Decoding the Climate Signal in the Tharsis Montes Fan-Shaped Deposits: The Dynamics of Tropical Mountain Glaciers. S. J. Kadish[1], J. W. Head[1], F. Forget[2], J. L. Fastook[3], and D. R. Marchant[4], [1]Dept. of Geol. Sci., Brown University, Providence, RI, 02912, USA (Seth_Kadish@Brown.edu), [2]Laboratoire de Météorologie Dynamique du CRNS, Université Paris, Paris, France, [3]Climate Change Institute, University of Maine, Orono, ME, 04469, USA, [4]Dept. of Earth Sci., Boston University, Boston, MA, 02215, USA.

Introduction: Fan-shaped deposits (FSD) extending to the NW of the Tharsis Montes on Mars (Fig. 1) are the remnants of Amazonian-aged, cold-based, tropical mountain glaciations [1-5]. Geomorphological analyses of the facies within the deposits have revealed a number of ice-related features including moraines and sublimation till [1-5], as well as subglacial volcanic features [6]. Atmospheric models [e.g. 7] have shown that ice/snow will accumulate on the western flanks of the Tharsis Montes during periods of high obliquity (>45°) (Fig. 1b). These have worked in conjunction with ice-sheet models (Fig. 1c) [8-11] to reproduce possible histories for the growth and retreat of the glaciers. An understanding of both the geomorphologies within the FSDs and the atmospheric and glacial dynamics is necessary as we continue to decode the climate signal left by these glacial deposits.

Here, we summarize the current progress and future steps required to extrapolate the full significance of the FSDs. In particular, we review the geology, ice-sheet models, and atmospheric models. Additionally, we stress the need for mesoscale models, which will be crucial in constraining equilibrium line altitudes (ELAs), accumulation rate distributions (ARDs) and various aspects of the evolution of the glaciers.

Tropical Mountain Glacier FSDs as a Climate Signal: The Tharsis Montes FSDs have been interpreted to be glacial in origin on the basis of their facies [1-5]. The most prominent units include concentric ridges tracing the distal margin of the FSD and a knobby facies distributed over much of the FSDs. These have been interpreted as drop moraines and sublimation till, respectively. The drop moraines form at the end of the glacier, where debris is deposited and builds up during periods of glacial equilibrium. The knobs form when supraglacial material is deposited upon rapid sublimation/down-wasting of the glacier. Although the units have been studied in detail [1-5], more information about the past climate of Mars is cryptically held within the FSDs – information that requires a better understanding of the atmospheric and glacial dynamics in the Tharsis region. These outstanding questions include, but are not limited to: 1) What causes the differences in relative orientation of the FSDs? 2) Where are the accumulation zones of each of the glaciers and what were the maximum thicknesses of the ice sheets? 3) How frequently have these glaciers formed, and did they necessarily all form at the same time? 4) Why does the knobby facies only cover part of each FSD? 5) What is the climate signal left by the drop moraines?

This last question, in particular, is aimed at the goal of using the existing geology to the reveal a record of the paleoclimate (Fig. 2). Solving this problem will require the efforts of geologists and modelers. To be successful, we will need an improved understanding of: 1) how ice migrates from the poles to the equatorial regions, 2) the rate at which ice can accumulate on the flanks of the Tharsis Montes 3) the sensitivity of the resulting glacial mass balance to its environment and, 4) the relationship between moraine morphology and glacial equilibrium.

Glacial Mass Balance and Equilibrium Line Altitudes: A crucial element of decoding the relationship between the geomorphologies in the FSDs and the past climate conditions (Fig. 2) is an understanding of the mass balance of glaciers on Mars. While the relationship between glacial dynamics and climate can be readily measured on Earth using a number of methodologies based on direct observations, remote sensing, hydrological evaluations and/or climatic calculations, the problem is much more complex on Mars. Efforts to investigate martian mass balance [8,12-13] have a number of poorly constrained parameters including: (1) the water vapor saturation of the atmosphere, (2) the atmospheric pressure, (3) the atmospheric dust content, (4) variations in obliquity and insolation, and (5) the historic lapse rate. From this, it is clear that more accurate meteorological data are needed, including continuous measurements of the water vapor distribution and dust content and a detailed knowledge of regional wind regimes.

