THE ORBITAL FORCING OF CLIMATE CHANGES ON MARS

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Abstract. Solar variability influences the climate of a planet by radiatively forcing changes over a certain timescale; orbital variations of a planet, which yield similar solar forcing modulations, can be studied within the same scientific context. It is known for Earth that obliquity changes have played a critical role in pacing glacial and interglacial eras. For Mars, such orbital changes have been far greater and have generated extreme variations in insolation. Signatures associated with the presence of water ice reservoirs at various positions across the surface of Mars during periods of different orbital configurations have been identified. For this reason, it has been proposed that Mars is currently evolving between ice ages. The advent of climate tools has given a theoretical frame to the study of orbitally-induced climate changes on Mars. These models have provided an explanation to many puzzling observations, which when put together have permitted reconstruction of almost the entire history of Mars in the last 10 million years. This paper proposes to give an overview of the scientific work dedicated to this topic.

Keywords: Q1

1. Introduction

After the analysis of the data returned by the Mariner 4 probe sent to Mars in the early 1960s, there was not much room left for the belief that Mars could currently host life. Besides the discovery of a tenuous CO_2 atmosphere (surface pressure $\sim$6 mbar), the surface appeared covered by billion year old craters which had remained almost pristine since the last heavy bombardment. At first glance, water had left landscapes almost intact, and Mars looked little different from our moon. This view has changed substantially over the decades that followed these first discoveries. Thanks to a succession of successful planetary missions, it eventually became evident that running water had carved a myriad of channels and river valleys. These water-related landforms were revealed by increasingly higher resolution pictures of the martian terrains. Recently, dendritic valleys presumably associated with precipitation episodes have been discovered in the equatorial regions (Mangold *et al.*, 2004), strongly supporting the idea that Mars once had an active hydrological cycle, with liquid water exchanging between the atmosphere, the surface and the subsurface. However, these features refer to the early youth of Mars when most of the atmosphere (several bars of pressure) was still present, and various greenhouse gases probably helped maintain the surface temperature above the melting point of

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water (Pollack *et al.*, 1987; Kasting, 1997; Sagan and Chyba, 1997). Aeons have passed since then, during which the atmosphere has progressively lost most of its original mass, making thermodynamical conditions inappropriate for liquid water. And while remnants of localized sporadic discharges have been localized (Malin and Edgett, 2000), large flows of liquid water have certainly not run on the surface in the recent past. It is water ice instead which has left numerous marks of its work on the geology. The picture is now growing that recent Mars ages (the last hundreds of millions of years) have seen multiple events of ice mobilization across the planet. Glaciers, debris aprons, and other ice-flow features are observed at several locations. With the aid of crater counting, many of these geomorphological features have been dated to around several millions of years, which incidentally corresponds to the last excursion of Mars' rotation axis into a regime of high obliquity. This is not a coincidence. Many authors have hypothesized that the planet has encountered multiple climatic changes related to the cyclic variations of its orbital parameters and that this has probably shaped a lot of the Mars we now know (Mustard *et al.*, 2001; Head *et al.*, 2003).

With the accumulation of data, models of various kinds have been developed to interpret observations. Our understanding of Mars history has made considerable progress with the advent of climate simulation tools. Originally developed for Earth, they were later modified to accommodate the specific martian conditions. Compared to Earth however, Mars models have to represent far fewer climatic components and thus suffer less complexity. While Earth climate modelers must deal with the impact of oceans, vegetation and human activity, simulating Mars climate essentially amounts to simulating conditions of a gigantic desert. In turn, Mars offers a good opportunity to exercise models by testing some of their basic foundations. These numerical tools have improved to the point that they now incorporate a fully coupled and self-consistent description of atmospheric circulation, radiative transfer, tracer-related processes and surface interactions. First used to investigate current climate, it has been realized that simply changing the model parameters controlling the orbit would provide an easy and natural spin-off to study Mars recent past climates (those which prevailed during the last hundreds of millions of years). This has been initiated near the end of the 1990s (Haberle *et al.*, 2000), and the interest of the scientific community has never stopped growing since.

In this paper, I attempt to describe the current state of knowledge about recent climatic changes on Mars and their effects on the spatial distribution of water at the surface. This is particularly timely as many pieces of the puzzle have been recently put together thanks to the use of climate simulation tools. As we shall see, Mars is far from being the dead planet some used to think it was.

2. Today's Mars Water Cycle

The current martian atmosphere is very cold (200 K) and dry. Only a thin layer of a few microns would form at the surface if all the water vapor precipitated out. The only known reservoir that appears able to exchange with the atmosphere is located at the North Pole and is commonly referred to as the Northern Permanent Cap (NPC). 3 km thick, 1000 km in diameter (Figure 1, left panel), it would create a global ocean of a few meters deep if melted. When exposed to sunlight in spring/summer (L_S between 60° and 150°), the cap surface warms up to 240 K, and water vapor is forced to sublimate. Despite a sluggish polar atmospheric circulation, water vapor spreads out equatorward, ultimately reaching southern hemisphere latitudes (see Figure 2 for the seasonal water vapor cycle). This transfer to the south is made possible by an overturning atmospheric cell extending between the tropics. A Hadley cell indeed fully develops at both solstices and reverses its orientation during a short season around each equinox. The seasonal cycle of water is characterized by a factor of 2 change in total humidity (Smith, 2002), with the largest fluctuations found at high latitudes where seasonal contrasts are strongest. Interestingly, summertime water vapor extraction from the cap is almost exactly balanced by a seasonal return flow

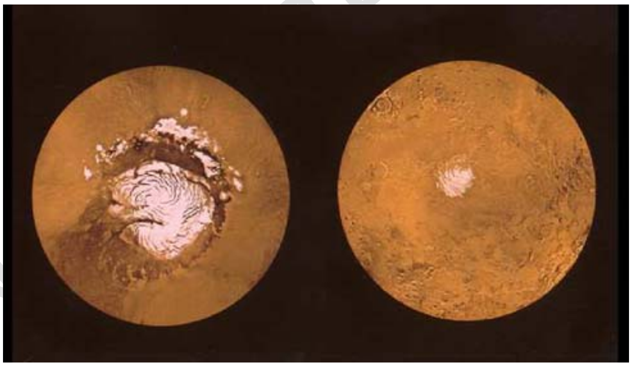

Figure 1. The northern polar cap (left) is composed of water and dust, and the surrounding terrain is relatively smooth. The southern cap (right) is smaller, and is thought to contain both water and carbon dioxide. These pictures are mosaics of images taken by the NASA Viking Orbiter spacecraft, and show each hemisphere from 65° latitude to the poles. Figure reprinted from Gierasch (Nature “News and Views”, 2002).

