EXPLORING THE NORTHERN MID-LATITUDE GLACIATION WITH A GENERAL CIRCULATION MODEL. J.-B. Madeleine[1,2] , F. Forget[1], J. W. Head[2], B. Levrard[3], F. Montmessin[4] [1]Laboratoire de Météorologie Dynamique, Institut Pierre Simon Laplace, Paris, France (jbmlmd@lmd.jussieu.fr), [2]Department of Geological Sciences, Brown University, Providence, RI 02912 USA (james_head@brown.edu), [3]IMCCE, Obs. De Paris, France, [4]Service 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 [1-3,16]. Detailed analysis of the Deuteronilus-Protonilus Mensae region (DPM; 30-50N 0-70E) suggests 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 km^2 [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 during periods of high obliquity (45°) [9,10]. However, these simulations could not explain how and why ice has accumulated in the Northern mid-latitudes [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 may be 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) A glacial climate: The thermodynamic state of the atmosphere under these orbital conditions results in increased meridional circulation, strong eastward jet during the northern winter [11,12] and associated stationary planetary waves. In our simulation, the new water cycle created by sublimation of the tropical glaciers combined with this winter flow pattern favors condensation and precipitation of water ice in geologically identified glacial regions [16]. It clearly appears that the inhomogeneity of the deposits within the mid-latitude band results directly from the structure of stationary planetary waves during the northern winter (see Fig. 1.a and 1.b).

The complete water cycle during the northern winter is characterized by 1) sublimation of the tropical mountain glaciers and movement of water vapor which extends from the southern uplands to the northern mid-latitudes (see the white dashed lines on Fig. 1.a); 2) transport of water vapor through the winter latitudinal temperature gradient by stationary planetary waves (see the meridional component of the 5.6 km winds on Fig. 1.a); 3) resulting poleward flux of water vapor and condensation by cooling of this warm and humid equatorial air (see the formation of a thick mid-latitude cloud belt on Fig. 1.a, particularly evident over the DPM region); 4) air-fall deposition of ice crystals and accumulation of surface water ice to form regional ice sheets (see the net ice accumulation map on Fig. 1.b); 5) differential sublimation and erosion of the deposits during northern summer and preservation in glacial regions.

3) 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.b). 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.

