Icarus 222 (2013) 415–418

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Note

Summary of the Marsrecent climate change workshop NASA/Ames Research Center, May 15–17, 2012

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ARTICLE INFO

Article history:
Received 3 July 2012
Revised 15 October 2012
Accepted 19 October 2012
Available online 27 October 2012

Keywords:
Mars
Climate
Polar
Ground ice

ABSTRACT

This note summarizes the results from the Mars recent climate change workshop at NASA/Ames Research Center, May 15–17, 2012.

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1. Background and context

Climate change on Mars has been a subject of great interest to planetary scientists since the 1970s when orbiting spacecraft first discovered fluvial landforms on its ancient surfaces and layered terrains in its polar regions. By far most of the attention has been directed toward understanding how "Early Mars" (i.e., Mars >∼3.5 Ga) could have produced environmental conditions favorable for the flow of liquid water on its surface. Unfortunately, in spite of the considerable body of work performed on this subject, no clear consensus has emerged on the nature of the early martian climate system because of the difficulty in distinguishing between competing ideas given the ambiguities in the available geological, mineralogical, and isotopic records.

For several reasons, however, the situation is more tractable for "Recent Mars" (i.e., Mars within ∼20 Ma). First, the geologic record is better preserved and evidence for climate change on this time scale has been building since the rejuvenation of the Mars Exploration Program in the late 1990s. The extended temporal coverage of the planet from orbit and the surface, coupled with accurate measurements of surface topography, increasing spatial resolution of imagers, improved spectral resolution of infrared sensors, and the ability to probe the subsurface with radar, gamma rays, and neutron spectroscopy, has not only improved the characterization of previously known climate features such as polar layered terrains and glacier-related landforms, but has also revealed the existence of many new features thought to be related to recent climate change such as polygons, gullies, concentric crater fill, internal structure of the polar layered deposits, latitude-dependent, and volatile-rich surface mantling.

Second, the likely cause of climate change – spin axis/orbital variations – is more pronounced on Mars compared to Earth. Spin axis/orbital variations alter the seasonal and latitudinal distribution of sunlight, which can mobilize and redistribute volatile reservoirs both on and below the surface. Within 20 Ma, for example, the obliquity is believed to have varied from a low of $\sim 15^\circ$ to a high of $\sim 45^\circ$ with a regular oscillation time scale of $\sim 10^5$ years. The amplitude of the corresponding variations for Earth is typically less than 2°. Mars, therefore, offers a natural laboratory for the study of climate change induced by significant spin axis/orbit variations on a terrestrial planet.

Finally, general circulation models (GCMs) for Mars have reached a level of sophistication that justifies their application to the study of spin axis/orbitally forced climate change. With recent advances in computer technology the models can run at reasonable spatial resolution for many Mars years with physics packages that include cloud microphysics, radiative transfer in scattering/absorbing atmospheres, surface heat budgets, boundary layer schemes, and a host of other processes. To be sure, the models will undergo continual improvement, but with carefully designed experiments they can now provide insights into mechanisms of climate change in the recent past.

Thus, within 20 Ma the geologic record is better preserved, the forcing function is large, and GCMs have become useful tools. While research efforts in each of these areas have progressed considerably over the past several decades, they have proceeded mostly on independent paths occasionally leading to conflicting ideas. To remedy this situation and accelerate progress in the area, the NASA/Ames Research Center's Mars General Circulation Modeling Group hosted a 3-day workshop on May 15–17, 2012 that brought together the geological and atmospheric science communities to collectively discuss the evidence for recent climate change on Mars, the nature of the change required, and how that change could be brought about. Over 50 researchers, students, and post-docs from the US, Canada, Europe, and Japan attended the meeting. The program and abstracts from the workshop are

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0019-1035/$ - see front matter Published by Elsevier Inc.
doi:10.1016/j.icarus.2012.10.009

available to the public at http://spacescience.arc.nasa.gov/mars-climate-workshop-2012/home.html.

