RESPONSE TIME-SCALES FOR MARTIAN ICE MASSES. M. R. Koutnik[1], E.D. Waddington[1], and T.A. Neumann[2] [1]University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195 (mkoutnik@ess.washington.edu), [2]University of Vermont, Department of Geology, Burlington, Vermont 05405.

Introduction: On Earth and Mars, changes in climate mean changes in precipitation, temperature, and/or radiation. Ice masses (e.g. glaciers, ice caps, ice sheets) respond to these changes by adjusting their length and thickness in attempt to equilibrate with the new climate. The response time is the time required to approach equilibrium following a step change in climate [e.g. 1, 2]. The response time is an e-folding time. Nye [1] showed how the response of ice masses to small perturbations in climate can be determined using linearized kinematic wave theory. From this solution, Jóhannesson et al. [2] identified natural time-scales to describe ice-mass response. Here we calculate response time-scales for Martian ice. By picking a range of ice temperatures, and making assumptions about ice dynamics, we can calculate a range of possible mass balance rates and time-scales. We compare these response times to the time-scales for Martian obliquity variations.

Theory: A change in mass balance (accumulation or ablation) will put the ice mass into a transient state. Kinematic waves of constant ice flux form to conserve mass as the ice adjusts to this change in mass balance [1]. We start from an ice mass that is initially in steady state (called the datum state; denoted with subscripted 0) with mass conservation given by,

$$\frac{1}{W_0}\frac{\partial q_0}{\partial x}+\frac{\partial h_0}{\partial t}=b_0 \qquad (1)$$

where $W_0(x)$ is flow-band width, $q(x)$ is ice flux, $h(x)$ is ice thickness, and $b(x)$ is the mass balance. To first order, the flux perturbation due to a small change in mass balance b_1 can be related to the perturbation in thickness $h_1(x)$ and slope $\partial h_1/\partial x$ by,

$$q_1 = c_0 h_1 + D_0\frac{\partial h_1}{\partial x} \qquad (2)$$

where $c_0(x)$ is the kinematic wave speed in the datum state:

$$c_0=\frac{\partial q_0}{\partial h_0}=(n+2)\bar{u}_0 \qquad (3)$$

and $D_0(x)$ is the kinematic wave diffusion coefficient in the datum state:

$$D_0=\frac{\partial q_0}{\partial \alpha_0}=\frac{nq_0}{\alpha_0} \qquad (4)$$

where $\bar{u}\ (x)$ is the depth-averaged horizontal velocity, α is the surface slope, and $n{\sim}3$ is the exponent in the constitutive relationship for ice flow [5]. Using these equations, the thickness perturbation for a known accumulation perturbation, b_1, is given by,

$$\frac{\partial h_1}{\partial t}=b_1-\frac{\partial c_0}{\partial x}h_1-\left(c_0-\frac{\partial D_0}{\partial x}\right)\frac{\partial h_1}{\partial x}+D_0\frac{\partial^2 h_1}{\partial x^2} \qquad (5)$$

If the velocity u_0(x) in the datum state is known, this equation can be solved numerically using standard advective-diffusive methods [6] to give the thickness change as a function of time for a given mass balance perturbation and defined properties of the datum state.

Propagation and Diffusion Time-scales: Rather than solve for the full time evolution, Jóhannesson et al. [2] recognized two significant dynamic-response time-scales from Equation 5, which describes the propagation and diffusion of a change in thickness. A propagation time-scale is given by [2],

$$\tau_C=\frac{l_0}{\bar{c}_0} \qquad (6)$$

where l_0 is the length of the ice mass in the datum state and $\bar{c}_0$ is the kinematic wave speed averaged along the length l_0. A diffusive time-scale is given by [2],

$$\tau_D=\frac{l_0^{\,2}}{\pi^2\bar{D}_0} \qquad (7)$$

where $\bar{D}_0$ is the kinematic wave diffusivity averaged along the length l_0. The time-scales depend on the datum velocity of the ice mass and therefore a theoretical or empirical relationship for that velocity must be known before we can find τ_D or τ_C.