Another necessary aspect to constraining the mass balance problem is to identify the elevations and gradients of the equilibrium line altitudes (ELAs) [9]. Fastook et al. argue that ice accumulation depends on the saturation vapor pressure of the atmosphere, which has an exponential temperature dependence. Ablation for martian glaciers is due primarily to sublimation, not melting. The rate of sublimation depends on saturation vapor density, and thus has the same exponential temperature dependence. It should be noted that, unlike on Earth, surface temperatures on Mars are not sensitive to altitude. As such, sublimation rates are weakly dependent on altitude, due only to minor changes in atmospheric pressure. Accumulation via precipitation, however, is more strongly altitude dependent because condensation takes place in the atmosphere, not on the surface, where temperatures do vary with elevation.

The vertical lapse rate on Mars is less than half of what it is on Earth; current estimates suggest that the dry adiabatic lapse rate on Mars is around 4.3 K/km, while on Earth it is 9.8 K/km [14]. Fastook et al. [9] note that the gradual reduction in temperature at high elevations means that both sublimation and accumulation rates will decrease. Sublimation, however, has an inverse dependence on atmospheric pressure, and because surface temperatures are independent of altitude, sublimation will decline less rapidly than accumulation as elevation increases, creating negative net mass balance at high elevations. Similar to Earth, we would also expect negative net mass balance at low elevations where there is declining relative humidity, increasing ventilation, and possibly some melting/sublimation. Based on this framework, Mars should have two ELAs – a high and a low elevation ELA, with positive mass balance in between, and negative mass balance above the upper ELA and below the lower ELA [9].

The thickness of the glacier cannot significantly exceed the elevation of the upper ELA because ice sublimates rapidly above this elevation. As a result, if the glacier were to reach this maximum thickness at its accumulation zone, additional accumulation would yield significant outward growth, extending the snout of the glacier. The gradient of the upper ELA determines the maximum thicknesses of regions downslope of the accumulation zone – if the ELA were perfectly horizontal, the maximum thickness would be constant as a function of distance away from the accumulation zone (Fig. 3). The gradient of the lower ELA determines the stability of the ice at the snout. Thus, the elevations and gradients of the ELAs can be manifested as significant changes in mass balance and in resulting ice configurations. Unfortunately, it is currently unclear what the elevations of these ELAs are in the Tharsis region, and what gradient they have as a function of distance from the Tharsis Montes.