2. Key questions and starting point

Some specific questions addressed at the workshop were: What constraints does the geologic evidence place on the magnitude, timing, and duration of climate change? How well do we know the orbital history of Mars and the magnitude, timing, and duration of its obliquity, eccentricity, and precessional variations? What is the present nature and distribution of the surface and subsurface volatile reservoirs of water and CO_2? And what changes to the climate system result from orbital variations, and how do those changes alter these volatile reservoirs? As the discussion began, there was general agreement among workshop participants on two main points:

2.1. Evidence for geologically recent climate change on Mars is strong

The existence of a variety of non-polar ice-related deposits that cannot be produced in today's climate system provides the strongest evidence for this (see Fig. 1). These include midlatitude glacial features (particularly in the Deuteronilus Mensae region where there is evidence for a large integrated glacial system comparable to Earth's continental ice sheets), concentric crater fill (where the floors of some midlatitude craters are filled and show parallel ridging), remnant CO_2 glaciers (where drop moraines left by cold-based glaciers appear to require soft flowing material), pedestal craters (where the ejecta blanket protects underlying ice while sublimation lowers the surrounding regions), and tropical mountain glacier deposits (on the NW flanks of Olympus Mons and the Tharsis Montes). The ages of these features span the Amazonian epoch (past 2–3 Gy), but many are geologically young. There is also a young, ice-rich, latitude-dependent mantle that is widespread in mid and high-latitudes of both hemispheres. The surface deposits that form this mantle are diverse in their morphology and topography, and include features such as polygons, layers, and gullies. This latitude dependent mantle appears to consist of a succession of meters-thick deposits whose deposition and removal is most likely related to orbitally forced climate change.

2.2. The main driver for recent climate change is spin axis/orbital variations

The lack of a stabilizing Moon, and the proximity to Jupiter lead to large variations in Mars' spin axis/orbit parameters. The most recent published calculations of these parameters (see Fig. 2) were updated for the workshop using the latest information on planetary and asteroid positions and show that the limits of predictability are ~60 My for orbital position, ~40 My for eccentricity, and ~20 My for obliquity. Beyond these times the solutions become chaotic. However, up until then these quantities can be accurately predicted, and they still show very large variations in eccentricity (~0–0.12) and obliquity (~15–45°) during the time for which they are predictable. This provides the climate modeling community with an accurate history of spin axis/orbit variations, which can be used to assess the consequences on the climate system.

3. Workshop results

The workshop program consisted of 33 half-hour talks organized into six sessions with ample time for discussion. Some of the highlights that emerged from the individual presentations and ensuing discussions include the following.

3.1. The origins of the subsurface water ice need further analysis

Neutron data from Mars Odyssey and radar data from Mars Express and the Mars Reconnaissance Orbiter have revealed the presence of near surface ice at middle and high latitudes of both hemispheres (Fig. 1). Vapor diffusion models are in remarkably good agreement with the observed spatial extent of this ice suggesting that vapor diffusion is a potential emplacement mechanism and that the ice is in quasi-equilibrium with present day atmospheric vapor abundances. However, the observed ice is not simply pore-filling ice; the measured concentrations imply almost pure ice. Vapor diffusion alone cannot explain this excess ice. One possibility is in situ segregation of pore ice by the flow of water through thin films that forms ice lenses. Some preliminary modeling work explored the feasibility of this mechanism, but the results depend on poorly constrained parameters. Another possibility is that the excess ice was created by direct snowfall from a past epoch when the

