LATE NOACHIAN ICY HIGHLANDS CLIMATE MODEL: EXPLORING THE POSSIBILITY OF TRANSIENT MELTING AND FLUVIAL/LACUSTRINE ACTIVITY THROUGH PEAK TEMPERATURES.

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Introduction: Ancient martian fluvial features, including valley networks (VN) [1] and open- and closed-basin lakes [e.g. 2,3], are indicative of liquid water flow on the surface of the southern highlands during the Late Noachian and Early Hesperian [4]. Models have suggested that under the influence of a younger Sun that emitted ~75% of the present luminosity [5], early Mars would be forced into a cold steady state with temperatures consistently <273 K [6,7]. In these models, greenhouse gases and CO_2 clouds are incapable of producing the additional warmth necessary for rainfall and runoff [6-13] while staying within reasonable source and sink constraints. It is likely that orbital parameters differed in the Noachian from the current values with potentially large variations in obliquity; [14] predicts an average obliquity over the past 4 Gyr of 41.8°, ranging from 25-55°. Adjusting orbital parameters, however, also does not induce a large enough temperature increase [6]. As previously mentioned and in contrast to the model-predicted ambient climate, there is geological evidence of fluvial and lacustrine activity on the martian surface. Here, we address whether the formation of these features is possible through transient warming, rather than requiring continuous temperatures above the melting point of water.

With models incapable of producing relatively continuous clement conditions [6,7], we consider a “cold and icy” planet with periods of transient warmth to permit rainfall/snowmelt and runoff for incision of the VNs and formation of the lakes.

Background: There are major differences between snow accumulation in a “cold and icy” climate and rainfall patterns in a “warm and wet” climate. Recent general circulation models (GCMs) show that when atmospheric pressure exceeds tens to hundreds of millibar, an altitude-dependent temperature effect is induced [6,7] and H_2O preferentially accumulates in the highlands, producing a “Late Noachian Icy Highlands” (LNIH) scenario [15]. In this context, [16] studied where precipitation would occur under a natural “cold and icy” LNIH scenario versus a gray-gas forced “warm and wet” scenario, finding that snow accumulation under a cold climate correlates much better with the VN distribution than predicted rainfall patterns do in a “warm and wet” climate.

However, melting of this surface snow accumulation must occur for incision of the VNs [17,18]. There are several end member options for transient atmospheric warming on early Mars including (1) periods of intense volcanism releasing high concentrations of sulfur dioxide into the atmosphere [13], (2) impact cratering-induced warming [19-21], and (3) the possibility of transient melting from peak seasonal temperatures elevating above 273 K [e.g. 15]. Punctuated volcanism could raise temperatures enough to permit snowmelt and runoff on the surface from the increased SO_2 in the atmosphere. However, the period of warmth would be relatively short-lived as the SO_2 would convert into aerosols and bring planetary cooling [13]. Impact cratering induces extremely hot conditions and intense precipitation through a hydrologic cycle that could last hundreds of years for large impacts [19,20]. However, the rainfall and runoff produced by this mechanism may be too intense and globally-distributed to produce the delicate and widely-spaced VN features and patterns.

The focus of this work is to use the Laboratoire de Meteorologie Dynamique (LMD) GCM for early Mars to test the latter of these hypotheses [15], that peak seasonal/daytime temperatures producing transient snowmelt and subsequent runoff in the equatorial regions could explain the nature and distribution of VNs. At Lake Hoare in the Antarctic Dry Valleys (ADV), where mean annual temperature (MAT) is far below freezing, seasonal and diurnal temperature variations permit 5-7% of the year to be >273 K; a duration proven sufficient to maintain the lake.

This work (1) expands upon the explored parameter space for early Mars [e.g. 6,7,16], specifically contributing an understanding of the effects from eccentricity variation and moderate greenhouse warming, (2) explores the possibility of seasonal melting through the use of a 3-D GCM to determine how regions with peak annual temperatures (PAT) >273 K correlate with the snow/ice distribution, producing melt, (3) calculates annual meltwater durations and volumes to place constraints on the total duration of this annually repetitive process for forming the VNs, and (4) highlights the importance of considering seasonal and diurnal temperature variation when considering climate, in addition to MAT (Fig. 1).

Methods: We employ the LMD GCM [e.g. 6,7,16] to test for transient melting under the conditions of PAT. We collect model data four times per model day, every six model hours, for the entire martian year. This ensures that we are capturing the absolute warmest daily temperatures (noon-time).