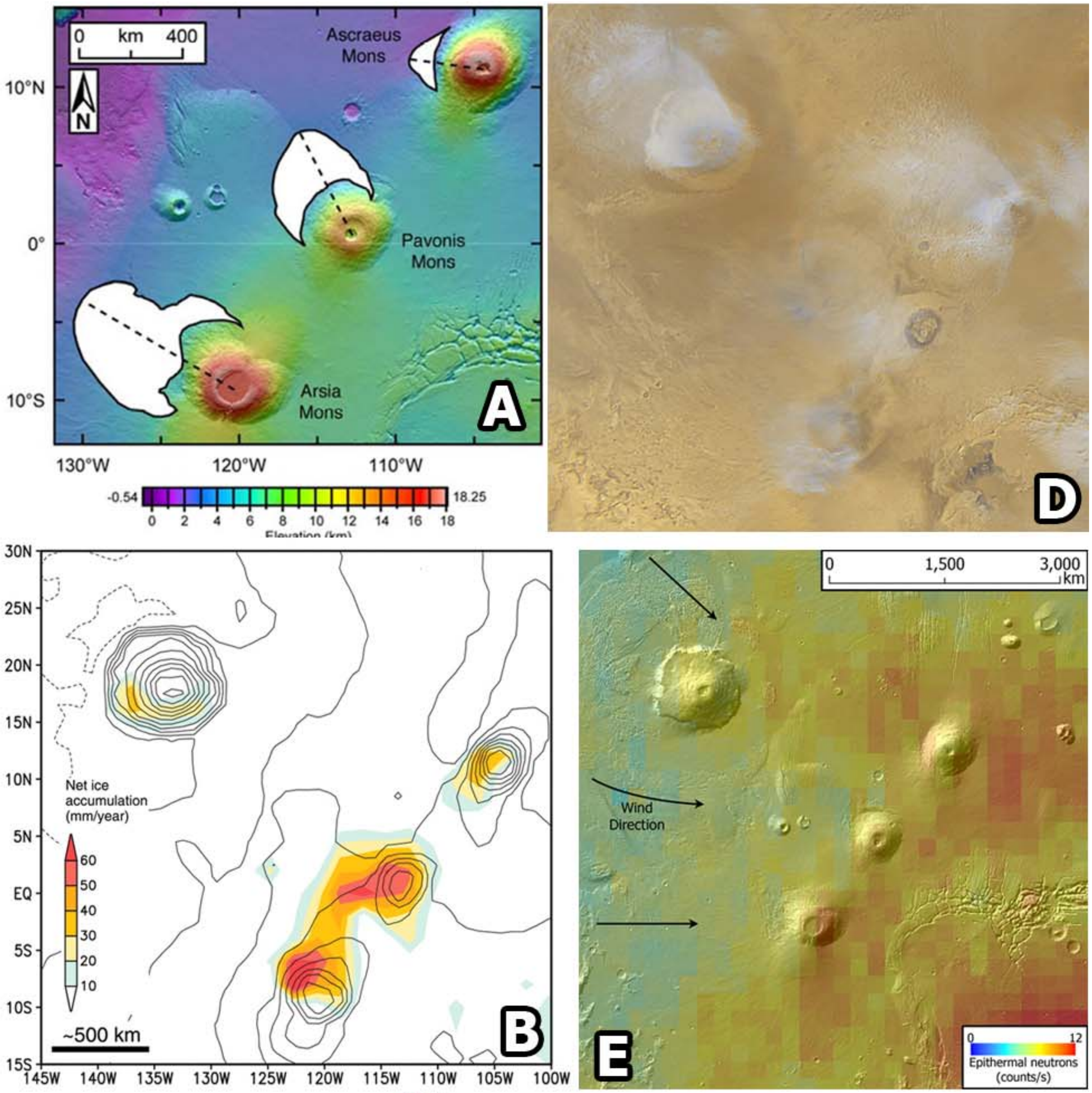
Despite these limitations, estimations for unknown values have allowed ice-sheet modeling by Fastook et al. [8-11] to provide possible histories for the growth and retreat of the Tharsis Montes glaciers. These histories match the orientation and maximum size of the glaciers with relative accuracy (Fig. 1c). The Fastook et al. model [8] uses bed topography, surface temperature, geothermal heat flux, and the accumulation rate distribution (ARD) as the primary inputs. The bed topography is quite well known, and the surface temperatures have been estimated based on climate models. The geothermal heat flux and the ARD remain less well-known.

Atmospheric Modeling: Results from mesoscale atmospheric models (Fig. 4) may help limit uncertainty in the ARD and constrain former ELAs. A mesoscale model of atmospheric circulation at Arsia Mons by Rafkin et al. [15] shows dust transport using a simulation of the thermal circulation. The simulation, which reflects some seasonal variations, predicts strong adiabatic cooling of the air as it rises up the western flank of the mountain, with a small vortex showing the wind changing directions as it rises over ~13 km in elevation. The more dominant flow, however, becomes horizontally divergent at the top of the thermal circulation, cooling to 135 K at 30 km in elevation. Rafkin et al. note that, at this height, water-ice clouds would be expected to form. Additional mesoscale models for this region are needed to improve our understanding of local wind regimes and the accumulation and ablation rates at each of the Tharsis Montes.

