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STRATIGRAPHIC AND ISOTOPIC EVOLUTION OF THE MARTIAN POLAR CAPS FROM PALEOCLIMATE MODELS. E. Vos^{1,2}, O. Aharonson^{2,3}, N. Schörghofer³, F. Forget¹, E. Millour¹, L. Rossi⁴, M. Vals⁴, F. Montmessin⁴, ¹Laboratoire de Météorologie Dynamique/IPSL, CNRS, Paris, France, ²Weizmann Institute of Science, Rehovot, Israel ³Planetary Science Institute, Tucson, Arizona, ⁴Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS/CNRS), Paris, France. (Eran.Vos@lmd.ipsl.fr)

Introduction: Mars harbors ice deposits in several forms, the most conspicuous are the North Polar Layered Deposits. Spiraling troughs cut into the polar cap expose a stratigraphy of alternating layers, which are often taken to indicate variations in polar ice/dust fluxes. The NPLD dust-rich layers are formed either at low levels of ice accumulation or by sublimation leaving lag layers [1, 2]. Laskar *et al.* [3] calculated the orbital elements over the last 21 Myr. During this time, the obliquity has varied between 15° and 45°. Approximately 4.5 Myr ago, the mean obliquity dropped from ~35° to ~25°, resulting in lower mean polar insolation. During this epoch, equatorial ice is thought to have migrated to the poles [4]. On Earth, The isotopic signal in ice cores from Antarctica and Greenland have revealed past climate oscillations. Mars lacks an ocean to buffer the atmospheric isotopic ratio as on Earth, thus the isotopic composition of the present atmosphere is driven by the evaporative fluxes of the caps. Observations from orbiters and ground-based telescopes measured the atmospheric D/H ratio to be in the range of $1-8 \times \text{VSMOW}$ [5], with an average of 4.6 ± 0.7 [5]. The atmospheric values provide evidence for both long-term net loss to space [6], as well as seasonal, cloud physics, and geographic source effects [7].

In this work [8], we provide quantitative results from the Mars PCM simulations that shed light on the stratigraphic and D/H isotopic evolution of the Martian polar caps. The simulations are initialized with a tropical ice reservoir that progressively migrates and accumulates at the polar caps. We explore the relation among the orbital elements, the surface ice distribution, atmospheric humidity, polar flux, and the isotopic ratio.

Methods: We use the Mars PCM with a water cycle that includes treatment of surface ice, atmospheric vapor and simple ice clouds and has been described in detail previously [9, 10]. In order to track the D/H ratio we use the HDO tracer described in Rossi *et al.* [11]. Temperature-dependent isotopic fractionation of water occurs at condensation either in clouds or directly onto the surface. The equilibrium solid-vapor fractionation coefficient (α) assumed is based on lab measurements [12] at temperatures above 233 K. The simulations reported here have a horizontal resolution of 64 by 64 by 29, corresponding to 2.8° in latitude, and 5.62° in longitude. We ran the GCM spanning the full range of paleo-orbital element combinations in the last 21 Myr [3]. The simulations were performed with an assumed past ice distribution in which surface ice is present in the tropics where accumulation is

predicted at high obliquity [13]. We tested thick and thin tropical ice layers. This case is designed to reach steady state, to investigate the fluxes and D/H ratio of ice reaching the polar cap with a persistent tropical source. In the thin test case, we initialize the model with a thin tropical ice layer to investigate the different stages of the evolution of ice migration as the finite initial source is exhausted.

Results: We begin with GCM simulations performed at various past orbital conditions with an initial thick tropical ice reservoir. More intense, shorter summers in one hemisphere drive more water vapor to migrate poleward due to the increased atmospheric humidity at warmer temperatures [8], which eventually lead to larger polar accumulation rates. The evolution of surface ice was tracked to derive a relation between polar cap growth rate and orbital elements (Figure 1a). In addition to obliquity controlling the annual mean insolation as a function of latitude, there is also a strong dependence on L_p . To study the hydrogen isotopic signal expected in the Martian polar cap, we analyze the results of the same simulations presented above. We calculate the mean D/H ratio of ice that condensed in the polar region and plot it in Figure 1b panel. The contours show D/H values in δD . The hydrogen isotopic anomaly depends on the orbital elements. A short, intense summer leads to higher D/H ratio of the accumulating ice. Notably, the polar δD value is negative for all cases. This occurs because as vapor transports from the tropics poleward, Ice first deposits in the intermediate latitudes and preferentially condenses out the heavy isotope. The atmosphere becomes depleted in the HDO, and therefore, water reaching the pole is isotopically light.