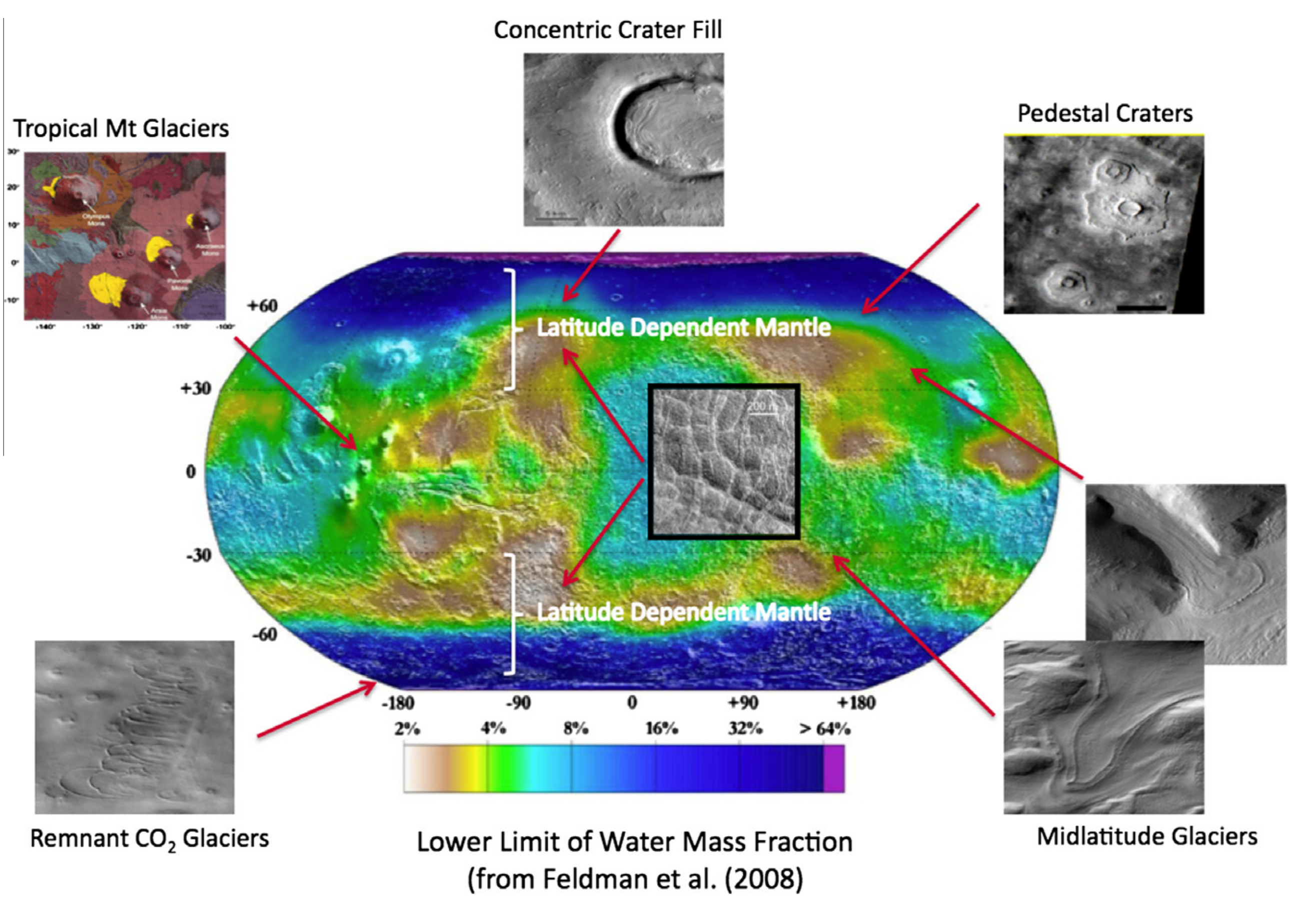

Fig. 1. Sample evidence for recent climate change on Mars. After Head and Marchant (2009). See text for details. (See above-mentioned references for further information.)