Parameter space explored. In this analysis, we focus on a range of pressures for a pure CO_2 atmosphere (600-1000 mbar) [e.g. 6], and explore the effects of a range of spin-axis obliquities (25-55°) and eccentricities (0-0.097) that correspond to predictions by [14] for the Late Noachian, assuming a solar luminosity 75% of the current value [5,23]. We specifically test 600, 800, and 1000 mbar atmospheres, each at obliquities of 25, 35, 45, and 55° and eccentricities of 0 (circular) and 0.097.

Additionally, we re-visit our parameter space including the addition of a small amount of greenhouse gas surrogate in the atmosphere, an addition that serves to strengthen the annual warming effect, to assess how much annual atmospheric warming could occur above 273 K under conditions where MAT is >225 K but still <273 K. Because of uncertainty in sources and sinks for specific greenhouse gases, we account for greenhouse warming by adding gray gas, which absorbs evenly across the spectrum at a defined absorption coefficient (κ). We choose a small κ to raise MAT by only a few degrees, maintaining an overall "cold and icy" climate (absorption coefficient κ=2.5e-5 kg m^{-2}; ~10 K additional warming).

Determine if regions with PAT >273 K correlate with the ice distribution. First, we produce MAT and PAT maps to determine what locations on the globe experience temperatures >273 K for at least one data point per year. In exploring this parameter space and analyzing the distribution of regions with PAT >273 K, we draw first order conclusions regarding whether transient melting of snow and ice may be responsible for VN formation by determining if regions of snow accumulation, PAT >273 K, and the VN distribution are correlated [16]. These results also lay the basis for determining whether or not repetitive yearly peak-condition melting events in similar locations over long periods of time could be responsible for more significant fluvial/lacustrine activity if yearly amounts are insufficient to explain the entire VN landscape, a situation that is observed in the ADV [15]. In summary, we search for regions with substantial snow accumulation (~1 km ELA; Fig. 2) that also have PAT above the melting point of water, permitting snowmelt and runoff at these locations.

Although peak seasonal melting can form fluvial features in the ADV [15], it is possible that peak temperatures >273 K (PAT maps; Fig. 3) on Mars may not last for more than a few hours yearly (>1 data point), which would be insufficient to cause the necessary scale of melting and erosion [17]. To reconcile this, we (1) produce temperature time-series at three VN locations to determine the annual duration of melt conditions and (2) assess the total amount of annual meltwater globally through "positive degree day" (PDD) calculations to determine if peak temperatures last long enough to provide sufficient melting [17,22] in comparison to the ADV and determine the number of years that this process must repeat to produce enough erosion for VN formation [18].

Our PAT maps place further constraints on the spin-axis orbital parameter space necessary to maximize transient melting. We compare regions where melting could occur to the VN distribution to determine the conditions most suitable for VN formation.

Constrain melt durations and quantities. Melting of the ice sheet and subsequent runoff lead to VN formation. Here, we focus on three specific VNs: Evros Valles (12°S, 12°E), networks near Kasei Outflow Channel (23°N, 55°W), and Parana Valles (24.1°S, 10.8°W) (Fig. 2). The chosen networks are widely spread and represent a global sample. We produce temperature time-series for one year at each of these VNs to determine the annual duration of and percentage of the year with temperatures >273 K.

Next, we quantify the annual amount of melt produced. We adopt the methods of [17] to calculate the amount of meltwater produced for a given number of PDD. For the purpose of this study, we define a PDD as having at least 6 hours >273 K, or one model data point per day (there are 4 points/day). We calculate the number of days with PDD≥1 at every model grid point (lat, lon) to produce a PDD map, which displays the PDD value across the planet. Comparing this map with the predicted LNIH ice distribution, we locate all model grid points with PDD≥1 and snow or ice present (PDD+snow map). Then, adopting the PDD conversion factor for Mars, 1.08 mm/PDD [17], we integrate over the PDD+snow map to determine the thickness of ice melted in one year. We convert this into a volume based on the area of overlapping PDD≥1 and snow/ice, and compare the amount of melt per year with the total amount of water required to form the VNs [18]. Thus, we can determine the number of years that this process must repeat to form the VNs, if possible at all, for all spin-axis orbital conditions considered here.

