

SNOWMELT RATES IN MODELED EARLY MARS CLIMATE SCENARIOS. K. E. Scanlon¹, J. W. Head,¹ and R. D. Wordsworth,² ¹Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA. ²School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA.

Introduction: The morphology of martian valley networks in high-resolution images [e.g. 1, 2] suggests that surface runoff, rather than groundwater sapping, is responsible for most valley networks. While rainfall is one possible explanation [e.g. 3–5], the lack of a plausible composition for the early martian atmosphere that would have provided enough greenhouse warming to sustain rainfall [e.g. 6–8] has motivated a search for alternative explanations. Furthermore, recent climate modeling indicates that, unlike the pattern of snow and ice preservation [9] and that of likely orographic enhancement [10], the pattern of rainfall in a hypothetical warm early martian climate may not be consistent with the distribution of valley networks [9].

The discharge rate of water through a valley network can be calculated from the morphometry of small internal channels where they are preserved [11 – 13]. To determine likely runoff rates from snowmelt under a variety of scenarios for early Mars, and assess their agreement with runoff rates calculated by other workers from observed channel dimensions, we conducted a series of global climate model (GCM) simulations of early Mars, inducing climate warming with a grey gas (i.e. an artificial, wavelength-independent absorption coefficient) of varying strength. We used the output from these simulations as input to an energy balance snowmelt model and compared the modeled and calculated runoff rates at five valley networks whose formative runoff rates have been calculated by other workers [11, 13].

We investigated four key questions: (1) Can snowmelt alone generate runoff of sufficient magnitude? (2) Can melt rates of order mm day⁻¹ to cm day⁻¹ be reached in regions where annual average surface temperatures are below 273°K and peak rainfall rates are below 1 mm day⁻¹? (3) Are modeled snowmelt rates larger in the valley networks with larger calculated runoff rates? (4) Is there a single climate scenario where modeled and calculated runoff best match for all valley networks studied?

Snowmelt model: The Utah Energy Balance (UEB) snowmelt model [14, 15] characterizes the depth, energy content, and surface age of a snowpack by solving the energy and mass balance equations

$$\frac{dU}{dt} = Q_{sn} + Q_{li} + Q_p + Q_g - Q_{le} + Q_h + Q_e - Q_m$$

$$\frac{dW}{dt} = P_r + P_s + M_r - E,$$

where Q_{sn} is net shortwave radiation, Q_{li} is incoming longwave radiation, Q_p is heat advection into the snowpack by precipitation, Q_g is ground heat flux, Q_{le} is outgoing longwave radiation, Q_h is sensible heat flux, Q_e is latent heat flux, Q_m is heat advection out of the snowpack by meltwater, P_r is rainfall rate, P_s is snowfall rate, M_r is melt outflow rate, and E is snow sublimation rate.

Since field data are obviously not available for Noachian Mars, we used climate fields from the Laboratoire de Météorologie Dynamique (LMD) early Mars GCM [8, 16] as input to the snowmelt model. Since a physically plausible combination of greenhouse gases that would substantially warm the early martian atmosphere has not yet been identified, we added a grey gas absorption coefficient κ in our GCM simulations to simulate a “warm, wet early Mars” [cf. 9]. We chose $\kappa = 2.5 \cdot 10^{-5}$, $5 \cdot 10^{-5}$, $1 \cdot 10^{-4}$, and $2 \cdot 10^{-4}$ m² kg⁻¹ in order to study a range of warmer climates; at our warmest study site, for example, temperatures only exceeded freezing for a few tens of sols at $\kappa = 2.5 \cdot 10^{-5}$ m² kg⁻¹, but exceeded freezing by ~10–20° for most of the year at $\kappa = 2 \cdot 10^{-4}$ m² kg⁻¹.

Only changes to constants (namely, gravitational acceleration, atmospheric heat capacity, and atmospheric specific gas constant) were necessary to adapt the UEB snowmelt model for Mars. We ran the model assuming a glacial substrate underneath snowpack [18]; model parameters are given in Table 1. For this abstract, infiltration was not considered. We chose valley networks to represent a range in spatial distribution (Fig. 1) and calculated runoff magnitude (Table 2).

Results and discussion: *Can snowmelt alone generate sufficient runoff?* When atmospheric pressure was set to 600 mb, even warming by the $\kappa = 2 \cdot 10^{-4}$ grey gas was insufficient to generate the required snowmelt rates, except at Paraná Valles and Evros Valles. In the warmest climates, however, with 1000 mb CO₂ and grey gas $\kappa =$

Table 1. Values used for model parameters.

Parameter	Value adopted	Ref.
Surface aerodynamic roughness	2×10^{-3} m	[17]
Snow density	450 kg m ⁻³	[18]
Liquid holding capacity of snow	5%	[19]
Snow saturated hydraulic conductivity	30 m hr ⁻¹	[20]
Thermally active depth	2.0 m	[21]
Snow emissivity	0.99	[23]
Snow albedo	0.6 – 0.9	-
Thermal conductivity of fresh snow	0.022	[23, 24]
Initial energy content	-9.7×10^4 kg m ⁻³	[14, 15]
Initial snow depth	20 m	[18]

Table 2. Valley networks studied.

