CONSTRAINTS ON MARTIAN CLIMATE HISTORY FROM ICY IMPACT CRATERS.

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Introduction

Subsurface ice is one of the major H_2O reservoirs on Mars [1] and plays a significant role in the long-term water cycle. Its overall geographic distribution and burial depth, as measured with neutron spectroscopy [2, 3, 4, 5], is consistent with the assumption that the vapor concentration at the ice and in the atmosphere have equilibrated [6, 7, 8]. On a zonal average, subsurface ice is expected poleward of about $\pm 55^\circ$ latitude on both hemispheres. However, in a surprise discovery, ice was found excavated by very recent impacts at latitudes 43°–56°N [9, 10]. These icy impact craters are further equatorward than the equilibrium geographic boundary of the subsurface ice, unless an atmospheric humidity higher than today's is assumed. Here, we explore what constraints the presence of almost pure ice as far equatorward as 43°N places on the climate history, based on simulations of the retreat of subsurface ice. Progress in subsurface ice modeling [11, 12] enables us to not only determine the equilibrium distribution but follow the evolution of the ice in response to temperature and climate change caused by orbital variations (Milankovitch cycles).

Model

Subsurface ice can be emplaced in two ways. Precipitation during a past climate period, when the obliquity was high, may have led to the formation of a perennial snow cover that subsequently densified. During retreat of this ice, any dust in the ice would remain as sublimation lag, leading to self-burial. The second emplacement mechanism, uncommon on Earth, is ice directly deposited from the vapor phase [13, 14]. It fills the available voids between soil grains and is thus called "pore-ice".

(It is conceivable that pore-ice in conjunction with thermal cycles can displace soil, leading to ice content in excess of pore volume. At present, this effect cannot be properly quantified, if it exists. This process is not considered here.)

The most recent precipitation dates from a different obliquity epoch [15, 16, 17]. An obliquity near 47° was last reached about 5640 ka ago; and an obliquity of 35° has not been exceeded since 632 ka ago [18].

The amount of water that sublimes from the cap varies strongly with the planet's axis tilt, and as a result the atmospheric water vapor content varies with time. Moreover, the atmospheric circulation has limited capacity to carry water vapor from the summer pole to lower latitudes.

Obliquity-dependent results from a GCM are used for the atmospheric humidity. They correspond to the version of the LMD-GCM used in Refs. [17, 19] and [20]. This is an important improvement over previous calculations [11, 12]. The partial pressure on the surface is approximated by

$$\ln p_1 = \begin{cases} \ln a_1 + \frac{\epsilon - 28^\circ}{b_1} & 10^\circ < \epsilon < 25^\circ \\ \ln a_1 + \frac{\epsilon - 28^\circ}{b_1} + c_2(\epsilon - 28^\circ)^2 & 25^\circ < \epsilon < 45^\circ \end{cases} \quad (1)$$

where ϵ is the obliquity, $a_1 = 0.20$, $b_1 = 7.8^\circ$, and $c_2 = -0.0034$.

The calculations use zonally averaged albedo, thermal inertia, and topography. The domain depth is 20 m. A soil porosity of 40% is assumed.

The subsurface ice model [12] uses asynchronous coupling (e.g., half-hour time steps for surface temperature and 100-year time steps for changes in subsurface ice content). This numerical method is five orders of magnitude faster than explicit vapor transport calculations. Its speed matches that of purely thermal models. The speedup is achieved primarily by solving time-averaged equations for vapor transport and ice volume change.

Results

The model is initiated with a cover of dirty ice, consisting mostly of ice and a small fraction of dust. Subsequently, ice is lost to the atmosphere by diffusion through the sublimation lag. Ice can reform by inward diffusion of atmospheric water vapor to fill the interstitial pores.

Figure 1a shows the result of one global model calculation. It is assumed a cover of dirty ice formed by atmospheric precipitation 1 Ma ago, consisting of 90% ice and 10% dust. At 0.5 m depth, the orginal ice sheet has retreated beyond approximately $\pm 50^\circ$latitude. At 3 m depth, the boundaries lie at about 40°N and 45°S. In this scenario, ice is still left at the latitude of the impacts. The impacts puncture the surface to a few meters [9], while neutron spectroscopy is most sensitive to the upper half-meter of the subsurface; hence this ice distribution is consistent with both of these observational constraints.

