ICE SHEET MODELING: MASS BALANCE RELATIONSHIPS FOR MAP-PLANE ICE SHEET RECONSTRUCTION: APPLICATION TO THARSIS MONTES GLACIATION.

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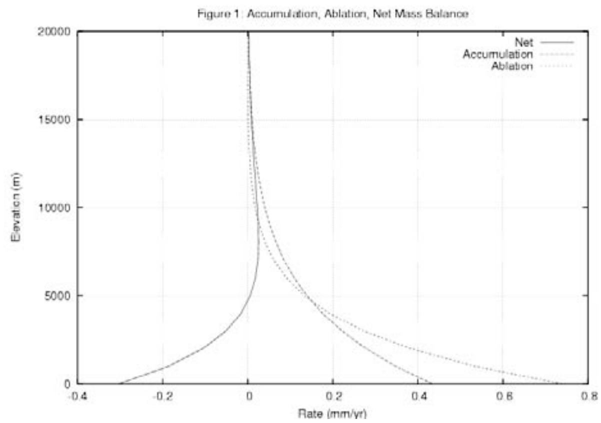
Introduction: Deposits on the flanks of the large Tharsis Montes volcanoes (Arsia, Pavonis, and Ascraeus Mons) have been recognized to be of glacial origin [1,2]. These Amazonian-aged deposits display three distinct facies, ridged, knobby, and smooth [3], each of which can be associated with different glacial processes [1]. The outermost ridged facies is thought to be the imprint of ice-margin drop moraines recording the fluctuations of a stable cold-based ice sheet. Inside this is the knobby facies, interpreted as a sublimation till deposited as the ice sheet sublimated during a period of major contraction of the ice sheet. Finally, contained within both of these is the smooth facies which may contain debris-covered glacial ice, similar to rock glaciers found in the Dry Valleys of Antarctica [1]. The deposits form fans trending to the northwest from each of the volcanoes and have been described elsewhere [1-4]. Steady-state flowband profiles have been shown to produce reasonable ice sheet configurations of a few hundred to a few thousand meters thickness. However, flowband modeling [5,6] makes estimates of volumes difficult, and steady-state modeling does not allow for the possibility that these ice sheets never attained full equilibrium configurations during the transient climatic conditions that accompany the large oscillations in obliquity that dominate the Martian climate [7].

Modeling Postulated chronologies for ice sheet behavior are emerging as a better understanding of Mars climate change driven by major variation in the obliquity is seen as allowing for ice sheets to form near the equator at high elevations on the flanks of the large volcanoes [1]. Ice sheet models, coupled with reasonable assumptions about the climate, can obtain estimates for the volumes of these ice sheets, better constraining the water budget for the planet [5,6]. Ice sheet models usually involve an integrated momentum-conservation equation based on the flow law of ice [9] coupled with a mass-conservation, or continuity equations to yield a differential equation for ice extent and thickness as a function of time [10,11].

Mass Balance Distribution Such an equation requires specification of the source of this mass at each point in the domain, the so-called mass balance. The mass balance consists of two parts, the annual accumulation (ice-equivalent snowfall, in m/yr) and the annual ablation (melting, sublimation, or other erosive processes that remove ice from the ice surface). The difference between these two is the net mass balance, which is the source (or sink if negative) in the continuity equation.

On Earth the mass balance can be measured for existing ice sheets, but for reconstruction of paleo-ice sheets a parameterization in terms of elevation and location on the planet is usually used. The accumulation part of the mass balance is usually taken to be proportional to the saturation vapor pressure, a measure of how much water the atmosphere can hold. The saturation vapor pressure is an exponential function of temperature, with a cold atmosphere holding much less water, and hence able to produce much less snow. We would expect the Martian situation to be similar.

On Earth, for most glaciers the ablation component is typically due to surface melting with liquid runoff from the ice sheet. This is calculated by imposing a seasonal amplitude onto the mean annual temperature at a location and counting



positive degree days. The melt rate is proportional to the number of positive degree days. Since the Earth is colder at higher elevations (the so-called lapse rate, usually linear) we usually see small positive mass balance at high elevations (cold, little snow, but no melting), large positive mass balance at mid elevations (warmer, so more snow, but still little melting), and then strongly negative mass balance at low elevations (warm, so plenty of snow, but much more melting). This leads to snow-capped mountains and highland growth of glaciers, with the concept of an equilibrium line (mass balance positive above and negative below).

On Mars, the temperature seldom reaches the melting point of water ice, the lapse rate is much smaller, and the dominant mechanism for mass removal is by sublimation. Two sublimation mechanisms are defined [12,13], buoyancy- and turbulence-driven. Both depend on the saturation vapor density (itself the saturation vapor pressure divided by the total pressure) and hence have the same exponential dependence on temperature as the accumulation component of the mass balance. With a lapse rate, falling temperature with elevation leads to declining accumulation and sublimation rates. With pressure in the denominator, sublimation declines less rapidly, leading to overall lower, and possibly negative, net mass balance. Thus on Mars we might expect snow-filled valleys rather than the snow-capped mountains we see on the Earth. Declining relative humidity, increasing ventilation (both of which affect sublimation),or some melting at lower elevations can lead to net negative mass balance at low elevation. Thus we might have two equilibrium lines (Fig. 1), a high and a low one, with positive mass balance only in between.