Results and Discussion: Fig. 3 shows a specific example from our study: MAT, PAT, and PAT >273 K maps for 25 and 45° obliquity, circular orbit, 600 and 1000 mbar CO_2 atmosphere, and moderate gray gas warming. We highlight the aforementioned results here because they provide the most seasonal melting. Importantly, without additional greenhouse warming, the studied VNs experience one or no days above freezing annually, which we determine is insufficient for formation of the VNs and lakes.

The maps in Fig. 3 highlight the dependence of MAT and PAT on obliquity and atmospheric pressure. As atmospheric pressure increases, so does MAT and the region of the planet with PAT >273 K. As obliquity increases, maximum solar insolation migrates towards the north pole (for precession considered here), migrating the region of PAT >273 K poleward as well. The third panel in Fig. 3 highlights regions with PAT >273 K in pink, corresponding to a significant portion of the globe, increasing in percentage for higher atmospheric pressure and shifting to the equator for low obliquities. Thus, we determine that high pressure, low obliquity conditions are most suitable to melting/runoff in equatorial regions.

With evidence that PAT can be >273 K in equatorial regions where VNs are abundant, we proceed to the VN portion of this study. One-year time-series at the three VN study sites are shown in Fig. 4. Under all conditions, each VN either approaches 273 K or is >273 K for a few data points per year, in contrast to the non-gray gas simulations. This even holds true for Parana Valles, whose southern location prevents it from receiving as strong of solar insolation as the other sites because of obliquity effects. Under many studied conditions, the VN sites experience a percentage of the year >273 K comparable to or more than what is observed in the ADV, implying that these conditions could be sufficient to form and sustain the VNs if the process repeats for many years.

Finally, we consider the total amount of melt produced by peak seasonal melting. Fig. 5 shows a sample map of the region with PDD≥1 overlaying the predicted LNIH ~1 km ELA (equilibrium line altitude) ice distribution [15]. The overlapping regions are used for PDD calculations, as previously described. Although the amount of melt produced through this process annually is very small, repeating this process for many years can produce a significant amount of melt (when including the influence of ~10 K additional warming). We are currently constraining how many years this process must repeat to explain the observed VN distribution.

Conclusions: Our results show evidence that peak summertime temperatures can exceed 273 K in areas of long-term snow and ice accumulation in equatorial regions of the southern uplands, allowing for transient melting that corresponds latitudinally with the VN distribution. We find that the best spin-axis orbital conditions to produce temperatures >273 K in the equatorial regions are low obliquity, because peak solar insolation is equatorial, and high atmospheric pressure, trapping more heat in the atmosphere; 25° and 1000 mbar CO_2. Increasing eccentricity increases the strength of seasonal cycles, thus increasing the magnitude of summertime conditions (eccentricity data not shown here). However, the predicted maximum eccentricity, 0.097 [14], is too low to force a large increase in temperature. Thus, while understanding the implications of eccentricity variations in the Noachian is important, it does not contribute to a large increase in seasonal warming.

Without additional greenhouse warming, our results suggest that the periods of heating are short lived and thus another contribution mechanism of transient atmospheric warming would be required for VN incision, such as impact cratering [19-21] or volcanism [13]. However, when considering at least 10 K additional greenhouse warming, we conclude that transient melting over long geologic timescales could occur through small amounts of yearly melting and erosion during the warmest hours of the martian summer season [15]. With at least 10 K of additional greenhouse warming, we find that it is possible that the fluvial features could form solely through seasonal temperature variation. Constraining the specific greenhouse gases responsible for this warming is the topic of future work.

In this work, we highlight the importance of considering seasonal temperature variation in a “cold and icy” climate. Although MAT is far below the melting point of water (~235 K), peak summertime temperatures can be >273 K in equatorial regions. Thus, we conclude that with moderate warming it is possible to form the VNs from snowmelt and subsequent runoff on long time scales. We have also contributed to broadening the parameter space explored for early Mars climate, contributing an understanding of the effects of eccentricity variations and moderate greenhouse warming, and have applied qualitative techniques to GCM data to determine meltwater totals from seasonal melting. Our ongoing work includes comparing our results, melt durations and volumes with previously calculated values [17,22] to address the required duration for this process to form the VNs and lakes.