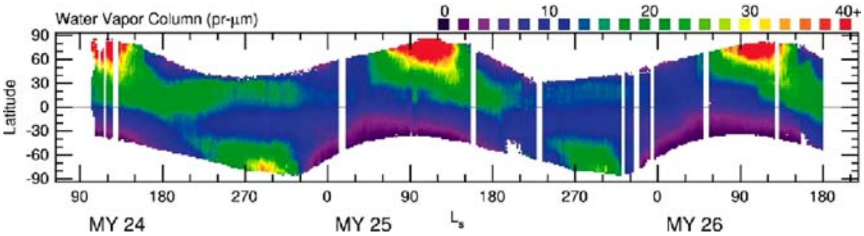

Figure 2. Multi-annual variations of water vapor abundances (in precipitable microns) in the martian atmosphere as observed by the Thermal Emission Spectrometer onboard Mars Global Surveyor. The x-axis gives the evolution of time expressed in aerocentric solar longitude, L_S. In this time reference, a Martian year corresponds to 360°, and northern summer solstice occurs at $L_S = 90°$.

occurring shortly before sublimation season. This has been first predicted by Global Climate/Circulation Model (GCM) computations (Houben *et al.*, 1997; Richardson and Wilson, 2002a) and is now confirmed by several observations showing the recurrent presence of an annulus of water ice slowly creeping to the poles during the spring retreat of the CO_2 seasonal frost (Titus and Kieffer, 2003; Bibring *et al.*, 2005). This return of water closes the annual cycle which thus seems to evolve in a quasi-stationary state.

While it was rapidly discovered that the NPC was made of water ice an dust (Kieffer *et al.*, 1976), the nature of the south residual cap (Figure 1, right panel) has long remained a subject of controversy. Thermal emissions from the surface indicate a temperature close to CO_2 saturation all year long, the result of an annually residing CO_2 ice cover slightly offset from the pole. The debate concerned the actual thickness of the residual CO_2 cap – was it thin? And if so, could it buffer the CO_2 atmospheric reservoir? Theoretical work (Byrne and Ingersoll, 2003) has suggested the CO_2 ice is only a few meters deep and stacked upon what can be considered the "true" component of the south residual cap: water ice. Recent mapping in the near-infrared (where H_2O and CO_2 ices can be identified and separated) by OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) onboard Mars Express and earlier mapping in the far infrared by TES (Thermal Emission Spectrometer) and THEMIS (Thermal Emission Imaging System) onboard Mars Global Surveyor (Titus *et al.*, 2003) confirm this: the CO_2 residual layer indeed forms a thin veneer above a much thicker layer of water ice which actually extends slightly beyond the limits of CO_2. Water ice is even seen at the surface away from the cap as detached and extended bright patches.

Besides the presence of the caps at the poles, water also resides in the shallow subsurface of the high latitude regions in both hemispheres (Feldman *et al.*, 2004). This buried reservoir should interact with the atmosphere on timescales on the order of thousands of years (Mellon *et al.*, 2004) and thus should have limited impact on the seasonal evolution of the water cycle (Böttger *et al.*, 2005). The discovery of subsurface water ice in such large quantities constitutes one of the greatest findings in recent years, yet begs the question of its origin.

3. Mars and Its Shaking Orbit…

If compared to the few watts change in the Earth energetic balance caused by human release of greenhouse gases, orbital cycles on Mars set a much higher standard of climate perturbations. As computed by Laskar and Robutel (1993) from numerical integration of the motion of the solar system bodies, planetary secular perturbations cause the orbit of Mars to experience large variations, largely because no moon can stabilize it like it does for Earth. Over the last 100 million years (Myr henceforth), Mars' obliquity has evolved in a chaotic zone ranging from 0° to 60°. Obliquity oscillations can nevertheless be reconstructed for the last 20 Myr (Laskar *et al.*, 2004; Figure 3, left panel). Changing inclination of the rotation axis has caused

