ICE SHEET MODELING: TERRESTRIAL BACKGROUND AND APPLICATION TO ARSIA MONS LOBATE DE-POSIT, MARS. J. L. Fastook, Climate Change Institute and Computer Science, University of Maine, Orono ME 04469, USA (fastook@maine..edu), J. W. Head, Department of Geological Sciences, Brown University, Providence RI 02912, USA, D. Marchant, Department of Earth Sciences, Boston University, Boston MA 02215, USA, D. Shean, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

Introduction: Scientific glaciology began when researchers recognized that certain landforms had been produced by large sheets of moving ice that covered wide expanses of the land-scape. Obviously, these moving ice mountains could only have existed if the world were colder. Had they come and gone repeatedly in the past, and if so, how many times? Is it possible that the ice age state of the world is actually its normal state? Would the glaciers come again, and when? All of these questions are as relevant to the planet Mars as they are to the planet Earth.

1. Problems of the Ice Age: With the advent of radiocarbon dating it was clear that the waxing and waning of the ice sheets had occurred in relatively recent geological time. It was demonstrated that climate was not constant in time, and that over the last 2.5 million years the ice sheets had come and gone several times. With glacial periods typically lasting 10^5 years, and interglacial periods 10^4 years, the ice age state is more the norm than the exception. Now similar evidence from Mars suggests that ice ages have come and gone [8, 15], and that proper understanding of these glacial imprints can expand our understanding of how much, and more importantly where, water exists on Mars.

1.1 Reconstructing paleo-ice sheets: Across the terrestrial landscape various features have been recognized as glacially created or modified (moraines, eskers, kames, drumlins, etc.). With traditional stratigraphy for relative ages, and radiocarbon for absolute ages, a chronology of ice sheet positions of the past has been developed for landforms across North America, Europe, and Asia. Few of these geological indicators give information about the ice sheets thickness; instead they only indicate where ice was present at a given time.

For Martian modelers the evidence is less well developed. There are no carbon dates, and stratigraphy is extracted from satellite images at often insufficient resolutions. How thick were the ice sheets that produced the deposits that define the visible outline of the ice sheet? Only by knowing the thickness can we estimate the amount of water in the Martian ice sheets.

Dynamic models allow us to reconstruct the shape of ice sheets of the past. The ice sheet margin is identified by glacial geological indicators, and then the interior thickness can be calculated from various conservation laws and constitutive relationships. As one develops these dynamic models, one must make assumptions about material constants that describe how ice responds to various forces. Often these parameters must be obtained experimentally by "fitting" the output of the model to the known configuration of an existing ice sheet. On Earth this can be done by modeling existing ice sheets such as Antarctic and Greenland. On Mars we can use our experience with terrestrial ice sheets. For instance, the hardness of ice, an important parameter in the flow law of ice, has been determined to vary as an exponential function of the temperature. While ice on Mars may contain more dust than terrestrial ice, it is still fundamentally the same material, and should follow the same behavior [3].

1.2 Interpreting glacial geology: Glacier modelers depend on geologists to provide constraints on the behavior of their models, while providing the geologists with a filter for understanding their field data. For example, terrestrial geologists often observe gouges on polished outcrops of bedrock. These striations are the primary indicators of the ice flow direction for geologists, but often cross-cutting patterns are observed, with multiple sets of striations in different directions on the same outcrop. Modelers can help geologists with a scenario of ice sheet behavior that will explain these different directions. Similarly on Mars, patterns of deposition with cross-cutting relationships can be interpreted as changes in the flow patterns created by changing climate. If the geologic record is incomplete or fragmentary, modeling can often help to "fill in the blanks," by the simple reasoning that if some event happened in one place under a certain set of conditions, then it must also have happened in another location with similar conditions. This can be especially important when looking at an ancient deposit that has been modified by subsequent non-cryospheric processes, such as wind erosion.

1.3 An ice sheet laboratory: In trying to understand the behavior of any ice sheet, one cannot design controlled experiments for a laboratory. Numerical models provide the only arena for doing "experiments" on ice sheets, answering questions such as: What happens to the shape of an ice sheet as the amount of snowfall increases or decreases? How rapidly does it respond to a change in external conditions? If the climate warms, does the ice sheet get bigger (more snow from the more moist air) or smaller (more melting by the warmer atmosphere)?

2. Model Input: The primary inputs to an ice sheet model are the bed topography, the accumulation rate, the surface temperature, and the geothermal heat flux.

2.1 Bed Topography: The bed topography is well-known on Mars, primarily from the Mars Orbiter Laser Altimeter (MOLA). This, combined with images from the Mars Orbiter Camera (MOC) provide most of the evidence for the existence of ice sheets on Mars. Ice sheet modeling requires topography at a resolution that is comparable to the ice thickness.