Figure 1b shows the result if it is assumed a global ice sheet formed 5 Ma ago instead of 1 Ma ago. The ice sheet has retreated further poleward. This ice distribution

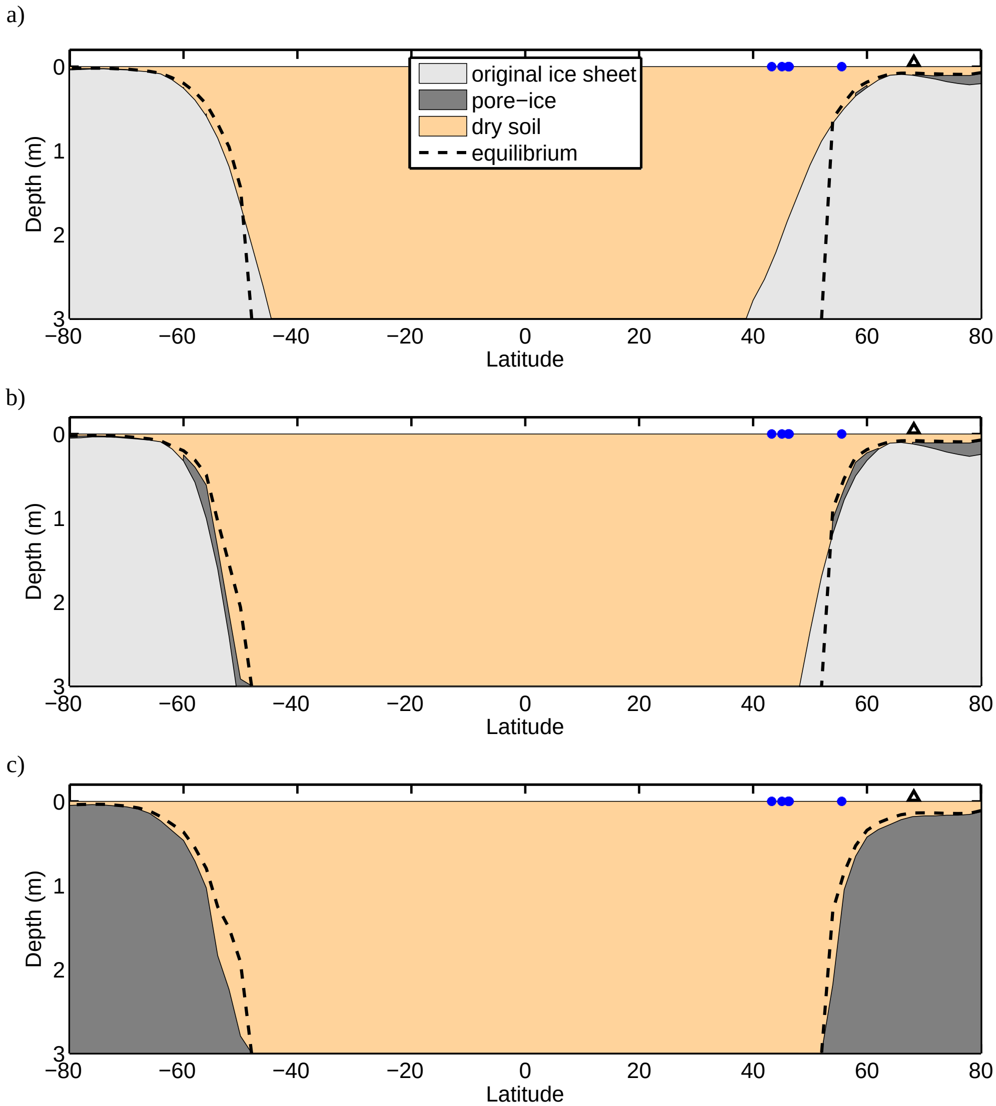

Figure 1: Present-day subsurface ice distribution as a function of latitude and depth beneath the surface. a) Ice sheet formed 1Ma ago. b) Ice sheet formed 5Ma ago. Dust content is 10% in both cases. c) No ice sheet initially. Light gray shows the original ice sheet, dark gray diffusively filled ground (pore-ice), and reddish the ice-free soil. The triangle marks the latitude of the Phoenix Landing Site and the blue dots mark icy impact craters. The dashed lines represent equilibrium predictions.

is inconsistent with the observations of small impact craters with icy floors at latitudes of 43°–56° [9, 10].

Figure 1c shows the results for a third climate scenario, where the subsurface is assumed to be entirely ice-free initially and only pore-ice forms. In this scenario, the margins consist entirely of pore-ice and the ice does not reach as far equatorward as the location of the impacts. These results are also inconsistent with the observations of small impact craters with icy floors. In addition, the scenario is inconsistent with the high hydrogen content measured by neutron spectroscopy at high latitudes [3, 4, 5].

Overall, these three model calculations (Fig. 1a-c), favor a climate scenario with a recent ice cover, which most likely would have formed by precipitation. If such an ice cover dates from more than a few million years ago, or there was none at all, it would be expected that latitudes equatorward of 50° are depleted from ice to a least a few meters depth.