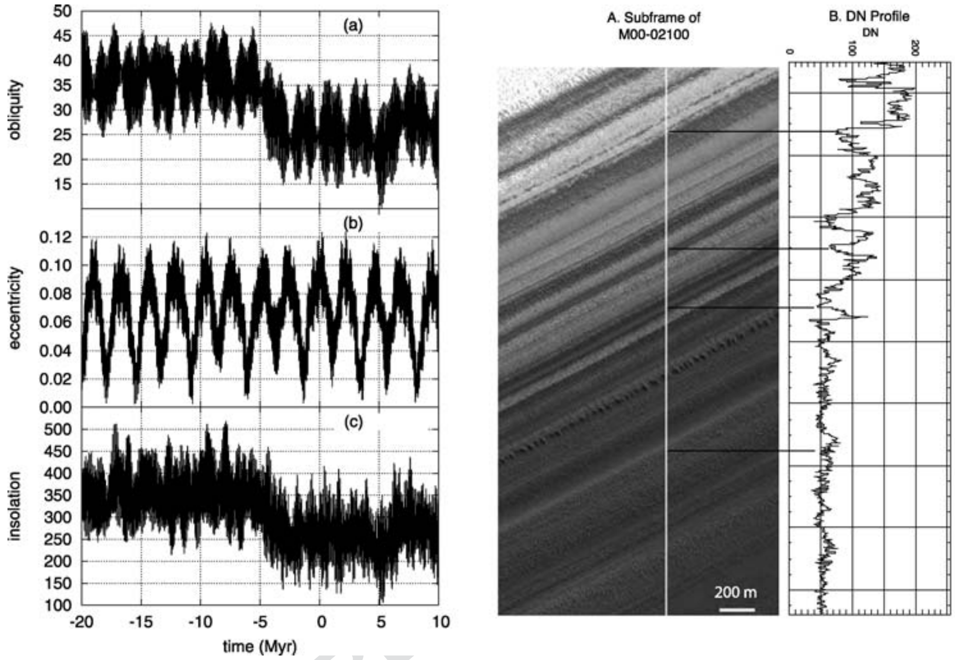

Figure 3. Left panel: (a) Obliquity, (b) eccentricity, and (c) insolation at the north pole surface at the summer equinox over the last 20 Myr and for the next 10 Myr. Figure reprinted from Laskar *et al.* (2004). *Right panel:* (a) Subframe of a MGS/MOC image showing an example of the succesion of bright and dark layers down the trough walls of the north polar layered deposits. (b) DN profile extracted from the same MOC image along the white line traced in the image. Reprinted from Milkovich and Head (2005).

insolation at the poles to vary by more than a factor of three during this period. Five million years ago, when obliquity was oscillating around a higher value (35°) than today (25°), pole insolation was about 50% greater than today.

Mars orbit changes are generally represented by their impact on the summer insolation at the poles since the only reservoirs of water directly in contact with the atmosphere are located there. The sequence of bright and dark layers found within the scarps and troughs of the NPC indicate variation in erosional and depositional rates of water ice, likely reflecting cyclic insolation conditions (Laskar *et al.*, 2002; Milkovich and Head, 2005; Figure 3, right panel). In the polar regions, the solar zenith angle in summer decreases when obliquity increases and surface temperatures are raised accordingly. It is estimated that the temperature at the North pole in summer (currently 240 K) would reach or exceed 270 K at obliquities greater than 45°. By virtue of the Clausius-Clapeyron law, this 30 K difference is exponentially translated into one or two orders of magnitude larger vapor pressure of water and thus into a sublimation process orders of magnitude stronger for the ice at the poles (Jakosky and Carr, 1985; Haberle *et al.*, 2000; Richardson and Wilson, 2002a; Mischna *et al.*, 2003; Levrard *et al.*, 2004; Forget *et al.*, 2006).

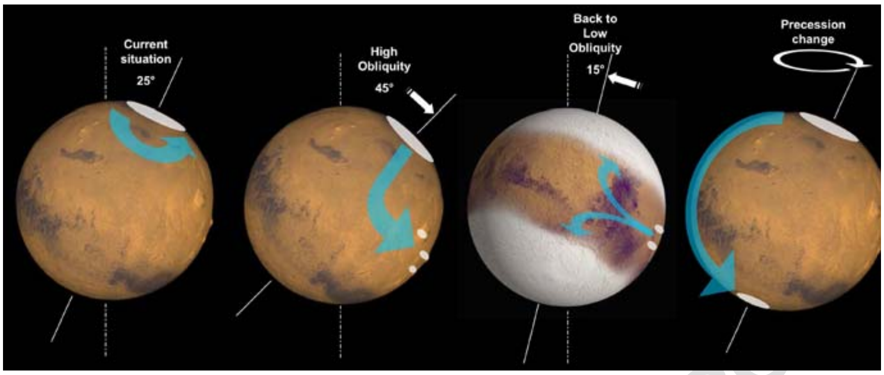

Figure 4. A summary of the recent (last millions of year) changes in the Mars orbital parameters and their consequences on the mobilization of water across the planet. In the first cartoon on the left, the blue arrow is reoriented to the north pole to indicate the seasonal sublimation and return of water to the permanent cap. All other cases with high, low obliquity and precession changes generate a permanent extraction of water from the cap towards locations indicated by the arrows.

Obliquity alone has not paced Mars climate in the recent ages; eccentricity and precession changes have yielded substantial, though milder, solar forcing variations. These two parameters are intimately related as the effect of precession on climate depends on eccentricity. Precession refers to the circular motion of the rotation axis (Figure 4) which cycles on a 50 kyr timescale. While eccentricity makes the climate seasonally asymmetric, precession determines the timing of closest approach to the Sun and thus decides which summer hemisphere receives more sunlight than the other (currently the South). Many studies (Laskar *et al.*, 2002; Hecht, 2003; Milkovich and Head, 2005) favor the precession factor, which has dominated the last 0.5 Myr cycle of insolation, as being one of the main controls on deposition of at least the first hundreds meters of the north polar terrains. This implies that even the smooth climatic changes caused by the precessing rotation axis of Mars have been sufficient to produce observable consequences on the geology. Presumably, changes due to obliquity may have been even more dramatic.

4. Precession Changes

One of the most puzzling aspects of martian geology is the great disparity in resurfacing ages between the polar layered deposits of the Northern and Southern hemispheres (Herkenhoff and Plaut, 2000). While the North polar layered deposits surface appears young (10–100 kyr or less), devoid of large impact craters, the South polar layered terrains has recorded impact events millions of years old (Plaut *et al.*, 1988). Astronomical forcing has no preferred pole, hence the existence of an additional mechanism of likely endogenic origin is required to produce such hemispheric asymmetry. Richardson and Wilson (2002b) have discovered part of the answer in their analysis of the annually averaged circulation pattern on Mars.