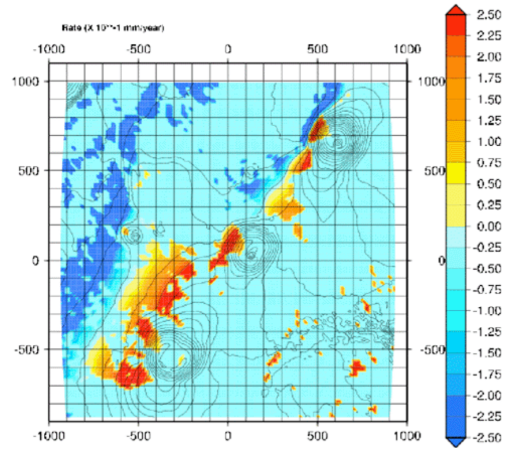


Figure 2. Modeled mass balance.

Spatial Distribution: All of this produces a mass balance distribution that depends on elevation, but the fan-shaped deposits are all on the northwest flanks of the volcanoes. This may be due to a snow tail in the lee of the volcanoes or to a cloud shadow that reduces ablation, or even to orographic effects as air masses move up the volcano slopes [e.g. 15-18]. Whatever the cause the climate parameterization needs some way to produce spatially non-uniform mass balance. One way to do this is to only allow accumulation where the surface slopes in a particular direction. We form the dot product between a unit vector in a specified direction (northwest) with a unit vector in the direction of the surface gradient (the cosine of the angle between these two vectors). Where this exceeds some threshold (0.9 would allow a range of 25 degrees) we allow accumulation and elsewhere only ablation. Figure 2 shows the distribution of net mass balance for the Tharsis Montes under these circumstances before the ice sheet has formed.

As the ice sheet grows the elevation- and orientation-dependent mass balance parameterization will respond to the changing ice sheet configuration. Fig. 3 shows ice thickness and surface elevations after 2.6 million years of growth. This is not an equilibrium configuration as the ice sheet is still growing. For comparison, Fig. 4 shows the glacial deposits.

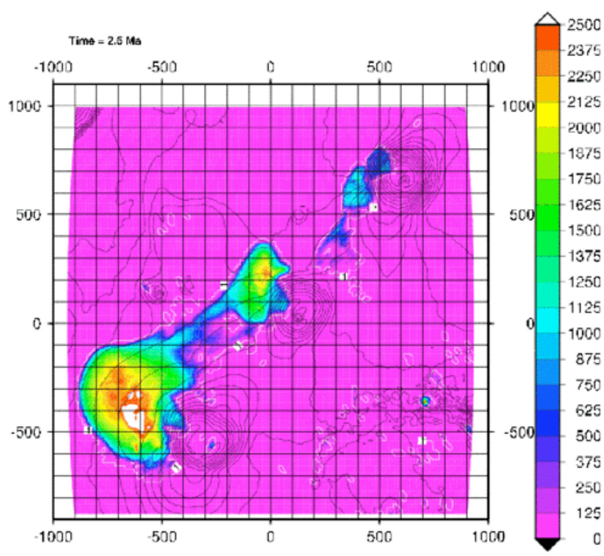


Figure 3. Surface thickness.

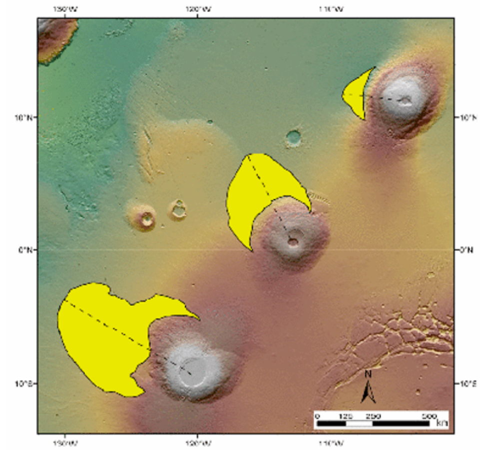


Figure 4. Glacial deposits [1,2].

Note the good agreement with the extensive Arsia Mons deposits. Also note that the presence of a slight topographic rise northwest of Pavonis Mons deflects the flow in a slightly more northward direction. Even the smaller Ascraeus Mons deposits are well represented.

Volumes and Areas: After 2.6 million years the combined volume of the ice sheets is 0.53 X 10^6 km^3. For comparison the North Polar Cap of Mars is thought to have a volume of approximately 1.5 X 10^6 km^3 [14]. The areal extent of the ice sheet is 0.51 X 10^6 km^2, approximately half the size of the present North Polar Cap. Interestingly the average thickness is ~1.02 km, very close to the estimated average thickness of the North Polar Cap (~1.03 km). A plausible mechanism would be to transport a significant portion of the NPC to the equatorial regions and deposit it on the flanks of Tharsis Montes.

Conclusions: 1) The properties of the martian atmosphere make the formation, accumulation, and behavior of snow and ice different from those on the Earth in significant ways (Fig. 1). 2) Using these guidelines, models of mass balance and spatial distribution on the western flanks of Tharsis Montes lead to patterns that are strikingly similar to the geological evidence for ice accumulation and glacial flow (Fig. 2, 3). 3) Areal and volumetric considerations predict accumulations that are consistent with the geologic evidence for the Tharsis Montes fan-shaped deposits; these volumes are comparable to about half the volume of the current North Polar Cap, implying that during periods of very high obliquity, a significant percentage of the polar cap is transported to the tropics. 4) Further refinements of these models will permit chronologies to be compared between predictions from obliquity cycle calculations [7] and the geologic record [1,2].

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