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

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**Introduction:** Climate models have suggested that under the influence of a younger Sun, with ~75% the present luminosity [1,2], early Mars would be forced into a cold steady state with mean annual temperatures (MAT) consistently below the melting point of water [3,4]. In contrast, there is geological evidence for fluvial and lacustrine activity during the Late Noachian and Early Hesperian, including valley networks (VNs) [5] and open- and closed- basin lakes [6]. With current models unable to produce relatively continuous clement conditions (MAT >273 K) [3,4], we consider the possibility of a "cold and icy" planet (MAT<273 K) and address the question: is formation of fluvial/lacustrine features possible from shorter periods of punctuated heating and associated snowmelt and runoff?

**Background:** General circulation models (GCMs) [3,4] show that when atmospheric pressure exceeds tens to hundreds of mbar, an altitude-dependent temperature effect is induced and $H_2O$ preferentially accumulates in the highlands, producing a "Late Noachian Icy Highlands" (LNIH) scenario [7]. The location of precipitation under a nominal "cold and icy" LNIH scenario versus a forced "warm and wet" scenario was examined by [8], who found that snow/ice accumulation under a cold climate is better correlated with the VN distribution than rainfall in a "warm and wet" climate.

The requirement remains, however, for melting of the snow/ice and runoff to incise the VNs [9,10]. There are several end member options for transient atmospheric warming on early Mars including: (1) $SO_2$-induced warming from periods of intense volcanism [11], 2) impact cratering induced warming [12], and (3) transient melting from peak seasonal temperatures [e.g. 7]. Punctuated volcanism could lead to snowmelt and runoff from the increased $SO_2$ in the atmosphere, but rapid conversion of $SO_2$ to aerosols (cooling) would prevent heating from extending beyond decades to centuries [11]. Impact cratering induces extreme high-temperature conditions and precipitation for a short duration (centuries) [12], but may produce too much rainfall to form the delicate and equatorially-concentrated VNs [13].

The focus of this work is to test (3), peak seasonal temperatures hypothesis, by 1) assessing whether regions with peak annual temperatures (PAT) >273 K correlate with the predicted snow/ice distribution, and 2) calculating meltwater volumes in order to place constraints on the cumulative duration required for this process to form the VNs. This work highlights the importance of considering seasonal and diurnal temperature variation in addition to MAT, and contributes an understanding of the climatic effects of modest greenhouse warming and varying eccentricity on early Mars.

**Methods:** We employ the Laboratoire de Meteorologie Dynamique (LMD) GCM for early Mars. In this analysis, we focus on a range of pressures (600, 800, and 1000 mbar) for a pure $CO_2$ atmosphere [e.g. 3] for a range of obliquities (25, 35, 45, and 55°) and eccentricities (0 and 0.097) in the Late Noachian [14]. We collect model data four times per model martian day (every six hours).

We also assess the addition of a small amount of greenhouse "gray gas" in the atmosphere in order to assess atmospheres with enhanced temperatures. Due to the uncertainty in sources and sinks for specific greenhouse gases, we account for the warming by adding gray gas, which absorbs evenly across the spectrum at a defined absorption coefficient. We choose a small absorption coefficient, κ, to raise MAT by ~18 K, maintaining an overall "cold and icy" climate ($\kappa$=2.5e-5 kg $m^{-2}$).

*MAT and PAT maps:* Is transient melting and runoff a viable mechanism for VN formation? We assess which spin-axis orbital conditions and atmospheric pressures produced PAT >273 K in the locations where VNs are abundant and snow/ice is predicted to accumulate, producing meltwater (Fig. 1).

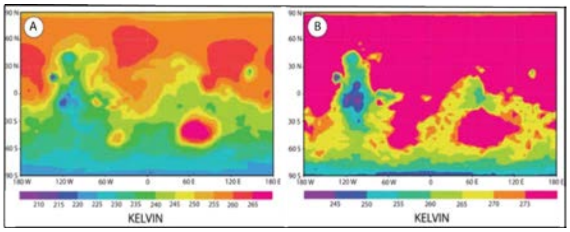

**Fig. 1: MAT (A) and PAT (B) maps for 25° obliquity, 1000 mbar $CO_2$ atmosphere, additional greenhouse warming.**

What percentage of the year >273 K would be required to cause melting and fluvial erosion? At Lake Hoare in the Antarctic McMurdo Dry Valleys (MDV) (MAT=~255 K), seasonal and diurnal temperature variations are >273 K for ~5-7% of the year, a duration sufficient to maintain the lake through fluvial input. While a similar percentage of the year may be sufficient to form comparable features on early Mars, our analysis thus far does not represent durations of conditions >273 K because each PAT data point represents only six hours. It is possible that temperatures >273 K may not last for more than a few hours yearly, which may be insufficient to cause the necessary melting and erosion [9]. To reconcile this, we 1) determine the annual duration of melt conditions at three VNs and 2) use "positive degree day" (PDD) calculations to assess the total global amount of annual meltwater produced [9,15] and the number of years that this process must be active to produce sufficient meltwater for VN formation.

*VN study:* We examine Parana Valles, Evros Valles, and the Kasei networks, which are distributed near the edges of the predicted LNIH ice sheet at locations that require melting of ice and subsequent runoff to form in this climate. We produce temperature time-series for one martian year at each VN to determine the fraction of the year with temperatures >273 K.

