MARS CLIMATE CHANGES AS SIMULATED BY TRADITIONAL GLOBAL CLIMATE MODELS..

F. Forget Laboratoire de Métérologie Dynamique, CNRS/UPMC/IPSL, Paris, France (*forget@lmd.jussieu.fr*)

Introduction. The variations of the Martian climate in the past thousands and millions of years have been explored for several years using "traditional" Mars Global Climate Models, i.e. design to simulate the present-day environment, but assuming a different obliquity or orbit. Doing so, they may have neglected key processes which have a small impact today but which may have played a major role in the past, such as the radiative effect of clouds (discussed by Madeleine et al. and Haberle et al., this issue), the potential change in surface pressure at high obliquity due to the release of frozen CO2 at the south pole and the desorption of high latitude subsurface CO2, or the atmospheric collapse at low obliquities.

Variation of temperature and seasonal CO_2 ice caps. Assuming that the atmosphere is relatively clear, surface temperatures can be estimated with some accuracy with Global Climate Models (Haberle et al. 2003, Newman et al. 2005) and, before that, by Energy Balance Model (Toon et al., 1980; François et al. 1990, Kieffer and Zent, 1992; Mellon and Jakosky, 1995).

At low obliquity (< 20°), the seasonal variations are small and the poles are cold all year long since the sun is always low in the sky. It is likely that thick permanent CO2 ice caps will form.

At high obliquity (> 30°), seasons are more obvious. At high latitude daily mean temperature can exceed 0°C in summer. At 60° obliquity, the equator-to-pole differences reaches 100 K at summer solstice. The latitudinal extension of the CO_2 cap strongly increases with obliquity. For the 60° obliquity experiment, the winter caps extend all the way to the equator. Thus, virtually the entire surface of the planet has a CO_2 ice covering at sometime during the year. Such a CO_2 ice cover tends to cool the surface on average, notably because its albedo is higher than bare ground. As a result, in Haberle et al. (2003)'s simulations, even at 60° obliquity the poles remain cooler on average than the equator in spite of the fact that they receive more insolation at the top of the atmosphere. Furthermore, the increasing extent of the bright seasonal CO_2 ice caps results in a decrease of the global mean annual temperatures with increasing obliquity (Haberle et al., 2003). This is probably true only if one assume that obliquity only impacts the insolation and the CO_2 cycle and that the Martian atmosphere remains the same. In reality, it is likely that the amount of airborne dust may change, that the surface pressure may vary with obliquity, and that water ice clouds may play a major role.

Changes in the General Circulation.

The changes in the atmospheric dynamics induced by the modification of insolation resulting from the variation of obliquities or longitude of perihelion can also be explored using General Circulation Models [Fenton and Richardson 2001, Haberle et al. 2003, Newman et al. 2005, Forget et al. 2006].

It is found that varying the areocentric longitude of perihelion has a certain impact on the circulation. It is stronger when perihelion aligns with solstice rather than equinox, and especially with northern solstice (due a bias from the martian topography) [Newman et al. 2005].

The influence of obliquity is much stronger, since it directly affects the latitudinal contrast in insolation and temperatures. This thermal contrast is the primary cause of atmospheric movements, and in particular of the meridional overturning Hadley cell formed between the spring-summer and the fall-winter hemispheres. All GCMs show a strong intensification of the Hadley circulation with increasing obliquity. This results in a strong increase of the surface wind speeds for increasing obliquity in the Hadley cell return flow (Trade winds, western boundary current and the monsoon–like summer tropics westerlies). The Hadley circulation dominates over baroclinic, thermal contrast (e.g., cap edge) and topographic flows. Most models (Fenton and Richardson 2001, Haberle et al. 2003) find that the latitudinal extension of the cell is not significantly affected, with only a poleward extension of the ascending branch at high obliquity. As a result, in most places the mean wind orientations are not modified. Among other things, this means that the observed alignment of dunes or other aeolian features with contemporary global wind fields does not necessarily imply that the dunes are contemporary or currently active (Fenton and Richardson 2001).

Dust lifting and dust storms

At obliquities lower than today, with a lower surface pressure and much weaker general circulation winds, the dust storm activity should be much reduced, and the Martian atmosphere clear.

At high obliquities, GCM simulations showed that surface winds and thus the dust lifting potential increases sharply with obliquity. It is greatest at times of high obliquity when perihelion coincides with northern summer solstice (Haberle et al. 2003, Newman et al. 2005). The expected increase in pressure should also contribute to increasing the lifting and transport potential.

