SURFACE ICE MIGRATION AND TRANSIENT MELTING EVENTS ON EARLY MARS.

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Background and Motivation

Understanding the processes that caused fluvial erosion and geochemical alteration on early Mars is a continuing challenge to planetary science. Key features of the observations include dendritic valley networks that are distributed widely across low to mid-latitudes over the Noachian/Hesperian terrain [1, 2], lacustrine deposits [3] in-situ observations of conglomerates in Gale Crater [4], and geochemical observations of phyllosilicate and sulphate minerals in many regions where the geomorphology suggests fluvial erosion [5, 6]. All of these features strongly suggest the presence of liquid water on the early Martian surface, at least episodically.

Based on these geological observations, many researchers have previously argued that the Martian climate passed through a warm, wet phase in the late Noachian and early Hesperian [7, 8]. This conclusion is not universally accepted; the phyllosilicate observations, in particular, have instead recently been interpreted as primarily due to subsurface hydrothermal processes, rather than alteration at the surface [6]. Nonetheless, elements of the geomorphology, particularly the valley networks, are difficult to explain in scenarios where the early Martian surface was always extremely cold.

A new hypothesis for the late Noachian climate

Many solutions to the early Mars climate problem have been proposed over the past few decades, including elevated atmospheric CO_2 [7], warming by CO_2 clouds [9], H_2O clouds [10], volcanic SO_2 emissions [11, 12], and warming by various reduced gases. In most cases, however, the early Martian climate has been simulated using simplified 1D models, which means detailed investigation of the hydrological cycle and local/seasonal climate variations has not been possible. Previously, we performed the first 3D simulations of the early Martian climate with accurate radiative transfer, and showed that even with cloud radiative effects taken into account, a CO_2-H_2O greenhouse would have been insufficient to raise early Martian mean surface temperatures above the freezing point of liquid water alone [13, 14].

However, we also found that due to the increase in surface-atmosphere thermal coupling with atmospheric

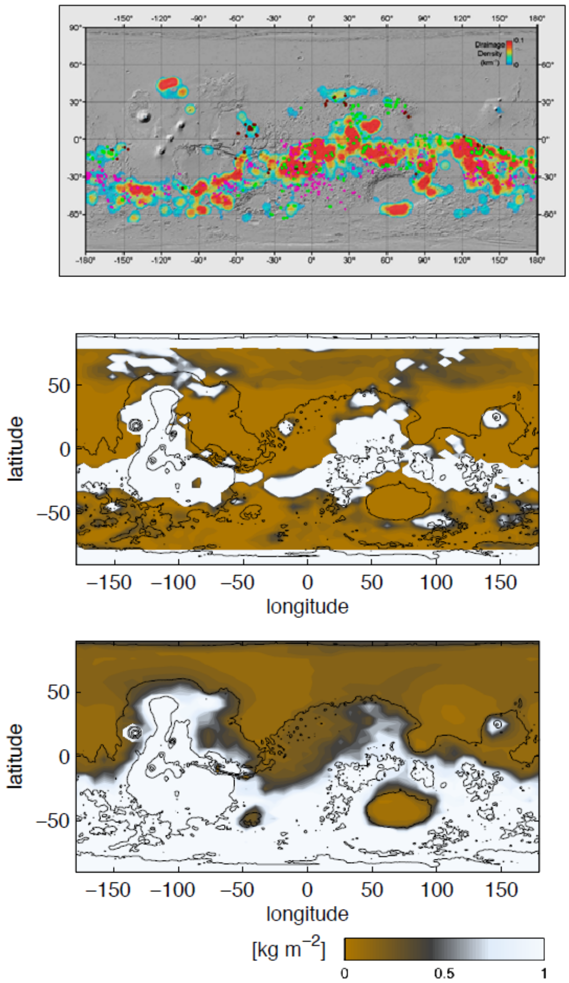

Figure 1: (top) Valley network drainage density, reproduced from [2]. (middle) Surface ice distribution on Mars after 15 years iteration assuming a 0.5 bar CO_2 atmosphere in GCM simulations with $64 \times 48 \times 15$ spatial resolution and obliquity of 40 degrees. (bottom) Equilibrium surface ice distribution under the same conditions from the simplified WTG model, which neglects all dynamical effects of the atmosphere on surface ice evolution.

pressure, H_2O would have migrated towards the highland equatorial regions where most valley networks are observed, even when annual mean temperatures were far below the freezing point of water [13]. This led Wordsworth et al. to propose the so-called 'icy highlands' hypothesis for early Mars, where transport of H_2O as ice/snow to the valley network source regions occurs in a cold climate on long timescales, and melting occurs episodically on much shorter timescales due to transient heating events such as volcanic eruptions or meteorite impacts. The key advantage of this hypothesis is that it circumvents the need for H_2O transport to the valley network source regions as rain during warm periods, as is necessary for e.g. post-impact steam atmosphere scenarios. However, to cause fluvial erosion, transient warm periods of some duration are clearly still required.