Volatile transfer between hemispheres is achieved by Hadley cells which are primarily driven by differential heating across latitudes and which tend to reduce temperature contrast by moving hot air masses to cold regions. On Mars, two components combine to make this process highly asymmetrical about the equator: topography and orbit eccentricity. The latter forces southern spring/summer to be currently 30% more exposed to the Sun than its northern counterpart as southern spring/summer seasons coincide with perihelion passage.

The argument involving topography is based on the fact that the southern hemisphere constitutes a plateau which is 2 or 3 kilometers higher than the northern plains. This has consequences for the meridional transport of volatiles. For reasons still not fully understood, circulation models indicate that the southern summer Hadley cell is many times stronger than its northern summer counterpart (Richardson and Wilson, 2002b), regardless of the eccentricity argument. This bias is in fact independent of any orbital factor and has acted since the formation of the North-to-South topographic dichotomy. Alone, the topographic forcing on circulation favors the accumulation of volatiles in the northern hemisphere and thus the storage of water and dust at the surface of the North polar region. If enhanced accumulation leads to a more effective resurfacing process, then the (Richardson and Wilson, 2002b) mechanism may have participated in making the north pole look younger than the South. This topographic bias led (Richardson and Wilson, 2002b) to speculate that water accumulation at the South pole would not be permitted on timescales shorter than 1 Myr. However, water transport does not uniquely depend on circulation strength; it also depends directly on atmospheric thermal conditions.

Martian Hadley cells are created by air masses converging in the summer tropics where they rise. At higher altitudes, they move to the opposite hemisphere where they sink into colder regions. The loop is completed as air masses cross the equator again, following a near-surface return flow motion. A similar circulation pattern is responsible on Earth for the well-known trade winds. With water, complications arise as it condenses during its ascent within the tropical upwelling zone. At aphelion (northern spring/summer), upward motion and subsequent adiabatic cooling is so efficient that the atmosphere becomes water-saturated before water vapor can reach the upper horizontal branch of the Hadley cell and be carried to the South. This large-scale condensation process has observable consequences since it produces the "Aphelion Cloud Belt" (Clancy *et al.*, 1996); i.e., a ring of clouds enshrouding the northern low latitudes. The same does not currently occur at perihelion since enhanced sunlight pushes the water condensation to sufficiently high altitudes so as to suppress cloud formation in the southern summer tropics. Clancy *et al.* (1996) proposed that when water sublimates from the pole whose summer coincides with the colder conditions of aphelion, it is forced to pool in the same hemisphere as a result of cloud precipitation and sequestration of humidity in the aphelion convergence zone. For the current orbital configuration, this process helps the northern hemisphere to retain water. This cloud-induced mechanism is called the “Clancy Effect” and has been supported and even quantified by several climate models (Richardson and Wilson, 2002a; Montmessin *et al.*, 2004).

Today, both topography and eccentricity conspire to make the North pole the preferred destination for water. However, the CO_2 residual cap imposes year-round freezing conditions which force water to condense and be permanently trapped when it is transported near the surface of the South pole. Stability of the residual CO_2 ice cap is another long-standing issue of the Mars climate, but it has been suggested that it may not survive more than a few hundreds or thousands of years (Byrne and Ingersoll, 2003). With such a CO_2 cold trap, a net North-to-South flux of water is unavoidable. But when the trap is absent, topography and eccentricity should have ample time to work against the presence of water ice at the South pole. If water ice instead of CO_2 was covering the South pole today, it would rapidly sublimate and transfer to the North (Richardson and Wilson, 2002b).

Half a precession cycle ago (25 kyr), perihelion passage was synchronized with northern summer (hereafter called “reversed perihelion”). The eccentricity effect was then favourable to volatile accumulation in the southern hemisphere and thus was opposed to the topography effect. With climate models gaining in maturity, it has become possible to confront the theory of Clancy *et al.* (1996) with that of Richardson and Wilson (2002a) to ascertain whether the cloud-induced mechanism could be strong enough in case of “reversed perihelion” to overcome the topographic forcing on circulation and let water accumulate in the South. This study was conducted with a Mars GCM developed at the Laboratoire de Météorologie Dynamique (LMD-France), where the only changes from the original version of the model were the removal of the current CO_2 cold trap at the south pole and a perihelion timing phased with northern summer (Montmessin *et al.*, 2004). In such a martian world, where the northern summer is warmer than the south, sublimation from the NPC is reinforced, and clouds no longer restrain the transport of water to the South. As expected by Clancy *et al.* (1996), water accumulates at the South pole where thermodynamic conditions are more favorable (Figure 5).

However, the model also predicts that the thermal structure of the atmosphere, which is highly sensitive to the abundance of airborne dust particles, would not vary seasonally with the same contrast as today. The potential for dust lifting should considerably diminish in a “reversed perihelion” climate. While (Montmessin *et al.*, 2004) can not yet propose a complete explanation for this behavior, it appears intuitively linked to the absence in the North of regional sources of dust as productive as in the South, like the Hellas basin where dust storms are regularly observed. Ultimately, the dust cycle, which currently has a pronounced maximum during southern summer, would remain constant in a reversed perihelion climate, substantially reducing the thermal contrast between the two seasons. This effect would not keep water from migrating to the south pole, rather transfer would be two or three times less efficient than in a reversed perihelion climate having the same seasonal contrast as today (see the comparison of the two curves in Figure 5).

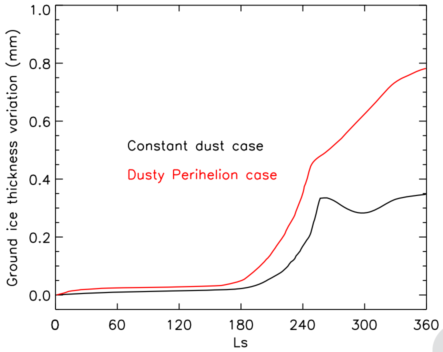

Figure 5. Results obtained by the model in a situation of reversed perihelion. The two curves show the thickness variation of water ice at the surface of the south pole during a martian year. In both cases, water ice accumulates at rates slightly less than 1 mm/yr. The red curve shows what would happen if the reversed perihelion climate had the same dust cycle and thus the same seasonal contrast as today. The black curve shows what would happen if the dust loading was low and had no seasonal variation, as might be expected from dust lifting predictions in a reversed perihelion climate.