When active dust transport is included in GCMs, a wind stress lifting parameter selected to produce realistic results for the current obliquity produces huge amounts of lifting for obliquities of 35°, due to the strong positive feedbacks between atmospheric dust loading, the atmospheric circulation and wind stress lifting (Newman et al. 2005). Can we conclude that at higher obliquities Martian meteorology would be marked by abundant and intense dust storms? This is not certain because the amount of dust lifted by the winds depends not only on the wind velocities, but also on the availability of dust. As on Mars today, the "recharging" of dust sources may limit the frequencies of large dust storms and the mean dust loading. At high obliquities, water ice may also play a major role due to the increased intensity of the water cycle (see below). On the one hand, surface ice may limit the availability of dust on a significant part of the planet. On the other hand, dust may be much more scavenged by ice atmospheric condensation and precipitation.

Modelling water cycle variations to understand past ice ages on Mars. While water is currently unstable at the surface of Mars outside the polar regions, Mars is partly covered by landforms resulting from the local accumulation of ice, such as debris-covered glaciers and ice mantles. These landforms are thought to have formed in the geologically recent past, when the climate system was not very different than today. The kilometers-thick polar ice caps themselves also appear to have formed relatively recently. They exhibit thousands of layers which are most likely related to periodic climate changes.Can we understand the formation of the ice-related landforms described above using models of the Martian climate and water cycle?

To first order, the characteristic of the present-day water cycle, as revealed by the measurements of column water vapor and clouds, are well reproduced and explained by Global Climate Models on the basis of universal physical equations.

In summer, the northern polar region is a source of water vapor that is transported away within the atmosphere. During the rest of the year, most of this water ultimately comes back to the northern polar cap through various transport mechanism. The cycle is closed and near equilibrium (Richardson and Wilson, 2002, Montmessin et al., 2004). On this basis, much has been learned by running climate models designed to simulate the details of the present day climate, but changing the orbital and obliquity parameters as expected in the past

Water cycle variations with perihelion.

Presently, Mars perihelion occurs at L_s=251°, near southern summer solstice (L_s=270°). As a result, the northern pole receives 30% less insolation than the southern pole at summer solstice, when water ice is exposed. This favors the stabilization of ice in the north rather than in the south. Using the LMD GCM, Montmessin et al. [2005] explored the impact of the reversal of perihelion season, which occurred as recently as 21,000 and 75,000 years ago. They found that in these conditions water ice at the North Pole was no longer stable and accumulated instead near the South Pole with rates as high as 1 mm/year. This could have led to the formation of a meters-thick circumpolar water ice mantle, and explain the origin of the small water ice sheet currently observed near the south pole [Bibring et al., 2004]. As perihelion slowly shifted back to the current value, southern summer insolation intensified and the water ice layer became unstable. The layer recessed poleward until the residual CO_2 ice cover eventually formed on top of it and protected water ice from further sublimation. The southern accumulation of water ice at reversed perihelion should be limited to a few meters at each cycle since, on average, the topography asymmetry favor the accumulation ice in the Northern polar regions: On the one hand, models suggest that the southern summer Hadley cell is many times stronger than its northern summer counterpart whose flow overturns in the opposite direction [Richardson and Wilson, 2002a]. On the other hand, the topography may prevent the formation of a Northern "dusty season" and the related atmospheric warming at reversed perihelion [Montmessin et al. 2005]. Thus water may be more cold-trapped on average in the northern hemisphere than in the southern hemisphere

Water cycle variation with obliquity

Reducing the obliquity. Assuming that the main ice reservoirs interacting with the atmosphere are the polar caps, at obliquity lower than today it can be expected that less water vapor will be present in the atmosphere because of the reduced polar summer insolation. Simulations performed with the LMD GCM with the current surface pressure as in Forget et al. (2006) but assuming an obliquity of 15° instead of 25.2° today yields column abundance reaching at most 15 pr-µm at summer high-latitude and about 10 pr-µm in the tropics (compared to 75 pr-µm and 15 pr-µm currently). The abundances are further divided by two in a simulation with obliquity set to 10°. Moreover, as mentioned above, it is likely that at such low obliquities the surface pressure may be much reduced and the atmospheric humidity even smaller. Less water vapor may affect the stability of subsurface ice (see below) and possibly the composition of the atmosphere, since less radicals will be produced by the photolysis of water vapor