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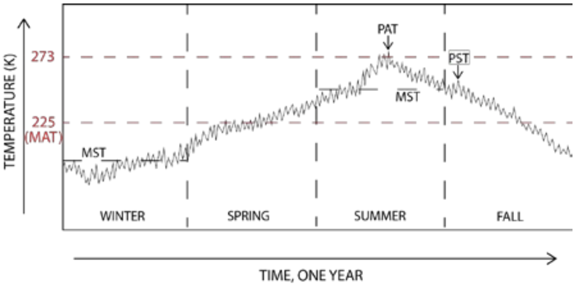

Fig. 1. Relationship among mean annual temperatures (MAT), peak annual temperatures (PAT), mean seasonal temperatures (MST), and peak seasonal temperatures (PST). PAT can be much greater than MAT, reflecting the warmest annual conditions. This example illustrates a possible case for “cold and icy” early mars, with MAT ~225 K and PAT >273 K.

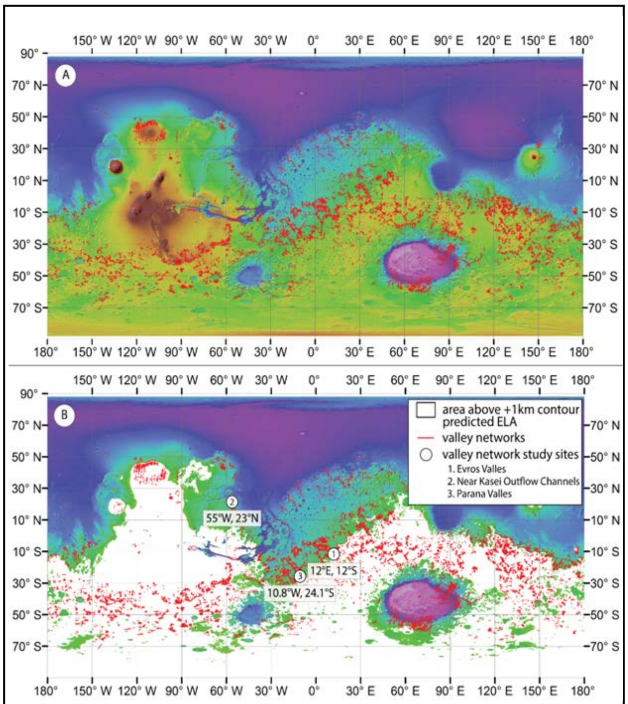

Fig. 2. Distribution of VNs and the predicted distribution of snow/ice in the LNIH model. (A) The VN distribution [1] in red lines, superposed on a MOLA topographic map (red is high, purple is low). (B) VN distribution superposed on the predicted LNIH ice distribution at 1 km ELA (equilibrium line altitude) [15]. Locations of the three VN study sites used for time-series analysis are included in the key and marked on the global map (B).