The dashed lines in Fig. 1 represent the equilibrium depth for the present ice content. (Ice content affects thermal properties and the equilibrium depth depends on the amount of ice present.) In Fig. 1a, the ice close to the surface is very close to equilibrium, but the ice

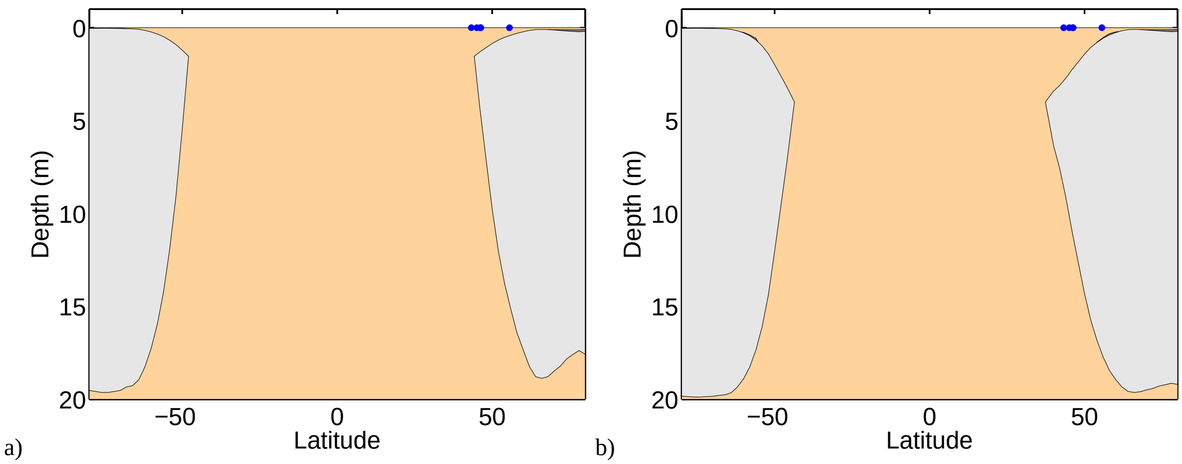

Figure 2: Present-day subsurface ice distribution for a) 5% dust and b) 15% dust. Both simulations evolved over 1 Ma. The initial ice cover is assumed to be 20 m thick. The blue dots mark the latitudes of icy impact craters.

buried more deeply has not yet reached equilibrium.

Figure 2 shows the result of a simulation with small dust content (5%) compared to high dust content (15%), and over a depth of 20 m. For a fixed latitude, a higher dust content leads to a greater burial depth. The depth depicted is the depth to the ice table, i.e. the thickness of the sublimation lag. The amount of ice lost is far greater than the burial depth. This suggests that the ice sheet must have been tens of meters thick, otherwise the entire layer would have been depleted at the latitudes of the impacts. At 5% dust content, a 20 m thick layer is barely enough.

Conclusions and Discussion

Part of the reason why the present model can produce ice at lower latitudes than previous model calculations, is simply because impact craters probe to greater depths than neutron spectroscopy. Deeper layers of the subsurface take a longer time to exchange vapor with the atmosphere. Only the shallow ice detected by gamma and neutron spectroscopy and probed by the Phoenix Lander is close to its equilibrium depth.

A second reason is the recent emplacement time. Emplacement times of 5 Ma or more are difficult to reconcile with the presence of an ice sheet at 43°N. Only more recent emplacement, and thus a recent precipitation event, of ice at least tens of meters thick are consistent with the observations. The icy impact craters point to a recent precipitation event.

A consequence is that the subsurface ice has not yet reached equilibrium with the atmosphere; it still retreats and thus acts as active source of water vapor. Figure 3 shows the water vapor output per year in units of precipitable micrometers. This amount is likely below detection threshold, but represents a source that must be

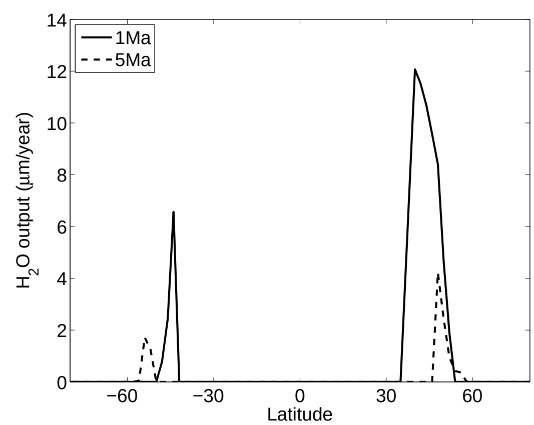

Figure 3: Present-day zonally averaged H_2O vapor output from the retreating subsurface ice for the climate scenarios shown in Fig. 1a,b. The results depend on emplacement time, dust content of the ice, and initial ice cover thickness and should be considered as example only.

balanced by a sink. If all of this H_2O would end up on the North Polar Cap, it would correspond to a deposition of a 181 μm thick layer annually for the 1 Ma scenario and 23 μm annually for the 5 Ma scenario. In the current era, there should be net deposition on the polar cap due to the retreating subsurface ice.

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