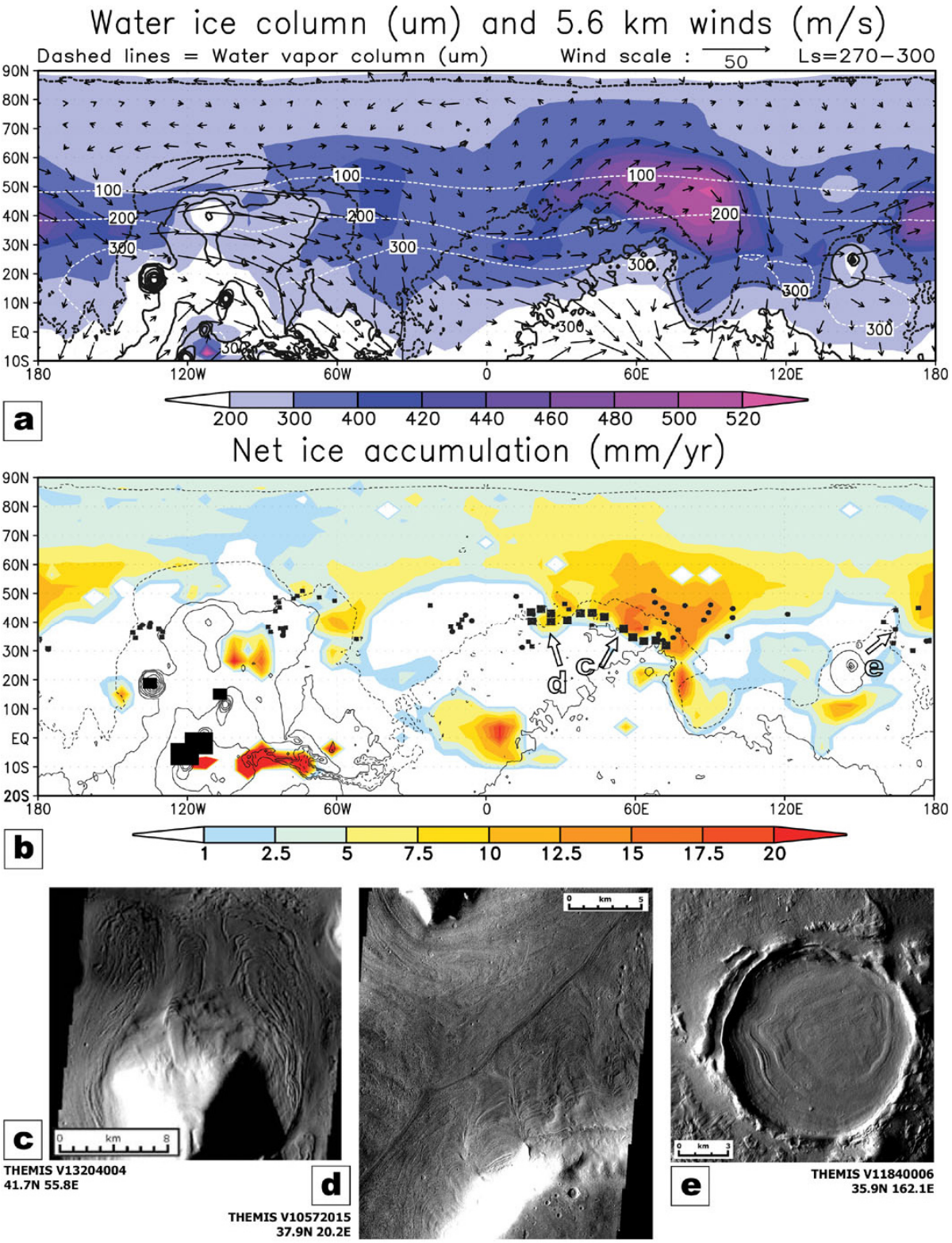

Fig. 1. *a)* Average cloud ice content (pr-µm) and 5.6 km winds for Ls = 270-300°. White lines indicate the water vapor column (pr-µm). *b)* Predicted ice accumulation (mm/yr) superposed on the map by S. Squyres [13]. Squares = lobate debris aprons ; Circles = small impact craters with concentric fill. Equatorial sources are also indicated by large squares. *c)* Two large LDAs surrounding a mesa in Coloe Fossae [14]. *d)* Transition from LDAs to LVF in Mamers Valles [15]. *e)* Viscous flow features inside a crater near Phlegra Montes.

Two other regions are Phlegra Montes (50N-160E) and Mareotis Fossae (44N-75W), where predicted accumulation is around 10 mm/yr. Based on terrestrial analogs and geomorphologic criteria, all these regions have been identified as being intermontaine valley glacial systems of climatic origin [3]. This regional cold-based glaciation is characterized by lobate debris aprons (LDA, see Fig. 1.c) surrounding massifs and valley walls, and lineated valley fill (LVF, see Fig. 1.d) flowing down-gradient on the floor of the valleys to form piedmont-type glaciers when extending out into the adjacent lowlands [2]. LVF occurs when accumulation in protected areas is favored, and may be partly fed from local plateau icefields [16, Fig. 6]. This meteorological control of glacial activity is consistent with climatic predictions on a broad scale basis, and further analysis of this interaction is key to understanding past water cycle and recent climate changes.

4) Regional analysis: Seasonal variations of surface ice deposits in four different regions (see Fig. 2.) clearly show constant precipitation during winter, with a period of enhanced accumulation (pointed out 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 µm. 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 on dust nuclei over glacial regions.

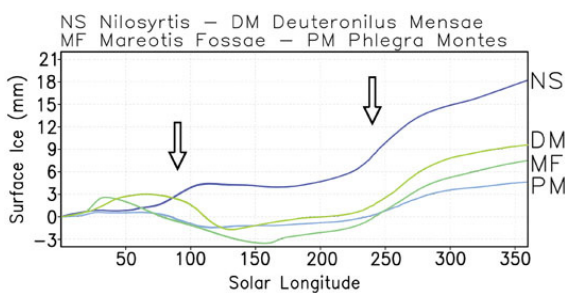

Fig. 2. Evolution of surface water-ice deposits (mm) during one martian year in four selected regions.

Sublimation of the deposits during the summer is also a major factor (first arrow on Fig. 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 Nilosyrtis 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 may 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 [16]. 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] Haberle et al. (2003) *Icarus, 161,* 66-89. [13] Squyres (1979) *J. Geophys. Res., 84,* 8087-8096. [14] Dickson et al. (2006) *LPS XXXVII,* Abstract #1317. [15] Kress et al. (2006) *LPS XXXVII,* Abstract #1323. [16] Head et al., 7th International Mars Conference, this volume.