Volume-Response Time-scale: For a spatially uniform step-change in mass balance, from $b_0\,(x)$ to $b_0\,(x)+b_1$, Jóhannesson et al. [2] found the response time to approach the new total ice volume, given by,

$$\tau_V=-\frac{H_{0\max}}{b_0(l_0)} \qquad (8)$$

where $H_{0\ \max}$ is the maximum ice thickness in the datum state and $b_0\,(l_0)$ is the mass balance (ablation) at the terminus in the datum state. The volume-response time-scale is longer than the propagation or diffusion time-scales. This means that wave propagation and diffusion distribute thickness changes (containing climate-change information), over the length of the ice mass quickly compared to the time it takes to accumulate the new steady-state volume [4].

Parameters for Mars: To calculate the propagation and diffusion time-scales for Mars, we need to make assumptions about the velocity field. We assume that internal deformation dominates (there is no basal sliding) and we represent horizontal velocity using the shallow ice approximation [e.g. 3,4], which uses the fact that the thickness of the ice is much less than the lateral extent. This gives

$$\bar{u} = \frac{2A(T)}{(n+2)}\left(\rho g \alpha\right)^{n} h^{h+1} \tag{9}$$

where ρ is density, g is gravity, α is the surface slope, and the softness parameter, A, is a function of temperature, T, following an Arrhenius relationship [3,4]. We consider pure ice under Martian gravity; the lower Martian gravity reduces the driving stress. At present, the average surface temperature is ~173 K and the basal heat flux is probably 0.025 $\mathrm{Wm^{-2}}$. We use the standard terrestrial value of n=3 for the flow-law exponent, meaning that deformation is dominated by dislocation creep [4].

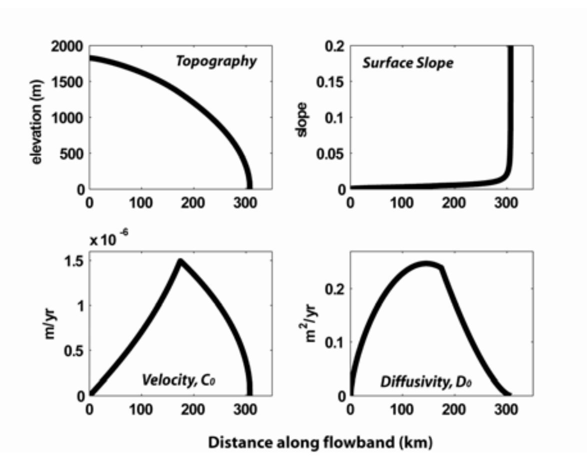

Figure 1. Topography and surface slope from Winebrenner et al. [7] using inter-trough MOLA topography from Titania Lobe, NPLD. Corresponding kinematic wave velocity and diffusivity for a flow-law exponent, n=3.

To illustrate these concepts, we use Martian topography adopted from Winebrenner et al. [7] for a flowband across Titania Lobe, North Polar Layered Deposits (NPLD). This surface is a reconstruction based on the inter-trough Mars Orbiter Laser Altimeter (MOLA) topography and an ice-flow model (not shown here). Figure 1 shows the ice-surface topography, associated surface slope, the kinematic wave speed, and kinematic wave diffusivity for this geometry and for the parameters chosen for Mars. By introducing dynamics and making assumptions about the ice temperature, we can infer steady-state rates of accumulation and ablation.

Present-day Response Time-scales: Using present-day surface temperature and heat flux, with Mars' gravity, the response time-scales are very long. This is because the rates of mass flux necessary to fit the topography under present-day Mars' conditions are very small. The diffusion time-scale is ~19 billion years and the propagation time-scale is ~113 billion years. These represent time-scales for propagation and diffusion over the full length of the ice mass. Using the ablation rate required to create this datum-state topography, with current Martian temperatures, the volume response time is even longer. This means that the topography fit by a steady-state flow model [7] was not generated in the current climate. We expect that the ice temperature at depth, where most of the deformation is occurring, was much warmer when this topography formed.