Spatial correlations between the valley networks and modeled surface ice distribution

Our most recent 3D simulations of ice equilibration at increased spatial resolution have broadly confirmed our previous results [13]. In addition, they have suggested several additional effects. First, at 0.5 bar and obliquities below 55 degrees, little migration of water ice to Arabia Terra is observed. Arabia Terra is notable for a relative absence of valley networks compared to the neighbouring Noachian terrain [2]. Previously, this has been interpreted as a result of late Noachian resurfacing [2, 15]. However, our results suggest that limitations on the rate of H_2O supply from the atmosphere due to adiabatic cooling may also have been important.

The relative absence of valley networks below around 60 °S is also interesting, particularly because at the most probable obliquity for early Mars predicted from dynamical models ($\sim 40°$; [16]), the temperature gradient between equator and pole is low even for low atmospheric pressures. At pressures above ~ 1 bar, the pole-equator temperature gradient becomes small for most obliquity values due to efficient atmospheric meridional heat transport. This suggests that if early Mars did have abundant surface water and warm, wet conditions caused by a thick atmosphere of CO_2 or other gases, valley networks would have formed over a wide range of latitudes on the southern terrain.

A simplified model of ice migration on early Mars

In our 3D simulations, the migration and equilibriation of surface ice is dependent on a diverse range of processes, including a) the net insolation pattern and hence the obliquity b) the decrease of temperature with altitude via the 'adiabatic cooling effect' under a denser atmosphere and c) atmospheric relative humidity variations caused by the large-scale dynamics. Previous work [17, 18, 19] has studied the importance of effects a) and

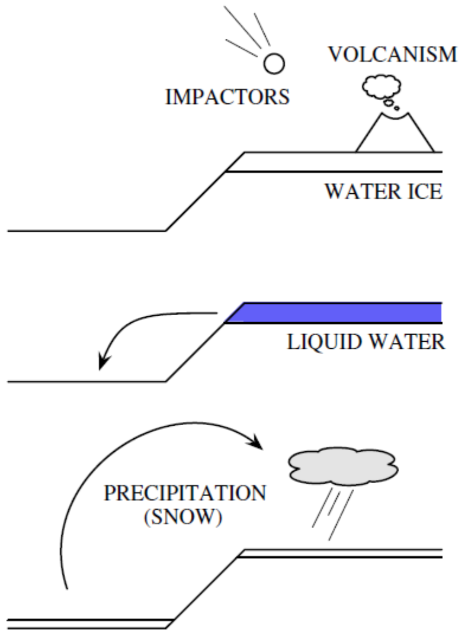

Figure 2: Schematic of the effects of transient heating events on early Mars under elevated CO_2 partial pressures (reproduced from [13]). Fluvial erosion on relatively short timescales is followed by much slower transport of H_2O as snow to high altitude regions.

c) on Mars in more recent paleoclimate scenarios, while the potential importance of b) was first demonstrated in [13]. To build an intuitive understanding of ice equilibriation on early Mars and explore parameter space, we have developed a reduced model that reproduces the basic features of the GCM results in a fraction of the computational time. The model relies on a weak temperature gradient (WTG) [20, 21] approximation coupled to a scheme to calculate insolation variations and the strength of the thermal coupling between atmosphere and surface. We are currently developing a simplified representation of the Hadley cell transport of water as a function of latitude and external parameters such as obliquity. By implementing this in the reduced model, we plan to determine the extent to which the latitude dependence of ice equilibration in the full GCM (Fig. 1) is caused by the mean meridional circulation as opposed to eddy effects.