The results of general circulation models [7] have been largely successful in matching the geologic observations of the location and extent of the FSDs. Modeling by Forget et al. predicts a strong northwesterly wind direction in the Tharsis region during the northern hemisphere summer at 45° obliquity. In their model, enhanced polar ice sublimation allows volatiles to accumulate in specific regions at low latitudes. In the Tharsis region, water vapor in the atmosphere moved from west to east, and rose upon encountering the slopes of the volcanoes, inducing adiabatic cooling. This caused H_2O to precipitate as snow and ice – from 30 to 70 mm/yr – on the western flanks, allowing glaciers several kilometers thick to form on thousand-year timescales (Fig. 1b). Forget et al. [7] also show that Ascraeus and Olympus only receive precipitation during the northern summer, whereas accumulation of ice can occur throughout the year at Pavonis and Arsia. During other seasons, Ascraeus and Olympus are exposed to weaker winds while Pavonis and Arsia experience precipitation from a symmetrical southern hemisphere monsoon circulation which occurs throughout the southern hemisphere spring and summer. This helps to explain the relatively small size of the FSD at Ascraeus (northern most volcano) relative to that at Arsia (southern most volcano) and Pavonis.

Discussion: Although data from future missions will likely be the key to cracking the code and ultimately relating the moraines to the history of the tropical mountain glaciers and the martian paleoclimate, much work can still be done to constrain unknown values and produce more accurate models. The collaborative effort produced by atmospheric models, ice-sheet models, and geological analyses can be continuously refined. In particular, we hope to advance this research via the following three methods: 1) Performing a detailed comparison of the three Tharsis Montes FSDs, which will include an accurate record the frequency (spacing) of moraine emplacement. 2) Working with glacial models [8-11] to identify how changes in the glacial dynamics (mass balance, ELAs, etc.) affect the evolution of the glaciers. Specifically, we aim to understand what conditions are necessary to produce long-standing periods of glacial equilibrium, during which time moraines are formed. 3) Running GCMs [7] using a zoom function on the Tharsis Region, which clusters the grid points in the area, increasing the local resolution of the model. This is not a replacement for mesoscale models, which should be used in addition to bridge the gap between atmospheric and glacial models. The GCM results will, however, help to reveal how variations in obliquity and atmospheric properties affect the accumulation of ice and snow on the western flanks of the Tharsis Montes.

References: [1] Head J. W. and Marchant D. R. (2003) *Geology, 31,* 641–644. [2] Shean D. R. and Head J. W. (2005) *JGR., 110,* E05001. [3] Milkovich S. M. et. al. (2005) *Icarus, 181,* 388–407. [4] Shean et al. (2007) *JGR, 112*, doi:10.1029/2006JE002761. [5] Kadish S. J. et al. (2008) *Icarus,* in press. [6] Head J. W. and Wilson L. (2007) *Ann. Glaciol., 45*, 1-13. [7] Forget et al. (2006) *Science, 311*, 368-371. [8] Fastook, J. L. et. al. (2004) *LPS* XXXV #1452. [9] Fastook, J. L. et. al. (2005) *LPS* XXXVI #1212. [10] Fastook, J. L. et. al. (2006) *LPS* XXXVII #1794. [11] Fastook, J. L. et. al. (2007) *LPS* XXXVIII #1119. [12] Greve, R. (2000) *Icarus, 144*, 419-431. [13] Schmidt, K. G. (2004) *LPS* XXXV, #1554. [14] Leovy, C. (2001) *Nature, 412,* 245-249. [15] Rafkin et al. (2002) *Nature, 419,* 697-699.