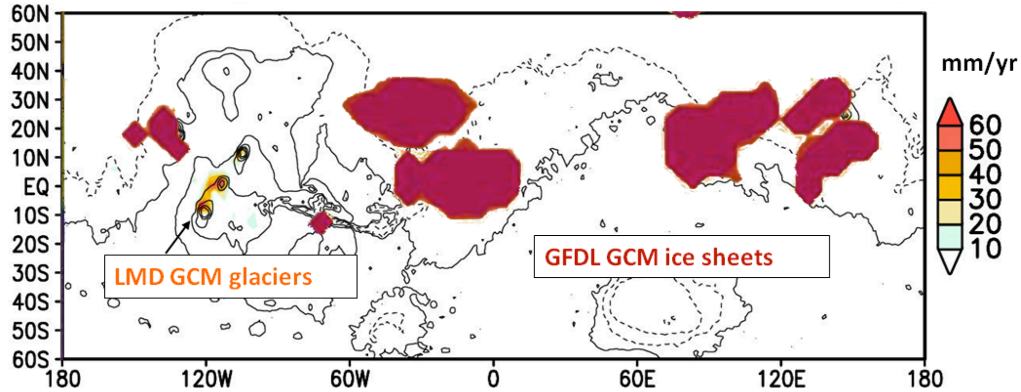

Figure 1. Comparaison of the permanent ice accumulation predicted at 45° obliquity, a circular orbit, and assuming a water ice northern polar cap by the GFDL GCM (red) [adapted from Mischna et al. 2003] and the LMD GCM (blue to orange, to illustrate the surface water ice accumulation) [Forget et al. 2006]. Superimposed MOLA topography contours are 3000 m apart. See text for a discussion of the differences.

Increasing the obliquity. As predicted by Toon et al. (1980) and Jakosky and Carr (1985) on the basis of energy balance calculations, GCM simulations performed assuming the same climate system and initial ice reservoirs (northern polar cap) as today, but assuming higher obliquities, have all shown that the amount of water vapor involved in the seasonal water cycle readily increases with obliquity because of the increase in polar temperatures (Richardson and Wilson, 2002b, Mischna et al. 2003, Levrard et al. 2004, Forget et al; 2006). Typically, at 45° obliquity, the column water abundance reach 2000 to 3000 precipitable micrometers above the northern permanent polar cap around summer solstice (compared to 75 pr-µm on present-day Mars) and about 100-300 pr-µm in the summer tropics (compared to ~15 pr-µm currently) [Richardson and Wilson, 2002b, Mischna et al. 2003, Levrard et al. 2004, Forget et al; 2006]. For moderate obliquities, in spite of the increased humidity, water remains unstable outside the polar regions and all the water transported by the atmosphere is recycled back to the polar caps as it is today. However, above an obliquity threshold ranging between about 35° and 45° (depending on the chosen orbit, the assumed dust loading, as well as the climate model itself), modelers found that the ice would start to accumulate outside the polar regions. Mischna et al. (2003) modeled that the ice tended to accumulate preferentially in regions of high thermal inertia or high topography whereas Forget et al. (2006) found that water ice accumulation (reaching 30 to 70 millimetres per year) occurs in four localized area on the flanks of the Tharsis Montes, Olympus Mons and Elysium Mons (Figure 1). After a few thousand years, such accumulations would form several hundred meters thick glaciers. The difference between the two models can be attributed to the cloud microphysics: Mishna et al. (2003) assumed constant cloud particle size set to 2 µm and thus prevented most precipitation, whereas Forget et al. (2006) included a simplified cloud microphysics which allowed the ice particles to grow with condensation and thus to precipitate where intense condensation was predicted.

The location of the glaciers predicted by Forget et al. (2006) could be compared to the location of the glacier-related deposits mapped in the Tharsis region based on geomorphology. The agreement is remarkable, with maximum deposition predicted on the western flanks of Arsia and Pavonis where the largest deposits are observed and lower deposition on the flanks of Ascraeus and Olympus. During that season, large amounts of ice tend to condense out on the western side of the volcanoes because of strong westerly winds blowing upslope. In such an upward flow the summertime water-rich air is strongly adiabatically cooled by 10 to 20 K. Water condenses and forms ice particles of 20 to 50 microns in diameters that sediment onto the surface (compared to 6-8 microns in the present-day Tharsis clouds). Forget et al. (2006) also performed high obliquity simulations assuming that ice was available in the south polar region (between 90°S and 80°S) rather than in the north, a likely condition with reversed perihelion, as mentioned above. Under such conditions, ice accumulation still occurs in the southern part of Tharsis, but the highest rates are now predicted to be in the eastern Hellas region, almost exactly where a unique concentration of ice-related landforms is observed. Interestingly, the process leading to ice precipitation differs from the one occurring on the volcanoes. In eastern Hellas, almost all the ice is accumulated during a 90 days period around southern summer solstice. At that time, the southern ice cap sublimes and releases large amounts of water vapor to the polar atmosphere. This water vapor is not easily transported toward the equator because the south polar region is isolated by a mid-latitude westward summer vortex, except near eastern Hellas. There, the deep Hellas basin forces a stationary planetary wave that results in a strong northward flow that transports large amounts of water out of the polar region. The moist and warm polar air meets colder air coming from northern Hellas, and the subsequent cooling results in strong condensation and precipitation.