In order to simulate the stages of poleward migration of ice from the tropics, we considered an initial ice distribution with a smaller amount ice, placed in the tropics. We use this approach as an approximation, as the stages of the migration of this limited deposit over the simulation timescale reflect those of a much larger deposit, migrating over a much longer time. The reservoirs evolve smoothly from year to year, and over the timescale of the simulation (100's of Mars years), they experience significant change. Figure 2a shows this evolution for a reference orbital element combination, with an obliquity of 25°, eccentricity of 0.093 and L_p of 90°. The simulation shown was run for 105 Mars years, but it is plotted as a function of the fraction of ice transported and not time, keeping with the idea that the evolutionary stages are maintained on longer timescales. At first, as long as the tropical reservoir is present, ice migrates to latitudes higher than $\pm 45^\circ$, but

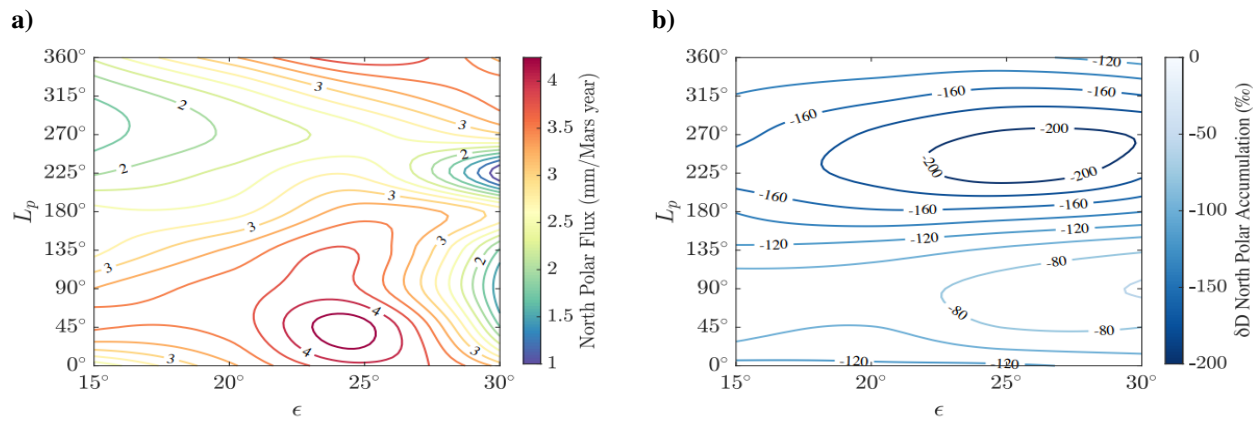


Figure 1: **a)** Simulation results of the North Polar ice flux as a function of obliquity noted as ϵ and L_p for eccentricity of 0.093 with a thick tropical reservoir. **b)** North polar ice accumulation D/H ratio for the same orbital configuration and ice distribution as in a).

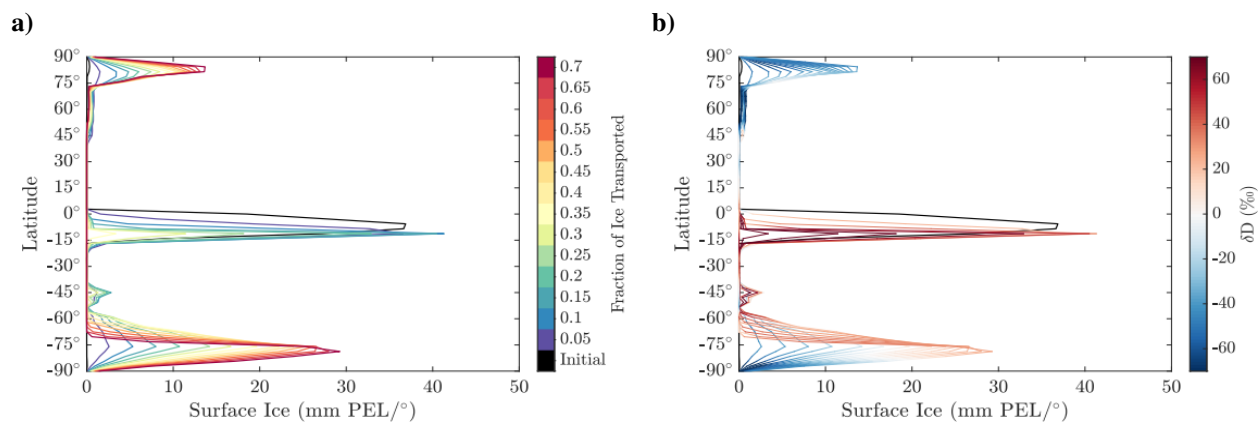


Figure 2: **a)** Surface ice evolution as a function of latitude and ice fraction transported. **b)** Surface ice and δD of the layers as a function of latitude for the same run as in a). The colors represent the D/H ratio of the mean value of the layer that was formed.

only a small portion of the ice that sublimated from the tropics reaches the polar caps. When ice is no longer available in the tropics, the planet's mean humidity drops, and ice migrates from these quasi-stable regions towards higher latitudes. As the simulation advances and more ice migrates, the location of the source migrates poleward. Thus, the upper layers of the cap are expected to represent a deposit that migrated from high latitudes, and not the cap mean value. Overall, most of the ice comprising the polar caps did not migrate directly, but rather temporarily resided in the mid-high latitudes before reaching the cap. The migration stages also affect the D/H ratio of the condensed ice. Figure 2b also plots the surface ice evolution like 2a, but here the colors represent the D/H ratio in units of δD . The simulations show that at any given instant, the most equatorial latitudes at which ice condenses are also most enriched in the heavy isotope. The remaining water in the atmosphere is relatively depleted in HDO, so ice that condenses poleward of this latitude is likewise depleted. Thus, the D/H ratio of growing ice on the polar cap de-

pends both on orbital parameters, and the source location and composition.

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