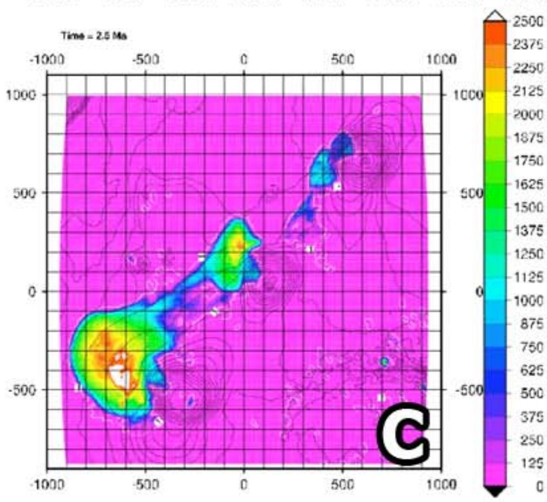


Figure 1: A) Map of the Tharsis Montes from Shean et al. (2005) showing the FSDs mapped in white. B) The GCM results from Forget et al. (2006). These show accumulation of ice on the NW or W flanks of each of the Tharsis Montes at an obliquity of 45°. C) The ice-sheet model results from Fastook et al. (2005), showing the thickness of the glaciers after 2.6 million years of growth. D) MOC2-144 release from Malin Space Science Systems/NASA. The color mosaic shows typical afternoon cloud cover on the western sides of the Tharsis Montes. E) Epithermal neutron data superposed on a MOLA hillshade of the Tharsis Montes. Regions with low epithermal neutron counts/sec correspond to high hydrogen levels (interpreted to be water-equivalent hydrogen). The westerly wind occurs at an elevation of 2 km, as shown by Forget et al. (2006). In this image (from Kadish et al., 2008) the windward sides of the Tharsis Montes have higher hydrogen concentrations than the leeward sides. This is likely the result of an orographic effect.

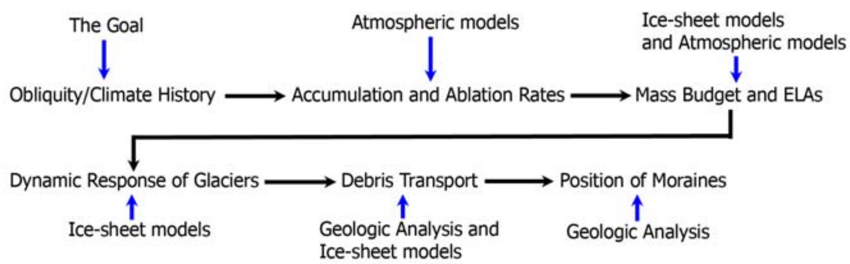


Figure 2: A chain of factors (and the most appropriate method for investigating them) relating martian climate to the FSDs. The obliquity of Mars dictates the amount of incident insolation for a given latitude; direct insolation on ice or ice-rich soil can lead to sublimation, increasing the concentration of volatiles in the atmosphere. The obliquity also affects the atmospheric dynamics, altering the magnitude and directionality of regional winds. Accumulation and ablation rates depend both on the saturation of volatiles in the atmosphere and on the regional winds. The mass budget of a glacier and the positions of the ELAs are controlled largely by the accumulation and ablation rates. The positions of the ELAs are also dependent on some key atmospheric properties. The mass budget and ELAs are necessary to establish a glacier's dynamic response to changes in climate, and therefore influence how debris will be transported in and/or on a glacier under different climate regimes, and the timing of debris deposition. The deposition of debris and the size of a glacier at equilibrium, as achieved via dynamic response to climate changes and mass loading, determine the position of the moraines.