Returning from high obliquity to lower obliquity. Using the LMD model like Forget et al. (2006) (but at lower resolution), Levrard et al. (2004) showed that when Mars returns to lower obliquity conditions, the low and mid-latitude glaciers formed at high obliquity becomes unstable, water ice partially sublimes and tends to accumulate in both hemisphere above 60° latitude. Once water is no longer available from the low and mid-latitude glaciers, water then tends to return to the poles (where it is now), but probably leave some ice under a dry layer. They suggested that such a process could explain the presence of the ice-rich mantling observed by geomorphology and detected by the GRS instrument aboard Mars Reconnaisance Orbiter (see section 0). Madeleine et al. [2009] extended these calculations taking into account the possibility that the atmosphere may be relatively dusty at high obliquity (see above). They showed that during periods of moderate obliquity (25°–35°) and high dust opacity (1.5–2.5), if water ice deposited on the flanks of the Tharsis volcanoes at higher obliquity is still available for sublimation, broad-scale glaciation in the northern mid-latitudes occurs, especially in the Deuteronilus-Protonilus Mensae region (0-80°E, 30-50°N), where large concentrations of lobate debris aprons and lineated valley fills are observed. They proposed that high atmospheric dust contents increase its water vapor holding capacity, thereby moving the saturation region to the northern mid-latitudes. Precipitation events are then controlled by topographic forcing of stationary planetary waves and transient weather systems, producing surface ice distribution and amounts that are consistent with the geological record. Moreover, not only is the modeled accumulation maximum in the regions where glacier-like landforms have been observed, but it is also 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, but at higher obliquity than in Levrard et al. (2004), which is more realistic.

Figure 2 shows an unpublished application of this work in which during half of the year the atmosphere is clear (so that ice accumulate in the Tharsis region like in Forget et al. 2006), and during the other half the atmosphere is dusty, so that the tropical ice moves to the mid latitudes as in Madeleine et al. (2009)

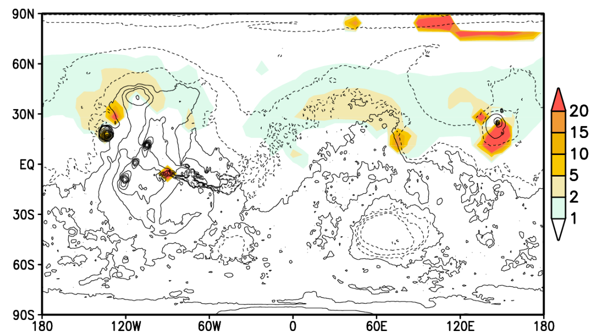

Figure 2. Ice accumulation predicted at 45° obliquity, present day excentricity, perihelion at Ls=270°, and a seasonally varying dust opacity: τ=0.2 for 0°< Ls < 180° and τ = 2.5 for 180°< Ls < 360° assuming a water ice northern polar cap (unpublished results, using the Forget et al. 2006 model)

Remaining modelling issues. GCM model studies have demonstrated that the present Mars Climate system forced by orbit and obliquity oscillations is able to mobilize large amount of ice around the planet. Overall, the agreement between observed ice-sheets, glacier landform locations and model predictions points to an atmospheric origin for the ice and permits a better understanding of the details of the formation of Martian glaciers. However, one must be careful when interpreting these simulations quantitatively, because the models used in the studies cited above may have neglected physical processes which may have played a key role in the past. These include:

– *Radiative effect of clouds*. While clouds play only a secondary role in the present day climate, they should have been much thicker at high obliquity or with non-polar sources. Preliminary GCM simulations performed by Haberle et al. and Madeleine et al. (Thi issue) suggest that their effect could completely modify previous GCM results. In particular, if one assumes that the cloud particle radii remain near 10 µm, clouds could induce a significant greenhouse effect able to significantly warm the planet at high obliquity.

- *Radiative effect of water vapor*. This is neglected on present-day Mars. As in the case of clouds, it may influence our results under past conditions, given the high water vapor holding capacity of the atmosphere.
- *Dust lifting and coupling* with the cloud microphysics, as well as scavenging of dust by water–ice particles.
- *Coalescence of ice crystals* induced by high precipitation events.
- *Physics of the ice deposits*: Latent heat exchange induced by sublimation or melting of the deposits, heating within the ice layer by absorption of solar radiation, and the protective effect of a dust lag (Mischna and Richardson, 2005).

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