We can also use present-day Mars' ablation estimates of ~0.2 mm/yr from Pathare and Paige [8] to get another estimate of the volume-response time-scale. For this ablation rate, and an ice thickness of 1800 m, the volume-response time is 9 million years.

For a comparable geometry and a surface temperature of -30 ºC, the terrestrial diffusion time-scale is ~1,750 years and the propagation time-scale is ~10,500 years. The corresponding ablation rate to maintain this topography in steady state at this temperature is 0.13 m/yr, giving a volume response time of 13,500 years. If there is higher ablation at the terminus, then the response time will be shorter. For example, the ablation rate at the terminus in Greenland is a few m/yr and the response time is ~1,000 years.

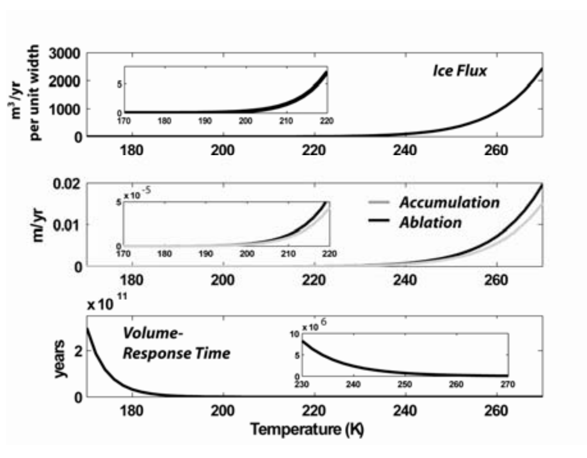

Figure 2. As temperature increases, ice flux, accumulation rate, and ablation rate increase, therefore the volume-response time decreases. Insets highlight changes over a limited part of the temperature range.

The present-day response time-scales for Mars are very long. This means that present-day ice flow is very slow and that currently mass balance has a dominant influence on the topography (this is not unexpected).

Implications for Surface Temperature: We use the volume time-scale (Equation 8) to identify a range of surface temperatures that give plausible response times. Different temperatures give different values of the softness parameter *A(T)* in the ice-flow law, in Equation 9. Figure 2 shows the accumulation rate, ablation rate, ice flux at the equilibrium line (~160 km along flowline), and volume-response time for a range of surface temperatures. Using ice thickness and slope values adapted from Winebrenner et al. [7], shown in Figure 1, we find steady-state rates of accumulation and ablation for a range of temperatures. These rates range from ~10^{-9} m/yr at 170 K to ~10^{-2} m/yr at 270 K. The ice flux, $q = \overline{u}(x)\, W(x)\, h(x)$, is the volume of ice that crosses the equilibrium line each year per unit flowband width. The ice flux ranges from ~10^{-4} m^3/yr at 170 K to ~10^{3} m^3/yr at 270 K. The volume-response times, for ablation rates at the terminus that vary with temperature, range from ~300 billion years at 170 K to ~9,000 years at 270 K.

If we consider that only response times less than 100 million years are plausible, the surface temperature must be at least 210 K. The associated accumulation and ablation rates are at least ~10^{-5} m/yr. It is interesting that at surface temperatures around 230 K, each additional degree increase in temperature significantly increases the mass-balance rate and decreases the response time.

Comparison to Martian Obliquity: Obliquity forcing on Mars has a periodicity of ~120,000 years [e.g. 9]. During periods of higher or lower obliquity, the temperature and mass balance are likely to change. In order for Martian ice to respond on obliquity time-scales, the temperature, mass-balance rate, or heat flux must be very different than today. From this analysis, the surface temperature would have to be ~268 K and the mass-balance rates would be ~10^{-2} m/yr.

We present response times for Martian ice masses. The range of plausible time-scales can be used to establish a range of plausible surface temperatures. We will further analyze the connection between these time-scales and variations in Martian parameters with variations in obliquity.

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