

MARS: A PROPOSED CLIMATIC SCENARIO FOR NORTHERN MID-LATITUDE GLACIATION. J. B. Madeleine^{1,2}, F. Forget¹, J. W. Head², B. Ilevrad³, F. Montmessin⁴ ¹Laboratoire de Météorologie Dynamique, Institut Pierre Simon Laplace, Paris, France (jbmlmd@lmd.jussieu.fr), ²Department of Geological Sciences, Brown University, Providence, RI 02912 USA (james_head@brown.edu), ³IMCCE, Obs. De Paris, France, ⁴Service d'Aéronomie, Institut Pierre Simon Laplace, Paris, France.

Introduction and abstract: Several features in the northern mid-latitudes of Mars have been interpreted as being cold-based glaciers similar to what is found in the Dry Valleys of Antarctica [1-3]. Detailed analysis of the Deuteronilus-Protonilus Mensae region (DPM; 30-50N 0-70E) suggest glacial modification of the dichotomy boundary during the Late Amazonian and formation of integrated valley glacial systems, probably resulting from a large-scale glaciation over several million km² [1]. Similarly, glacial deposits on the western flanks of the Tharsis [4-6] and Olympus [7,8] volcanoes show different episodes of advance and retreat suggesting long-term glacial cycles [6], and spectacular glacier related landforms have been observed in the eastern Hellas region [8].

These studies all point to major accumulation of water-ice in these regions under different orbital conditions. It has been shown through climate modeling that the Tharsis and Olympus tropical mountain glaciers, and the Eastern Hellas glacial deposits were probably formed by precipitation and deposition of water-ice on the western flanks of the volcanoes [9, 10], during periods of high obliquity (45°). However, these simulations could not explain how and why ice have accumulated in the Northern mid-latitude [9]. Here, we propose a new climatic process able to induce these accumulations. We examined the meteorological conditions after this period of high obliquity, when the tropical mountain glaciers were a new possible source of atmospheric water, and the obliquity was leaning towards lower values (35°). We show that, assuming a relatively dusty atmosphere, the resulting climate favors the formation of a thick cloud belt in the northern mid-latitudes of Mars, with precipitation and accumulation of ice in regions in good agreement with geological observations. Not only is the modeled accumulation maximum in the regions where glacier-like landform has been observed, but it is found that everywhere poleward of ~50° latitude, some ice could have accumulated. This could explain the origin of the ice-rich mantling detected by the GRS instrument aboard Mars Odyssey, as in [10], but at higher obliquity, which is more realistic.

1) Reference simulation: To focus on the northern mid-latitudes, we study the climate under an obliquity of 35°, with an eccentricity of 0.1 and an argument of

perihelion of 270°. The visible dust optical depth is set to 2.5, based on the probable high dust opacity of the atmosphere under these conditions [11]. Four sources of water-ice are located on the western flanks of the great volcanoes where past glaciers are observed, and both polar caps are removed. Dust is not carried by the simulated winds, and water vapor is radiatively inactive.

2) Predicted water-ice deposits: The resulting simulation predicts strong accumulation of ice in three regions of the northern mid-latitudes where glacial landscapes are clearly identified (see fig. 1.a). The largest glaciation is observed in the DPM region mentioned above, where the accumulation of ice is around 10-20 mm/yr. Over a high obliquity period of approximately 50 ky, this accumulation could create a regional ice sheet of 500 to 1000 m thickness, within an order of magnitude of the observations. Two other regions are Phlegra Montes (50N-160E) and Tempe Terra (40N-60W), where predicted accumulation is around 10 mm/yr. Many other regions like the south-east of Alba Patera, or Terra Meridiani show interesting accumulations of ice due to other meteorological mechanisms, but cannot be detailed here.

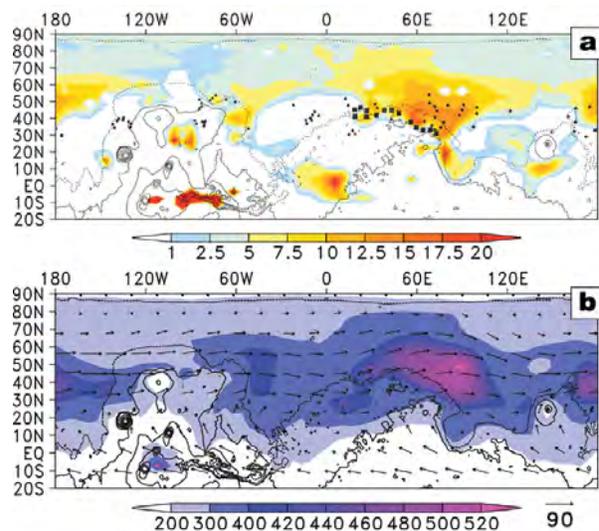


Fig. 1. a) Predicted ice accumulation (mm/yr) superposed on the map by S. Squyres [12]. Squares = lobate debris aprons ; Circles = small impact craters with con-

concentric fill. *b*) Average cloud ice content (pr- μm) and atmospheric winds for $L_s = 270\text{-}300^\circ$.