Transient melting events

We are currently testing the plausibility of the icy highlands hypothesis by simulating the changes in surface temperature, melting rates and runoff caused by a variety of forcing mechanisms. We perform simulations

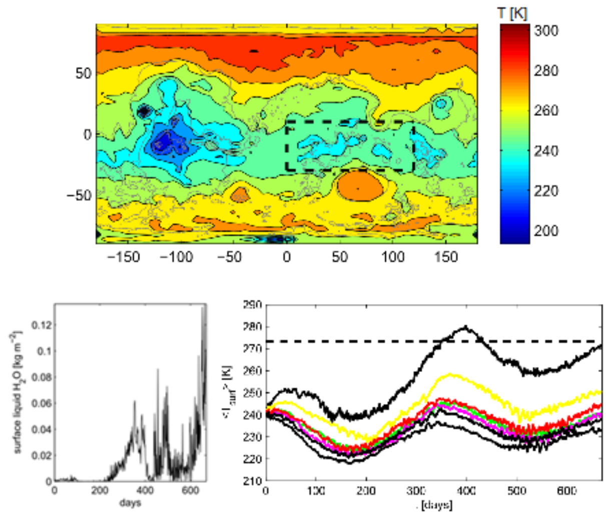

Figure 3: (top) Maximum diurnal mean surface temperature in standard 'cold' state at 0.5 bar, 40 degree obliquity. (bottom left) Diurnal mean temperature vs. time averaged over area denoted by the rectangle in the top panel for different forcing combinations (SO_2 amount, dust, H_2O cloud parametrization, surface albedo, $+5\%$ increase in solar constant). (bottom right) Surface liquid water amount vs. time for the most extreme forcing case.

using the same generalised code as in [13], starting from the equilibrium ice distributions described in that paper. We find a significant warming effect by SO_2 / H_2S, in agreement with other authors [11, 22]. However, even when the effects of SO_2 destruction by photolysis are neglected, the maximum plausible warming effect at 0.5 bar CO_2 pressure is insufficient to cause significant melting of ice deposits alone.

We currently find significant discrepancies from other studies in our modeling of the H_2O greenhouse effect. Recently, it has been proposed that stable impact-induced runaway greenhouse atmospheres are possible on early Mars [23]. However, this conclusion is based on the assumption of radiative equilibrium in the low atmosphere, which requires unphysically high supersaturation of water vapour [24]. Under more realistic assumptions, the small decrease in outgoing longwave radiation with surface temperature past the peak value in a clear-sky runaway greenhouse atmosphere is not sufficient for hysteresis under early Martian conditions [21].

H_2O cloud warming represents a more subtle and interesting case. In an independent recent 3D GCM study of the early Martian climate [10], high altitude water clouds were found to cause warming sufficient to allow surface liquid water in some cases. We are currently unable to reproduce these results: indeed, in our simulations with water cloud particle sizes fixed at 12 μm, we find a small net cooling effect vs. our standard assumption of fixed $[CCN] = 1 \times 10^6$ [25]. The main reasons for this appear to be a) the inclusion of CO_2 clouds in our simulations, which tends to dampen H_2O cloud radiative effects and b) the fact that in our moist convection scheme, significant amounts of H_2O are not lofted to high altitudes. On Earth, moistening of the stratosphere is a complex process that depends on details such as the detrainment rate of ascending air in convective cells and the efficiency of precipitation, and the validity of complex terrestrial convection schemes in a Martian context cannot be assumed. To constrain the uncertainty in H_2O cloud warming on early Mars, we plan to perform sensitivity studies using a range of representations of moist convection, entrainment and cloud microphysics.

Other effects such as increased levels of atmospheric dust, a reduced ice surface albedo, small increases in the atmospheric content of reduced gases and a slightly increased solar constant all cause small (< 5 K) perturbations to the baseline climate state at 0.5 bar in isolation. Nonetheless, because of the nonlinearity in the climate system due to H_2O vapour absorption in the IR and visible, in combination these effects can cause warming sufficient to raise summertime mean temperatures above 273 K in the valley network regions and hence significant melting (Fig. 3). Work is ongoing to test runoff and hence erosion rates under such conditions.

Conclusion

Despite the continuing challenges in producing transient warming episodes under realistic forcing, the icy highlands scenario still appears to be a viable interpretation of the basic state of the Martian climate in the late Noachian. Indeed, our 3D ice evolution simulations at increased resolution are beginning to suggest that many of the spatial features of the Noachian valley network distribution may be explainable in terms of the local availability of surface H_2O in a predominately cold climate. Under the most favourable possible conditions for surface warming, we find that mean summertime temperatures above zero and hence significant melting of highland snow/ice deposits becomes possible. Explaining how such conditions could arise self-consistently remains a huge challenge. Nonetheless, we argue that rather than focusing on individual effects, as has typically been done in the past, the key to understanding Noachian warming episodes lies in understanding how multiple effects interact in the full climate system. This is a strategy that necessitates the use of complex 3D GCMs in combination with simpler models to guide intuition.

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