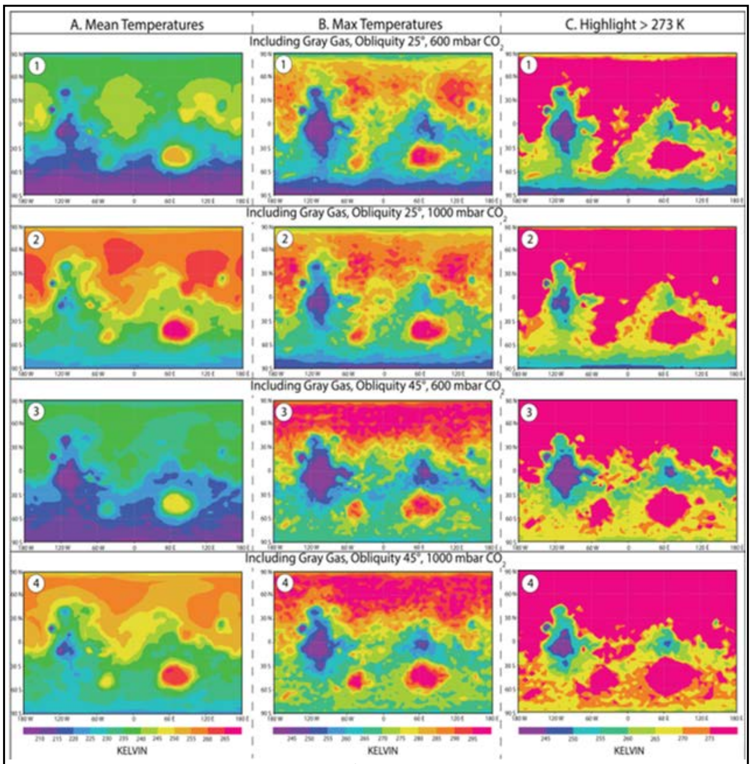

Fig. 3. MAT (col A) and PAT (col B) for a CO_2 atmosphere and circular orbit with the addition of gray gas to induce additional warming. Shown are these MAT/PAT values in conditions of different obliquity (rows 1 and 2 at 25°; rows 3 and 4 at 45°) and different atmospheric pressure (rows 1 and 3 at 600 mbar; rows 2 and 4 at 1000 mbar). Col (C) shows PAT, highlighting all data points ≥273 K in pink.

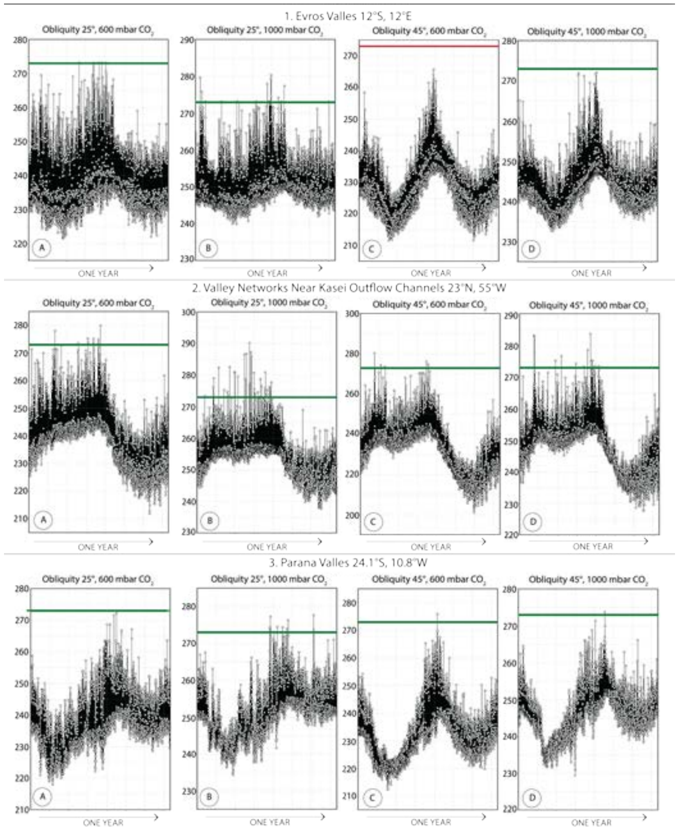

Fig. 4. Temperature time-series; same conditions as fig. 3. Data for three VNs distributed at different lat and lon (see Fig. 2). Obliquity and pressure: (A) 25°, 600 mb; (B) 25°, 1000 mb; (C) 45°, 600 mb; (D) 45°, 1000 mb. Horizontal lines provide reference for temperatures approaching 273 K. Green: temperatures approach (<5 K below) or are >273 K for ≥1 data point per year. Red: temperatures approach, but do not exceed 273 K (>5 K below). The gray gas ~10 K increase forces all studied VNs to be >273 K for ≥1 data point per year (does not occur without extra warming). This is most important for Parana Valles, because obliquity prevented temperatures from reaching 273 K in non-gray gas simulations. Evros Valles experiences max 3% of the year >273 K, the Networks near Kasei experience max 5.1%, and Parana Valles experiences max 1.2%.

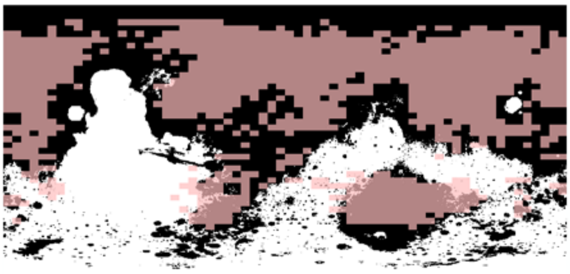

Fig. 5. Pink: PAT >273 K (PDD≥1) for the case of 25° obliquity, 1000 mbar CO_2 atmosphere, and circular orbit (no gray gas). This data is plotted over the predicted 1 km ELA snowline [15], showing an overlap of PAT >273 K and the snow/ice distribution. We calculate number of PDD in overlapping regions (pink on white), then perform calculations described in the text.