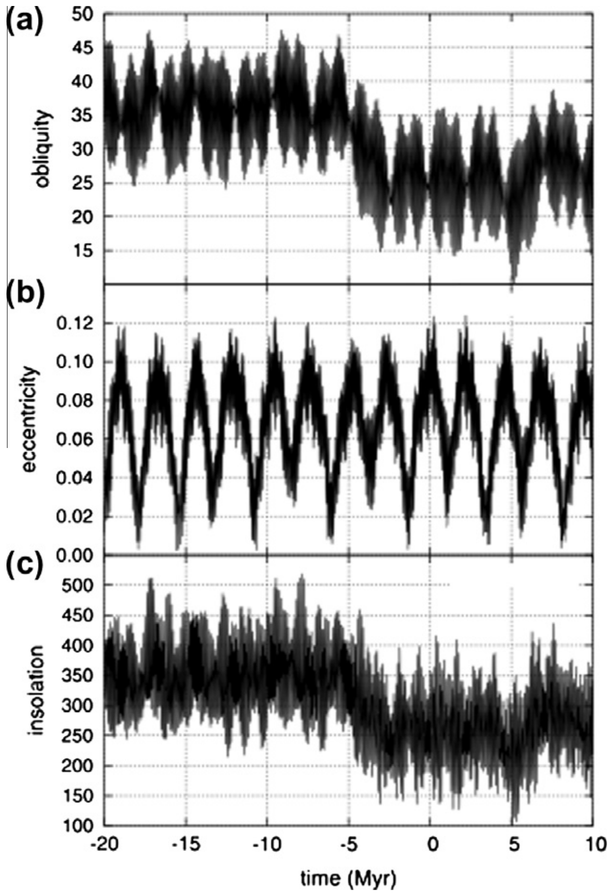

Fig. 2. (a) Obliquity (degrees), (b) eccentricity, and (c) insolation (W m^{-2}) at the North Pole for the past 20 My and the next 10 My. From Laskar et al. (2004).

obliquity was high. Then as the obliquity decreased, a dusty lag deposit protected the ice from subliming away. As mentioned earlier, there is evidence for past glacial activity and glacial flow models and GCMs are beginning to show how this is possible. However, while snowfall could explain the excess ice, it seems inconsistent with the presence of surface rocks, which should be buried and not visible under this scenario. Vapor diffusion, ice lenses, and snowfall may each be viable emplacement mechanism for subsurface ice on Mars, but for now the relative roles of each remain uncertain.

3.2. The north polar layered deposits are young

Topographic and radar data show that a several km thick deposit of water ice exists at the North Pole with a volume roughly equivalent to ~10 m deep global equivalent water layer. How and when was this polar deposit formed? The calculated orbital history for the past 20 My shows that the mean obliquity exceeded 35° until about 5 Ma. If the ice is older than 5 My then it would need a thick sublimation lag to survive. Yet radar data do not indicate the presence of such a lag. Ice accumulation models that incorporate the obliquity variations suggest that the north polar layered deposits (NPLD) began forming ~4 Ma and could accumulate to the observed thickness during that time. Furthermore, the internal stratigraphy they predict is consistent with the radar data and suggests that the NPLD has not flowed significantly. Thus, the NPLD is likely to be a geologically young feature.

3.3. Atmospherically significant amounts of CO_2 ice are buried at the South Pole

The situation at the South Pole is entirely different from the North Pole. CO_2 ice survives near the South Pole all year long and the volume of the surface deposits appears to be equivalent to ~3% of the present atmospheric mass. However, radar data suggest that ~5 mb of CO_2 global equivalent is buried beneath the south polar residual cap. When this deposit was created and how it has been stabilized is uncertain but its radar-implied cleanliness suggests that it probably came from the atmosphere during a low obliquity period. Thus, this could represent an exchangeable reservoir of CO_2 that can lead to high surface pressures at high obliquity and low surface pressures at low obliquity, relative to current surface pressure. Given the present size of the atmosphere/cap system (~7 mb), this means the surface pressure could fluctuate between ~0.5 and 12 mb. The presence of gullies, crater clusters, and remnant CO_2 ice glaciers, support the notion that surface pressures have varied in the recent past.

