007) *Nature* 449, 7159. [7] Mellon, M. T. and Jakosky, B. M. (1995) *JGR,* 100, E6, 11781-11799. [8] Schorghofer, N. (2010) *Icarus*, 208, 598-607. [9] Mischna, M. A. et al. (2003) *JGR,* 108, E6, 5062. [10] Mischna, M. A. and Richardson, M. I. (2005) *GRL,* 32, L03201. [11] Laskar, J. et al. (2004) *Icarus,* 170, 343. [12] Chamberlain, M. A., and Boynton, W. V. (2007) *JGR*, 112(E6), 1-20. [13] Schorghofer, N. and Forget, F. (2012) *Preprint submitted to Icarus.* [14] Fisher, D. (2005) *Icarus*, 179, 387-397. [15] Zent et al. (2011) LPSC XLII. [16] Zent et al. (2012) Mars Recent Climate Change Workshop.