Name	Lat.	Lon.	Runoff [ref.]
Evros Vallis	12°S	12°E	4 mm day ⁻¹ [13]
Licus Vallis	3°S	126°E	3 mm day ⁻¹ [11]
Paraná Valles	24.1°S	10.8°W	1.1 cm day ⁻¹ [11]
Unnamed VN #1	0°N/S	23°E	5 cm day ⁻¹ [13]
Unnamed VN #2	6.6°S	134.7°E	5.5 cm day ⁻¹ [11]

$2 \cdot 10^{-4}$, snowmelt rates were faster than those inferred from observations at all valley networks studied. In Paraná Valles (Fig. 2) and Evros Valles, more than sufficient snowmelt also occurred in climates with 1000 mb CO_2 and grey gas $\kappa = 1 \cdot 10^{-4}$.

Can sufficient snowmelt rates be reached in regions with minimal rainfall and below-freezing average surface temperatures? In some simulations at Evros and Paraná Valles, sufficient runoff was generated with annual average temperatures 2 – 4 degrees below freezing. Elsewhere, annual average temperatures exceeded freezing at all sites where modeled snowmelt met or exceeded calculated runoff. Rainfall was not a major component of runoff in most simulations; only in the $\kappa = 1 \cdot 10^{-4}$, Evros Vallis simulation is rainfall alone sufficient to explain the runoff rates calculated from channel morphometry.

Are modeled snowmelt rates larger in the valley networks with larger calculated runoff rates? Is there a single climate scenario that best fits the runoff rate data? In all of our simulations, regardless of atmospheric pressure, added absorption, or spin-axis obliquity, Licus Vallis experienced the smallest peak snowmelt rates in our simulations, followed by Evros Vallis, consistent with the calculated runoff rates. Modeled snowmelt rates for Paraná Valles, however, were similar to those for the unnamed valley networks, which are calculated to have formed under runoff rates $\sim 5\times$ as rapid as that at Paraná. Rainfall is unlikely to explain the discrepancy, as it is not consistently greater at the unnamed valley networks than at Paraná Valles. Accordingly, there is no one “best fit” climate, as the closest match for Paraná is substantially colder than the closest match for the other sites.

Conclusions: We find that in artificially warmed early Mars climates, snowmelt can occur at rates comparable to the formative runoff rates estimated for several martian valley networks. Snowmelt begins quickly enough that time-limited warming mechanisms such as crater impacts or sulfur dioxide [e.g. 25, 26] would only need to remain in the warming phase for short periods of time if the magnitude and recurrence of warming was sufficient. However, sufficiently high melt rates do not occur in scenarios with annual average temperatures more than a few degrees below freezing; significant warming above the “icy highlands” baseline is required, and the mechanism for this warming is still unknown.

Simulated rainfall rates are lower than snowmelt rates by at least one order of magnitude except for two regions in the $\kappa = 1 \cdot 10^{-4}$ simulation (Unnamed Valley Network #1 and Evros Vallis), indicating that snowmelt is likely to have been an important factor in valley network development even if part of the fluvial activity was due to rainfall. Our results are inconsistent with the valley networks forming in a climate as warm as our warmest simulation. This is due to (1) snowmelt rates in our warmest simulation exceeding the formative rates calculated for the valley networks and (2) snowmelt occurring

continuously throughout the year in our warmest simulations, which is inconsistent with geomorphologic evidence for intermittent fluvial activity [e.g. 12].

Trends in snowmelt rates between valley networks correspond with trends in calculated formative runoff rates, with some exceptions; these exceptions may reflect the influence of varying snowpack buildup between warm intervals, rainfall distribution in warmer climates, or varying substrate properties affecting infiltration.

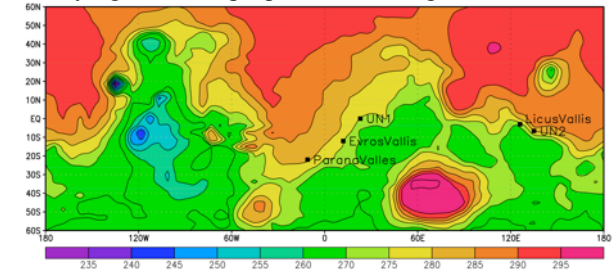


Fig. 1. Study sites (black markers) and annual average surface temperature (shaded) in the 1000 mb, 25° obliquity, $\kappa = 1 \cdot 10^{-4}$ scenario.

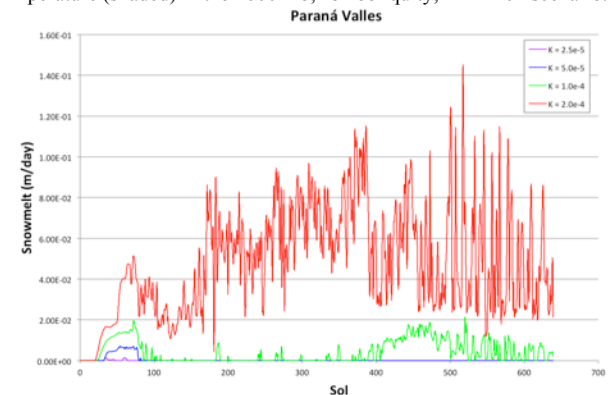


Fig. 2. Snowmelt runoff rates, in m day^{-1} , at Paraná Valles, in climates with 1000 mb CO_2 , 25° spin-axis obliquity, and grey gas $\kappa = 2.5 \cdot 10^{-5}$ (purple), $5 \cdot 10^{-5}$ (blue), $1 \cdot 10^{-4}$ (green), and $2 \cdot 10^{-4}$ (red) $\text{m}^2 \text{kg}^{-1}$.

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