Provided the obliquity is not too high, precession changes can be responsible for a pole-to-pole migration of water. Very recent (∼10 kyr) orbital configurations may have allowed water to accumulate in the South, in contrast with the million years timescale hypothesized by Richardson and Wilson (2002a). Is the exposed water ice in the South a remnant of such precession induced water transfer? Possibly, but it requires additional understanding of the layering process in the South polar region. Does it explain the discrepant ages of the two poles? Partially, since the proposed mechanism is made asymmetric by its relation to the dust cycle. Still, the existence of a precession-induced water transport mechanism is consistent with the thickest portion of the NPC which shows strong correlation with the recent precession-dominated insolation signal. As modelled by Mischna *et al.* (2003), at times of high obliquity, precession changes could also have led to a redistribution of water between the two hemispheres, but at low latitudes.

5. Mars Water Cycle at High Obliquity

The effect of obliquity has long been suspected to have had strong consequences for the martian water cycle. Based on calculated insolation variations at the poles, Jakosky and Carr (1985) have suggested that episodes of high obliquity could have caused water to precipitate at low latitudes very early in the planet's history, when the Tharsis topographic bulge was not even formed.

Jakosky and Carr (1985) have probably inspired our modern view of recent climate changes on Mars, although their conclusion may have been somewhat misleading. Their study was based on simple theoretical arguments, assuming thermodynamical conditions at the surface determine the zones where water ice

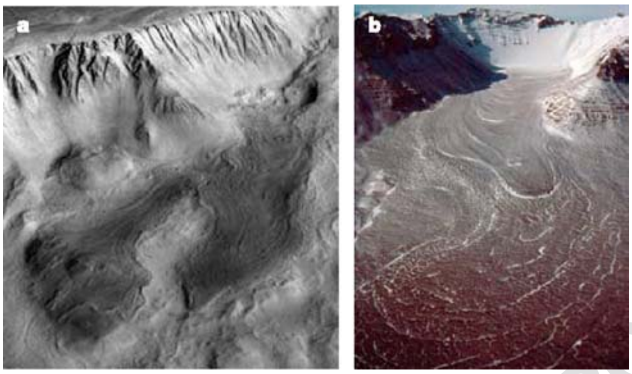

Figure 6. Deposits from a young lobate rock glacier at the base of the Olympus Mons scarp (138°W, 18°N). (a) Perspective view looking southwest towards the 6 km-high scarp. Note lobate deposits extending about 20–25 km from the base of the alcoves (from right centre towards lower left) darkened for emphasis. HRSC data from Mars Express. (b) Perspective view of the upper ∼5 m of a debris-covered rock glacier emerging from a cirque in Mullins Valley, Antarctic Dry Valleys on Earth. Note the morphologic similarity to features at the base of Olympus Mons. Figure and caption reprinted from Head *et al.* (2005).

can be stable. At high obliquity, these zones should be confined to near the equator where Sun exposure in summer is weaker than at the poles. However, the first simulations based on a GCM set with a high obliquity configuration (Haberle *et al.*, 2000) have showed that if water indeed accumulates at low latitudes, the pattern is not uniform in longitude, but instead concentrates almost uniquely near elevated places like the Tharsis region. Mischna *et al.* (2003), who also pioneered simulation of the water cycle at high obliquity with a GCM, made similar conclusions as Haberle *et al.* (2000). However, they found a correlation with thermal inertia in addition to that with topography, a result somewhat contrasting with other climate models.

Surface properties are indeed not uniform, but albedo and thermal inertia alone are not sufficient to explain the preferred ice accumulation zones predicted by the model. In fact, another factor not accounted for by Jakosky and Carr (1985) controls these emplacements, and circulation is the key.

As illustrated by Figure 6, some Tharsis volcanoes exhibit the presence of features on their flanks that bear a striking resemblance to features created by precipitation-fed glaciers on Earth (Head and Marchant, 2003). Remarkably, these glaciers are about 4 Myr old (Neukum *et al.*, 2004), contemporaneous with the most recent regime of high obliquity on Mars (later, obliquity transitioned to lower values, as at present). To account for the formation of these putative glaciers, Forget *et al.* (2006) have added to previous work by running the LMD model at much higher spatial resolution (with a grid about 8 times more refined) and by using a more sophisticated cloud model wherein cloud particle size is predicted, rather than set constant and left unchanged from its present value as in previous

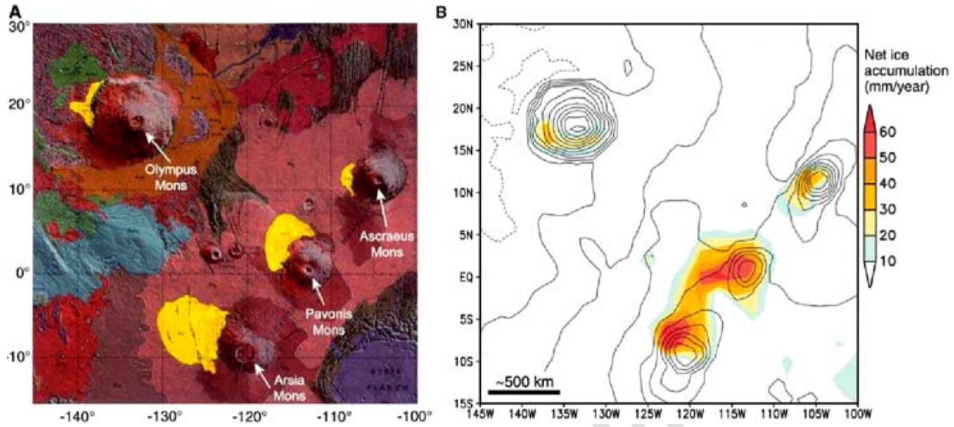

Figure 7. (a) Geologic map of the Tharsis region showing the location of fan-shaped deposits of Amazonian age (yellow) located on the northwest slopes of the Tharsis Montes and Olympus Mons. (b) Net surface water ice accumulation in the Tharsis region simulated with a 45° obliquity and assuming that surface water ice is present but sublimating at the North pole. Superimposed topography contours. Reprinted from Forget *et al.* (2006).