3.4. Clouds may play a significant role in past climates

As noted earlier, GCMs have demonstrated the potential to mobilize and redistribute ground ice in response to orbital variations. As the obliquity increases the water cycle intensifies and the atmosphere becomes wetter and cloudier. Above a critical obliquity value (nominally ~35°), the NPLD is no longer stable and water is transferred into non-polar ice sheets. In some of the simulations, the location of the non-polar deposits is in very good agreement with observations. However, none of these earlier simulations included the radiative effects of the clouds. Several workshop presentations examined the role of radiatively active clouds and found conflicting results. In some cases, the clouds were found to produce a strong greenhouse effect warming surface temperatures by many 10's of Kelvins. In other cases, the effect was minimal. The discrepancies may be related to how the models represent cloud microphysical processes and their radiative effects, which are only now beginning to be included in the models and which differ from model to model. Thus, just as for Earth, clouds and their radiative effects will be a challenge for future GCM research.

3.5. Present buried water ice may still be retreating

One of the surprising recent discoveries on Mars is the presence of nearly pure ice at shallow depths just equatorward of the predicted stability boundary. This ice was exposed in several small fresh impact craters at northern midlatitudes and disappeared within a few months time. Its existence suggests that midlatitude buried ice extends to lower latitudes than can by seen by Mars Odyssey and is perhaps the remnant of an earlier ice mantle that is still retreating. Modeling studies were presented that support this idea provided the ice mantle was emplaced less than 1 Ma. This allows high latitude ice to equilibrate, as is observed, while low latitude ice is still retreating. The loss rates at mid latitudes are equivalent to ~10 μm of water per unit area per Mars year, which may be returning to the poles.

3.6. Melting of subsurface water ice may have occurred at low obliquity

High obliquity states received most of the attention at the workshop because of their destabilizing effect on polar volatiles. However, there are some potentially important effects of the low obliquity state that center on the nature of subsurface water. At low obliquity permanent CO_2 ice caps can form that lower surface pressure. Lower surface pressures decrease the soil thermal conductivity, which can lead to increased subsurface temperatures as the planetary heat flow becomes trapped by the development of an insulating layer near the surface. Modeling studies were presented that showed melting was possible depending on the magnitude of the pressure drop and strength of the heat flow. The consequences of this effect imply that episodic subsurface melting of ground ice could be a regular feature of spin axis/orbitally induced climate change.

3.7. Ripples and dunes indicate shifting wind patterns

Eolian processes play a major role in shaping the martian surface and ripples and dunes are an expression of them. Their orientation provides information on wind directions at the time they were formed. Mesoscale models and GCMs are beginning to explore the relationship between eolian-inferred wind directions and past climates. One such case discussed at the workshop was related to the ripples observed at Meridiani Planum by the Opportunity Rover. The morphology of superposed craters in the Meridiani ripple field indicates they were active 50–200 Ka and that the ripple-forming winds were primarily from the east as opposed to today's southeasterly winds. Simulations for selected orbital conditions during the past 50–200 Ky do show changes in wind direction and strength, but the simulated changes fall short of explaining the observed wind shift and suggest that other factors must be involved.

4. Conclusions

It was clear from workshop presentations that there has been much progress in understanding recent climate change on Mars. Most notably are the quasi-quantitative characterization of volatile reservoirs in the polar regions and near-surface ground ice in middle and high latitudes. However, many questions remain. Some of the keys ones identified at the end of the workshop were: What is the threshold obliquity for the release and uptake of the CO_2 buried at the South Pole? What is the precise link between the formation of the NPLD and climate? Is there any evidence in the geologic record that would confirm the predicted obliquity variations for the past 10 My? What precisely are the origins of subsurface ice and did it ever melt? Is there any evidence in the geologic record to support the possibility of a significant cloud greenhouse effect? How did the CO_2, dust, and water cycles change and interact during these climate changes? Progress towards answering these questions will come from continued analysis of imaging, radar, and other remote sensing data as well as modeling studies of the surface, subsurface, and atmosphere. Hopefully, the workshop motivated its participants to continue working on these questions so that the next time they meet, some answers will emerge.

Acknowledgments

We are grateful to the Space Science and Astrobiology Division at NASA/Ames Research Center and the Planetary Exploration Division at NASA Headquarters for their support of this workshop.

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