3) Cloud distribution: The inhomogeneity of the deposits within the mid-latitude band results directly from the structure of stationary planetary waves during the northern winter. At this season, the sublimation of the tropical mountain glaciers provides a large amount of water vapor to the atmosphere, which is carried to the mid-latitudes by the stationary planetary waves (see the deflection of the atmospheric winds on figure 1.b). A poleward flux of water vapor leaving the equator can thus be observed, and this warm and humid equatorial air condensates as it crosses the winter latitudinal temperature gradient. The resulting mid-latitude cloud belt shows high water-ice contents over the glacial regions (see figure 1.b), and provides sufficient precipitation to form regional ice sheets.

4) Regional analysis: Seasonal variations of surface ice deposits in three different regions (see fig. 2.) clearly show constant precipitation during winter, with a period of enhanced accumulation (pointed by the second arrow) at the beginning of this season. A detailed analysis of this period reveals the passing of low pressure systems due to baroclinic waves, with precipitation events of around $10\ \mu\text{m}$. These waves, stabilized by the topographic high of the dichotomy boundary, could play a major role in the mid-latitude glaciation, because they also result in the formation of dust storms. Large weather systems could therefore arise from these local dust storms, propagating along the dichotomy boundary and creating ideal conditions for nucleation of ice crystals over glacial regions.

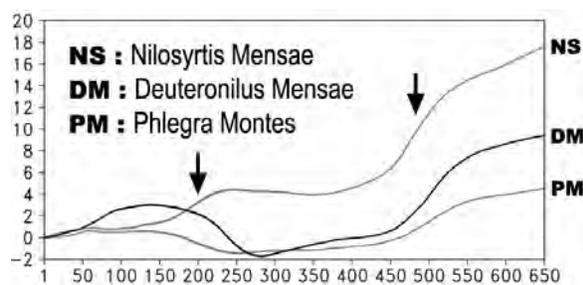


Fig. 2. Evolution of surface water-ice deposits (mm) during one martian year in three selected regions.

Sublimation of the deposits during the summer is also a major factor (first arrow on figure 2.), especially in the DPM region, and mainly depends on the altitude, temperature and wind strength. Apart from the winter cloud distribution, the accumulation is thus enhanced in the fretted terrains of the DPM region, where increased surface pressure, low insolation and

protected topography can preserve the deposits during the summer. Surprisingly, ice builds up even during the summer in Nilosyrts Mensae, where precipitation is favored by a strong cyclonic circulation at the edge of Isidis Planitia.

5) Impact of dust on precipitation: None of our simulations performed with a dust optical depth lower than 1 were able to reproduce satisfactory ice deposits in the mid-latitudes, suggesting that a high dust opacity is required to create the glaciation. Many reasons account for this tendency: 1) the higher temperature of a dusty atmosphere in the mid-latitudes and resulting high saturation vapor pressure increases the water vapor content of these latitudes; 2) the intensified latitudinal temperature gradient between 30° and 60°N increases the circulation and the zonal wind, and thus favors the propagation of stationary waves and baroclinic instabilities, both playing a major role in the glaciation; 3) cooling of the surface during the day stabilizes the surface ice deposits by lower short-wave fluxes and 4) dust cooling enhances the condensation process during the night.

Future work: This study is a first step in the understanding of the climate during the northern mid-latitude glaciation. The sensitivity of this mechanism to orbital parameters is currently being analysed, and some simulations already suggest that the mid-latitude glaciation does not occur with higher obliquities or polar water sources. Obliquity, eccentricity and argument of perihelion have a significant impact on the stability of the glaciers, and sensitivity studies will provide major insight into the understanding of the observed glacial cycles. Improvements of the model are underway in order to refine the comparison with glacial geomorphology, for instance by coupling the water cycle and the dust cycle, taking into account the radiative feedbacks of water vapor and ice crystals, and performing high resolution simulations in the glacial regions.

References: [1] Head et al. (2006) *Geophys. Res. Lett.*, 33. [2] Head et al. (2006) *Earth Planet. Sci. Lett.*, 241, 663-671. [3] Head and Marchant (2006) *LPS XXXVII*, Abstract #1127. [4] Head and Marchant (2003) *Geology*, 31 (7), 641-644. [5] Shean., Head and Marchant D. R. (2005) *J. Geophys. Res.*, 110, E05001. [6] Marchant and Head (2006) *LPS XXXVII*, Abstract #1422. [7] Milkovich, Head and Marchant (2005) *Icarus*, 181, 388-407. [8] Head et al., *Nature* 434, 346 (2005) [9] Forget et al., (2006) *Science*, 311, 368-371. [10] Levrard, Forget, Montmessin, Laskar, *Nature* 431, 1072 (2004) [11] Newman, Lewis and Read (2005) *Icarus*, 174, 135-160. [12] Squyres (1979) *J. Geophys. Res.*, 84, 8087-8096.