works (Mischna *et al.*, 2003; in the work of Haberle *et al.*, 2000, ice clouds are not modelled, the atmospheric holding capacity is limited by water saturation). If precipitation is indeed a key aspect of glacier formation, then it demands that models properly represent cloud particle fall, which depends almost uniquely on particle size. The higher spatial resolution adds a significant benefit as it allows one to resolve the dimensions of many observed glacial features, not to mention the fact that it also simulates wind patterns more accurately.

Like other GCMs, the (Forget *et al.*, 2006) LMD model produces a much more intense water cycle at high obliquity than it does at the present obliquity, with 30 times more water sublimating from the NPC. However, the locations of accumulation are restricted to a few small areas while other models predict much more extended and sometimes totally different zones. These areas are found on the flanks of volcanoes in the Tharsis region, but also on Olympus (Figure 7) and Elysium Mons, precisely where glaciers are thought to have developed. Provided the predicted accumulation rates existed for thousands of years, the (Forget *et al.*, 2006) model suggests that precipitation could have created water ice edifices hundreds of meters thick. Water only precipitates in these regions because a monsoon-like circulation pattern conveys it to the volcanoes. As this wet air blows over the flanks, it cools and condenses, forming icy particles ten times larger than in today's martian clouds. Particles rapidly precipitate, and water ice accumulates on the windward side of the volcanoes.

The (Forget *et al.*, 2006) study also predicts precipitation in the southern mid latitudes, explaining new observations of geologically recent ice flow features in a small area located east of the Hellas crater rim. The working hypothesis for the explanation of these features is based on the results presented in the previous section which indicate that precession changes could lead to water accumulation at the south pole. Eventually, such transfer could create a significant reservoir similar to the NPC, but this time in the South. If such was the case 5 Myr ago, when Mars was in the high obliquity regime, huge amounts of water may have been extracted from this southern ice cap, intensifying the water cycle just as did the NPC at high obliquity. This time however, water would not only precipitate in the Tharsis region but would also be deposited east of Hellas. Again, this is precisely where many geomorphological features (tongue-shaped lobes, hourglass-shaped craters filled by debris-covered glacier) have been detected, and, again, this is due to a particular circulation pattern that is imposed by the huge topographic depression of Hellas.

6. From High to Low Obliquity

In the previous part, we have seen how the high obliquity climate that prevailed several Myr ago has created several localized ice reservoirs outside the polar regions. Even though these sources are now extinct, they were probably active during the rapid transition from the high to low mean obliquity regimes that occured 4 Myr ago. To understand to where water could have been mobilized in such circumstances, the LMD model was used again (Levrard *et al.*, 2004). Figure 8 shows the predicted map of water accumulation when the model assumes only one source of water located in the Tharsis region and an obliquity decreased to 15°, a value reached several times since the obliquity transition. The model suggests that high latitudes would become the preferred location for water at the surface. Even when the equatorial water source is exhausted, the stability pattern remains almost unchanged. Except for the outer latitudinal edges which are slightly eroded, water resides poleward of 60° in both hemispheres. Nearly 10 meters could have accumulated during an obliquity cycle of 15°, lasting 60 kyr.

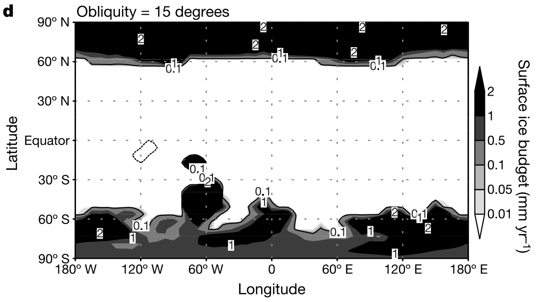

Figure 8. Surface water ice budget in mm per martian year after ten years of simulation for an obliquity of 15°and with an equatorial ice reservoir situated in the Tharsis region whose boundaries are indicated by a thick solid line. This reservoir is set to be the only active water source. Reprinted from Levrard *et al.* (2004).

In that case, atmospheric circulation does not solely determine where water is stable on the surface, but rather a simple energy balance argument can explain the result. With decreasing tilt of the rotation axis, the equatorial reservoir becomes highly exposed, and water sublimates massively in spring and summer. Released water accumulates in the fall/winter high latitude regions where temperature conditions (imposed by the presence of a seasonal CO_2 frost cover) favor ice stability at the surface. Deposition rates are so large compared to sublimation rates that ice is able to survive through spring and summer. Ice accumulation does not exhibit significant zonal structure even though it is a little less uniformly distributed in longitude and latitude in the southern than in the northern hemisphere. The more pronounced structure in the South is probably the result of a strong poleward stationary flow heavily loaded in humidity, escaping from the Hellas basin in spring and leading to a preferred deposition of water in the eastern hemisphere.