2.2 Surface Temperatures: While there are measurements of the current surface temperature on Mars (216-218 K near the equator [2]), for ice sheet reconstructions it is necessary to have some estimates of how the climate may have changed in the past. One estimate of temperature based on a climate model for periods of high obliquity is 207-213 K [12].

2.3 Geothermal Heat: This is very poorly constrained

for Mars [17, 16]. The expected values for Tharsis could be much higher or lower than the planetary mean, depending on time of formation and crustal thickness estimates.

2.4 Accumulation Rate: On Earth, glaciers usually have an equilibrium line altitude (ELA) above which the accumulation rate is positive (increasing ice thickness) and below which it is negative (decreasing ice thickness). The forward flow of ice balances these two components determining the length and overall mass balance of the glacier. If the positive component dominates, the glacier will advance and grow larger. If the negative component dominates the glacier will shrink.

Mars may require two ELAs, a lower one that is analogous to the terrestrial ELA, positive above and negative below, and an upper one that is the reverse. This is necessary because higher elevation on Mars can lead to increased sublimation rates and lower snowfall rates. For demonstration purposes we define an accumulation-rate distribution (ARD) as a parabolic function of elevation with two ELAs and a maximum rate midway between.

3. Preliminary Results: A flowband version of the



Figure 1: Growth with a fixed accumulation-rate distribution



Figure 2: Growth with a variable accumulation-rate distribution

University of Maine Ice Sheet Model (UMISM) [4] has been modified to work on Mars. UMISM participated in the EIS-MINT experiments for model intercomparison [10] and is recognized as an important tool for study of both current and paleo terrestrial ice sheets [1, 5, 6, 9, 11, 13, 14]. UMISM uses the standard shallow-ice approximation (neglect all stresses except the basal driving stress). Internal temperatures are calculated from specified surface temperatures and basal heat fluxes and then used to calculate the mechanical properties of the ice. This model is well suited for the cold-based glaciers of Mars, although it can also accommodate melting events that might result from anomalously high heat fluxes on the flanks of a volcano such as Arsia Mons. The model also includes components for glacial isostasy and for movement of basal melt water beneath the ice sheet.

A 1360 km long flowband extending from the Arsia Mons summit, across the three facies identified in [7] and on down to the zero-elevation level is modeled. Figure 1 shows the growth of a glacier over 10^6 years with a lower ELA at 3600 m, an upper ELA at 6000 m, and a peak accumulation of 1 cm/yr.

In this case the ARD is fixed. It does not vary as the ice sheet grows. An alternative case, shown in Figure 2, uses a similar scheme, but the elevation used in the ARD function is now the ice surface. As such the ARD changes as the ice sheet configuration changes. Different ELA elevations (5000 and 6900 m) are required to match the distribution of glacial deposits. The fact that the ARD depends on the elevation of the growing ice sheet requires the lower ELA to be higher so that there is sufficient ablation to stop the glacier growth at the 2600 m level of the glacial deposits. The final shapes of the glaciers are similar, but the temporal and spatial response is clearly different.

These experiments show the potential of ice sheet modeling to help determine how the climate may have changed in the past on Mars [7, 8, 15]. The experiments here show what the distribution of accumulation and ablation would need to be in order to produce the recognized distribution of glacial deposits. Estimates of temperature, basal heat flux, precipitation, and sublimation can be better constrained by geological, geophysical, and meteorological data, which will aid further modeling.

References: [1] R. P. Ackert et al., Science, 286:276-280, 1999. [2] S. M. Clifford. JGR, 98(E6):10973-11016, 1993. [3] W. B. Durham et al., Third Mars Polar Science Conference, CD-ROM #8132, 2003. [4] J. Fastook. JGR, 92(B9):8941-8949, 1987. [5] J. Fastook et al., J. Glac., 41(137):161-173, 1995. [6] J. Fastook and P. Holmlund. J. Glac., 40(134):125-131, 1994. [7] J. W. Head and D. R. Marchant. Geology, 31(7):641-644, 2003. [8] J. W. Head et al., Nature, 246:797-802, 2003. [9] P. Holmlund and J. Fastook. Boreas, 22(2):77-86, 1993. [10] P. Huybrechts et al., Ann. Glac., 23:1-12, 1996. [11] W. Karlén et al., AMBIO, 28(5):409-418, 1999. [12] M. T. Mellon and R. J. Phillips. JGR, 106(E10):23165-23179, 2001. [13] J. Näslund et al., Quat. Sci. Rev., 22(2-4):89-102, 2003. [14] J. Näslund et al., J. Glac., 46(152):54-66, 2000. [15] D. E. Shean et al. LPSC35, this volume, 2004. [16] T. Spohn and et al. Space Sci. Rev., 96:231-262, 2001. [17] M. T. Zuber et al., Science, 287:1788-1793, 2000.