*PDD analysis:* We define a PDD as having at least 6 hours >273 K, or at least one data point per day, and determine number of PDD at each model grid point. Adopting the PDD conversion factor for Mars, 1.08 mm/PDD [9], we find the thickness of ice melted at all model grid points where PDD ≥1 and LNIH snow/ice is present. Next, we determine the total (global) thickness/volume of ice melted in one martian year. We then compare the amount of annual meltwater to the total volume required to form the VNs [10] to determine the number of years that this process must operate in order to carve the VNs.

**Results and Discussion:** We include a specific example from our study that represents optimal conditions for equatorial melting: 25° obliquity, 1000 mbar $CO_2$ atmosphere, circular orbit, and additional greenhouse warming (MAT=243 K). Lower obliquity concentrates maximum solar insolation near the equator and a thicker atmosphere increases the greenhouse effect. Thinner atmospheres prevent the studied VNs from experiencing melting conditions for ≥ 1 day annually, a duration insufficient for VN formation. Additionally, we find that varying the eccentricity in our models does not contribute to further seasonal warming and melting events.

Our models show that PAT can be >273 K in regions where both VNs are abundant and snow/ice accumulates (Fig. 1). Time-series at the three VN study sites show that each VN either approaches or exceeds 273 K for a few data points each year (Fig. 2). In this case, the VNs experience conditions above freezing for a fraction of the year comparable to the MDV, implying that these conditions might be sufficient to form the VNs if this process operates for a sufficiently long duration.

For these conditions, a volume of $2.92 \times 10^{10}$ $m^3$ (~$2 \times 10^{-4}$m GEL) meltwater is produced annually (Fig. 3). If 3-100 m GEL is required to form the VNs [10], this process must repeat for ~$1.5 \times 10^4$ to ~$5 \times 10^5$ years to produce enough meltwater. Previous analysis suggest that VN formation may have required a cumulative $10^5$-$10^7$ years of runoff [16]. In concert with the predicted distribution of meltwater (Fig. 3), our results indicate that this mechanism could plausibly be responsible for VN formation.

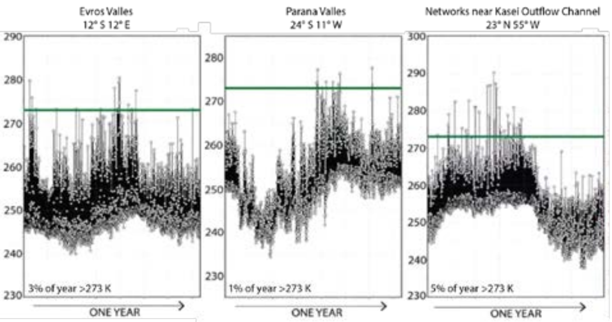

**Fig. 2: Temperature time-series at three VNs.**

Critically, we have not yet considered runoff rates. At any grid point, the maximum thickness of ice melted annually is ~30 cm (Fig. 3). Unless all meltwater is produced and runs off within one day, runoff rates are lower than required [mm-cm/day; 16,17]. Thus, while significant meltwater is produced in our models, slightly warmer conditions may be required to generate the necessary higher runoff rates, a subject of ongoing work.

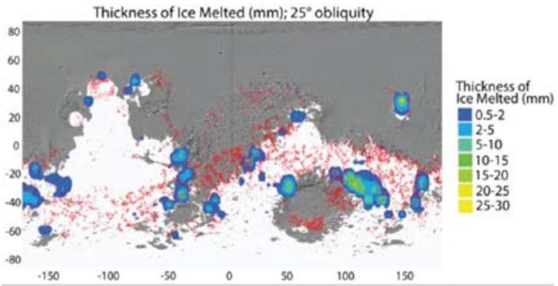

**Fig. 3: Results of PDD calculations overlain on VN distribution.**

**Conclusions:** We highlight the importance of considering seasonal/diurnal temperature variations along with MAT to assess melting in "cold and icy" early Mars climate scenarios. We find that ow obliquity and high atmospheric pressure are required to produce temperatures >273 K in the equatorial regions. PAT >273 K durations are not conducive to VN formation in the nominal MAT=225 K "cold and icy" climate and we suggest that additional heating is required, such as by impact cratering [13] or volcanism [11]. Under warmer conditions (MAT=243 K), however, transient melting of snow/ice can occur during the warmest hours of the summer season. Under these conditions, a sufficient volume of meltwater can be produced to form the VNs, although runoff rates may be too low.

**References:** [1] Gough (1981), Sol Phys, 74, 21-24. [2] Sagan and Mullen (1972). [3] Forget et al. (2013), Icarus 222, 81-99. [4] Wordsworth et al. (2013), Icarus 222, 1-19. [5] Hynek et al. (2010), JGR 115, E09008. [6] Fassett and Head (2008a), Icarus 195, 61–89. [7] Head and Marchant (2014), Antarc Sci 26, 774-800. [8] Wordsworth et al. (2015), JGR 120, 120119. [9] Fastook and Head (2015), PSS 106, 82-98. [10] Rosenberg and Head (2015), PSS 117, 429-35. [12] Halevy and Head (2014), Nat Geo Lett [13] Segura et al. (2002), Science 298, 1997-80. [14] Palumbo and Head (2017), MAPS, In Review. [15] Laskar et al. (2004), Icarus 170, 343-64. [16] Scanlon et al. (2013), GRL 40, 4182-87. [17] Hoke et al. (2011), EPSL 312, 1-12. [18] Scanlon et al. (2016), Icarus, In Review.