Again, these results find an echo with the recent observations of the Gamma Ray Spectrometer (GRS) (Mars Odyssey Mission) which have revealed the presence of subsurface water ice in the first meters of the martian regolith. Data indicate that closer to the equator, water ice is buried deeper. There is a sharp latitudinal cut-off around 60°, equatorward of which water ice is either not detected or in very low quantity. Levrard *et al.* (2004) propose that the return to present obliquity, with the equatorial source completely exhausted, desiccated the upper portion of the high latitude ice that is predicted by the model to have been deposited under conditions of low obliquity. Because water ice crystals that precipitate on the surface are formed on airborne dust particles, sublimation of such ice would leave dust particles behind and progressively create a protective lag which would act as a thermal insulator, preventing further sublimation. In this explanation, what has been seen by GRS would simply be the remainder of the water ice sublimated from equatorial glaciers at low obliquity and deposited at higher latitudes then hidden below a dust layer which thickened during the desiccation process.

Another convincing explanation has been proposed to explain the GRS discovery. Mellon *et al.* (2004) and, more recently, Mellon and Feldman (2005) showed that the GRS mapping of subsurface water ice coincides almost exactly with the stability zones of ground ice which have been deduced from a 1D regolith model. This would suggest water was emplaced by diffusion from the atmosphere through the regolith pores, instead of having been deposited at the surface during the obliquity transition. In the (Mellon and Feldman, 2005) explanation, climate change is not invoked since ground-ice distribution reflects the mean climatic conditions that have prevailed during the last hundred to thousand years.

7. Conclusion

The story of recent martian climates is slowly emerging (a summary of it is given in Figure 4). We now see Mars as a planet whose water has cycled on the surface among several specific areas during the last hundreds of millions of years. In fact, computations show that the most probable obliquity over the last 4 billions of years has been 41.8° (Laskar *et al.*, 2004), which implies that the planet has spent most of its time with the poles facing the Sun much more than today. As a consequence, current Mars probably renders a false image of its usual appearance. Until recently, active glaciers at low latitudes and no ice at the poles may have been closer to its common look.

Now that most orbital configurations have been explored, it will be hard for climate models, if they remain in their current state, to produce again such original findings. They need to evolve. Important improvements concern the implementation of several feedbacks still ignored. All the water cycle studies presented in this paper have been conducted without the effects of wind on dust lifting, without the radiative effects of water ice clouds, without the effects of latent heat... Other efforts will have to be made regarding the representation of surface modifications resulting from evaporation and deposition processes. Such modifications subsequently affect the exchange of water between the soil and the atmosphere and they also determine the aspect of layered deposits and thus have implication for our interpretation of Mars climate history.

Although models still need significant improvements, they have already provided believable, although still debated, answers to many questions posed by the Mars geology. It is fascinating to realize these tools can be used to study a planet other than that for which they were originally designed. Terrestrial models find in Mars an alternative application that suggests an underlying level of consistency. Is it now the time for Mars to give back to Earth research? Possibly. While more and more scientific projects are now turned to the characterization of climates in desert environments, it would be interesting to see what can be learned from Mars conditions that could help with the understanding of those encountered in terrestrial places. Among the possible by-products of the study of Mars is the refinement of dust/sand storm predictions, and the understanding of how mineral and condensate particles interact. This would provide more perspectives into the so-called indirect effect of aerosols on the Earth climate; as on Mars, clouds and dust are perfectly isolated from other kinds of particles. Mars, like other telluric objects, must be used as a full-scale experimentation chamber that nature has given to humanity to understand its own habitat.

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References

Bibring, J. P., Langevin, Y., Poulet, F., Gendrin, A., Gondet, B., Berthé M., Soufflot A., Drossart, P., Combes, M., Bellucci, G., Moroz, V., Mangold, N., Schmitt, B., and the OMEGA team: 2004, ‘Perennial water ice identied in the south polar cap of Mars’, *Nature* **428**, 627–630.

Bibring J. P., Langevin, Y., Gendrin, A., Gondet, B., Poulet, F., Berthé, M., Soufflot A., Arvidson, R., Mangold, N., Mustard, J., Drossart, P., and the OMEGA team: 2005, ‘Mars surface diversity as revealed by the OMEGA/Mars express observations’, *Science* **307**, 1576–1581.

Böttger, H. M., Lewis, S. R., Read, P. L., and Forget, F.: 2005, ‘The effects of the Martian regolith on GCM water cycle simulations’, *Icarus* **177**, 174–189.

Byrne S., and Ingersoll, A. P.: 2003, ‘A sublimation model for Martian south polar ice features’, *Science* **299**, 1051–1053.

Clancy, R. T., Grossman, A. W., Wolff, M. J., James, P. B., Rudy D. J., Billawala, Y. N., Sandor, B. J., Lee, S. W., and Muhleman D. O.: 1996, ‘Water vapor saturation at low latitudes around aphelion: A key to Mars climate?’, *Icarus* **122**, 36–62.

Feldman, W. C., *et al.*: 2004, ‘The global distribution of near-surface hydrogen on Mars’, *J. Geophys. Res.* **109**, doi:10.1029/2003JE00216.

Forget, F., Haberle, R. M., Montmessin, F., Levrard, B., and Head, J. W.: 2006, ‘Formation of glaciers on Mars by atmospheric precipitation at high obliquity’, *Science* **311**, 368–371.

Haberle, R. M., McKay C. P., Schaeffer, J., Joshi, M., Cabrol, N. A., and Grin, E. A.: 2000, ‘Meteorological control on the formation of Martian Paleolakes’, In *Lunar and Planetary Institute Abstracts*, 31st Annual Lunar and Planetary Science Conference, Houston, Texas, abstract no. 1509.

Head, J. W., and Marchant, D. R.: 2003, ‘Cold-based mountain glaciers on Mars: Western Arsia mons’, *Geology* **31**, 641–644.

Head, J. W., Mustard, J. F., Kreslavsky, M. A., Milliken, R. E., and Marchant, D. R.: 2003, ‘Recent ice age son Mars’, *Nature* **426**, 797–802.