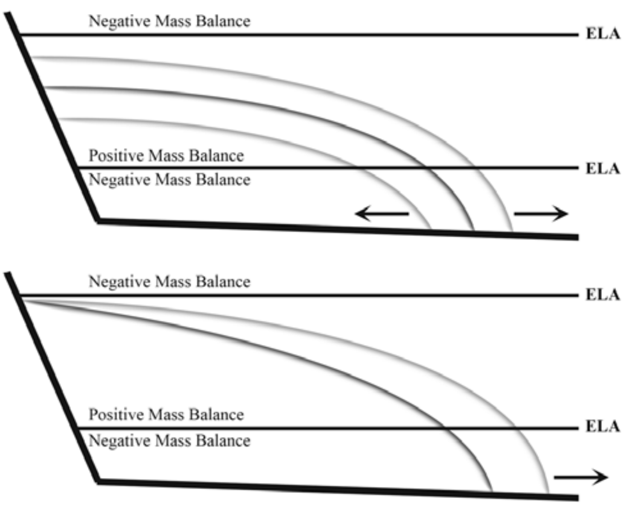


Figure 3: A conceptual diagram showing how the position of horizontal ELAs can affect the shape of a glacier, as well as how it responds to changes in accumulation and sublimation. Above: A glacier which has an accumulation zone between the two ELAs can remain in steady-state. Increases or decreases in accumulation have positive feedback; a slight increase in accumulation increases the ratio of surface area at positive mass balance elevations to negative mass balance elevations, encouraging further growth. A small decrease in accumulation will decrease the ratio of surface area at positive mass balance elevations to negative mass balance elevations. This lowers the ratio of accumulation to sublimation, leading to further glacial recession and a potential collapse of the glacier. Neither of these deviations from steady-state would necessarily change the shape or slope of the glacier. If, however, the glacier grew until its accumulation zone reached the elevation of the upper ELA, further growth would likely lead to a change in the shape and slope of the glacier. Because accumulation above the upper ELA rapidly sublimates, the highest elevation at which the glacier contacts the mountain cannot change significantly. Instead, additional accumulation will occur away from the flank of the mountain, causing the glacier to increase preferentially its length rather than its thickness. Again, the ratio of the surface area at positive mass balance elevations to negative mass balance elevations will increase, yielding additional growth. As this occurs, the shape of the glacier will change: it will become much longer, and minimally thicker, decreasing its overall slope as it gets larger. (From Kadish et al., 2008)

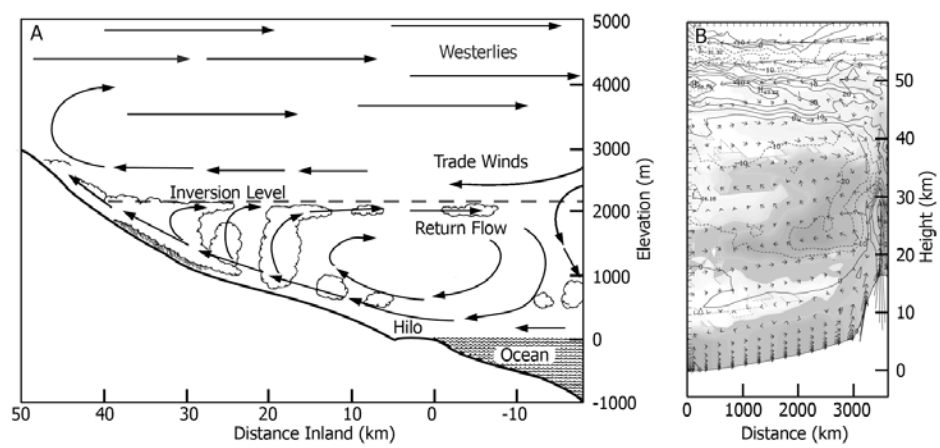


Figure 4: Mesoscale models of the atmospheric circulation at Hawaii (modified from Garrett, 1980) and Arsia Mons (modified from Rafkin et al., 2002). In the Hawaii model, differential heating of the land and sea during the day drive combined anabatic and sea breeze winds. The air cools adiabatically as it carries moisture up the eastern flank of Hawaii where it eventually encounters the trade wind inversion at an elevation of ~2200 m. The majority of orographic clouds cannot rise above this level, and thus precipitation is heaviest at this elevation. The inversion also causes a return flow, which is strong enough to overcome weak trade winds. At higher elevations, between 3000 and 4000 m, wind shear occurs from westerlies overlying the trade winds. The Arsia model, which was created to show dust mixing and transportation, reveals some similar atmospheric behaviors. The arrows in the figure indicate wind velocity vectors in the plane of the page. Below an elevation of 10 km, a westerly wind blows up the flank of the mountain. The air in this rising branch is cooled adiabatically. Between 10 and 15 km, a return flow can be seen which overcomes the westerly wind. Just above this, at ~20 km, the westerly wind again dominates. This is overlain by easterly winds at ~25 km, causing wind shear between the strata. Although the *Rafkin et al.* (2002) model is run without water vapor in the air, they note that it would, "...not be unexpected for a water-ice cloud to develop at the top of the thermal circulation" (Rafkin et al., 2002), and orographic clouds have been observed in MOC images on the Tharsis Montes and Olympus Mons (see MOC release No. MOC2-144). (From Kadish et al., 2008)