Head, J. W., Neukum, G., Jaumann, R., Hiesinger, H., Hauber, E., Carr, M., Masson, P., Foing, B., Hoffmann, H., Kreslavsky, M., Werner, S., Milkovich, S., van Gasselt, S., and the HRSC team: 2005, ‘Tropical to mid-latitude snow and ice accumulation, flow and glaciation on Mars’, *Nature* **434**, 346–351.

Hecht, M. H.: 2003, ‘What is the time scale for orbital forcing of the Martian water cycle?’, In *International Conference on Mars Abstracts*, Sixth International Conference on Mars, Pasadena, California, abstract no. 3285.

Herkenhoff, K. E., and Plaut, J. J.: 2000, ‘Surface ages and resurfacing rates of the polar layered deposits on Mars’, *Icarus* **144**, 243–253.

Houben, H., Haberle, R. M., Young, R. E., and Zent, A. P.: 1997, ‘Modeling the Martian seasonal water cycle’, *J. Geophys. Res.* **102**, 9069–9083.

Jakosky, B. M., and Carr, M. H.: 1985, ‘Possible precipitation of ice at low latitudes of Mars during periods of high obliquity’, *Nature* **315**, 559.

Kasting, J. F.: 1997 ‘Warming early Earth and Mars’, *Science* **276**, 1213.

Kieffer, H. H., Martin, T. Z., Chase, S. C., Miner, E. D., and Palluconi, F. D.: 1976, ‘Martian north pole summer temperatures – dirty water ice’, *Science* **194**, 1341–1344.

Laskar, J., and Robutel, P.: 1993, ‘The chaotic obliquity of the planets’, *Nature* **361**, 608–612.

Laskar, J., Levrard, B., and Mustard, J. F.: 2002, ‘Orbital forcing of the martian polar layered deposits’, *Nature* **419**, 375–377.

Laskar, J., Correia, A. C. M., Gastineau, M., Joutel, F., Levrard, B., and Robutel, P.: 2004, ‘Long term evolution and chaotic diffusion of the insolation quantities of Mars’, *Icarus* **170**, 343–364.

Levrard, B., Forget, F., Montmessin, F., and Laskar, J.: 2004. ‘Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity’, *Nature*, **431**, 1072–1075.

Malin, M. C., and Edgett, K. S.: 2000, ‘Evidence for recent groundwater seepage and surface runoff on Mars’, *Science* **288**, 2330–2335.

Mangold, N., Quantin, C., Ansan, V., Delacourt, C., and Allemand, P.: 2004, ‘Evidence for precipitation on Mars from dendritic valleys in the valles Marineris area’, *Science* **305**, 78–81.

Mellon, M. T., and Feldman, W. C.: 2005, ‘Martian ground ice and equilibrium with atmospheric diffusion’, *AGU Fall Meeting Abstract*.

Mellon, M. T., Feldman, W. C., and Prettyman, T. H.: 2004, ‘The presence and stability of ground ice in the southern hemisphere of Mars’, *Icarus* **169**, 324–340.

Milkovich, S. M., and Head, J. W.: 2005, ‘North polar cap of Mars: Polar layered deposit characterization and identification of a fundamental climate signal’, *J. Geophys. Res.* **110**, E01005, doi:10.1029/2004JE002349.

Mischna, M. A., Richardson, M. I., Wilson, R. J., and McCleese, D. J.: 2003, ‘On the orbital forcing of Martian water and CO2 cycles: A general circulation model study with simplified volatile schemes’, *J. Geophys. Res.* **108**, 5062, doi:10.1029/2003JE002051.

Montmessin, F., Haberle, R. M., and Forget, F.: 2004, ‘Making water ice permanent at the South pole 25,000 years ago’, In *Lunar Planet. Sci. Conference Abstracts*, 35th Lunar and Planetary Science Conference, League City, Texas, abstract no. 1312.

Mustard, J. F., *et al.*: 2001, ‘Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice’, *Nature* **412**, 411–414.

Neukum, G., *et al.*: 2004, ‘Recent and episodic volcanic and glacial activity on Mars revealed by the high resolution stereo camera’, *Nature* **432**, 971–979.

Plaut, J. J., Kahn, R., Guinness, E. A., and Arvidson, R. E.: 1988, ‘Accumulation of sedimentary debris in the south polar region of Mars and implications for climate history’, *Icarus* **76**, 357–377.

Pollack, J. B., Kasting, J. F., Richardson, S. M., and Poliakoff, K.: 1987, ‘The case for a wet, warm climate on early Mars’, *Icarus* **71**, 203–224.

Richardson, M. I., and Wilson, R. J.: 2002a, ‘Investigation of the nature and stability of the Martian seasonal water cycle with a general circulation model’, *J. Geophys. Res.* **107**, 5031, doi:10.1029/2001JE001536.

Richardson, M. I., and Wilson, R. J.: 2002b, ‘A topographically forced asymmetry in the Martian circulation and climate’, *Nature* **416**, 298–301.

Sagan, C., and Chyba, C.: 1997, ‘The early faint sun paradox: Organic shielding of ultraviolet-labile greenhouse gases’, *Science* **276**, 1217–1221.

Smith, M. D.: 2002, ‘The annual cycle of water vapor on Mars as observed by the thermal emission spectrometer’, *J. Geophys. Res.* **107**, doi:10.1029/2001JE001522.

Smith, M. D.: 2004, ‘Annual variability in TES atmospheric observations of Mars during 1999– 2003’, *Icarus* **167**, 148–165.

Titus, T. N., and Kieffer, H. H.: 2003, ‘Temporal and spatial distribution of CO$_2$ snow and ice’, *International Conference on Mars Abstracts*, Sixth International Conference on Mars, Pasadena, California, abstract no. 3273

Titus, T. N., Kieffer, H. H., and Christensen, P. R.: 2003, ‘Exposed water ice discovered near the south pole of Mars’, *Science* **299**, 1048–1051.

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