GLOBAL CLIMATE MODEL PREDICTIONS FOR A TRANSIENT CHANGE FROM A LONG-LIVED “COLD AND ICY” CLIMATE TO A SHORT-LIVED “WARM AND WET” CLIMATE IN THE LATE NOACHIAN-EARLY HESPERIAN.  A. M. Palumbo\textsuperscript{1} and J. W. Head\textsuperscript{1}, \textsuperscript{1}Department of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912 USA (Ashley_Palumbo@Brown.edu).

\textbf{Introduction:} Geologic evidence, including valley networks (VNs) [1] and lakes [e.g. 2,3], suggests that the early martian climate was “warm and wet” with above-freezing temperatures and rainfall [4-6]. In contrast, climate model results suggest that the early climate was “cold and icy” with temperatures far below freezing, surface water trapped as ice in the highlands [7,8], and most fluvial activity explained by punctuated heating and snow/ice melting, not rainfall. Thus, there are two end-member climate scenarios for early Mars: “warm and wet” and “cold and icy”.

Recent climate modeling efforts have attempted to constrain the distribution and characteristics of rainfall in a “warm and wet” climate by forcing artificial greenhouse conditions to simulate a climate with global mean annual temperature (MAT) above freezing [9,10]. These studies find that (1) precipitation is dominated by snowfall, not rainfall, (2) Tharsis remains below freezing year-round and some water is cold-trapped there, (3) unless there is an ocean in the lowlands, rainfall is almost non-existent, and (4) even if there is an ocean, rainfall is not predicted in areas with abundant VNs [9,10]. Similar to the model-predicted “cold and icy” climate, fluvial activity in the simulated “warm and wet” climate is dominated by snowmelt, not rainfall.

Here, we use 3D global climate model (GCM) simulations and analyses of the distributions of VNs and lakes in order to determine whether the formation of these features is more consistent with snowmelt in a long-lived “warm and wet” Noachian climate or snowmelt in a long-lived “cold and icy” Noachian climate with one or more periods of punctuated heating.

\textbf{Methods:} We aim to determine the distribution of meltwater produced through summertime melting of surface snow/ice in the highlands in a long-lived “warm and wet” climate (without an ocean, following [10]), and (2) produced through melting of widespread snow/ice in the highlands during periods of punctuated heating in a long-lived “cold and icy” climate. The model-predicted distribution of meltwater in comparison to the distributions of VNs and lakes provides insight into whether the long-lived climate was “warm and wet” or “cold and icy” with punctuated heating.

We implement the 3D LMD GCM [10,11] and utilize a total of four simulations: (1) “warm and wet” with 25° obliquity, (2) “warm and wet” with 45° obliquity, (3) “cold and icy” with 25° obliquity, and (4) “cold and icy” with 45° obliquity.

The simulations with a “cold and icy” climate [11] were generated for a 1 bar CO2 atmosphere [12], 25° and 45° obliquity [13], a circular orbit [13], and 75% of the present solar luminosity [14]. The global MAT in these simulations is \(~225\) K and most surface water is trapped as ice in the highlands.

The simulations with a “warm and wet” climate [10] use the same approach and parameter values as those with a “cold and icy” climate but have additional greenhouse warming forced in the model by the introduction of atmospheric gray gas. We use gray gas coefficients of \(\kappa = 7.5 \times 10^{-3} \text{ m}^2/\text{kg}\) and \(\kappa = 9.5 \times 10^{-3} \text{ m}^2/\text{kg}\) for simulations with 25° and 45° obliquity, respectively [10], which produces global MAT \(~275\) K. We do this to satisfy the temperature requirement of a “warm and wet” climate: above-freezing surface temperatures [e.g. 5].

For all simulations, the GCM was run at a spatial resolution of 65x49x25 (lon x lat x alt) and hourly data was collected. These spatial and temporal resolutions are sufficient to capture the regional and seasonal variation that is necessary to complete our analysis.

\textbf{Results:} We discuss our results by (1) analyzing the model-predicted meltwater distributions for the different climate scenarios and (2) comparing the results with the distributions of VNs and lakes in order to determine which of the climate scenarios is more consistent with formation of the VNs and lakes.

\textit{Meltwater distributions in a long-lived “warm and wet” climate.} We identify regions where meltwater production occurs within one year as regions in which snow/ice accumulates (fig 1a) but snow/ice is only present for part of the year (minimum annual snow/ice thickness of zero; fig 1b), implying that the accumulated snow/ice melted. This method provides a reasonable proxy for the distribution of meltwater for two key reasons: (1) if snow/ice accumulated but is not present for a full model year, the accumulated snow/ice has melted, and (2) in regions where ice is present year-round, the ground is never exposed and so those areas could not experience typical fluvial regolith erosion and VN formation. It is important to note that this method does not make predictions about runoff rates, runoff distances, or meltwater volumes.

We then compare the distribution of VNs and lakes with the model-predicted distribution of meltwater to estimate the percentage of VNs and lakes that could have formed through snow/ice melting and runoff in this
climate scenario. For the simulation with $25^\circ$ obliquity, we find that 27% of VNs and 14% of lakes are located in areas where meltwater is predicted (fig 1c, table 1). For $45^\circ$ obliquity, we find that 58% of VNs and 46% of lakes are located in areas where meltwater is predicted (fig 1c, table 1).

Fig. 1. GCM results for a long-lived “warm and wet” climate for 25° (top) and 45° (bottom) obliquity. Shaded in blue are (a) areas where snow/ice accumulates at some point in the year, (b) areas where snow/ice is present year-round, and (c) areas of predicted melting. VNs are drawn as lines and lakes are drawn as circles.

Meltwater distributions in a long-lived “cold and icy” climate with punctuated heating. To estimate regions in which meltwater would be produced during a punctuated heating event in a long-lived “cold and icy” climate, we compare the GCM-predicted yearly minimum snow/ice distribution in a “cold and icy” climate (fig 2a) with the yearly minimum snow/ice distribution in a “warm and wet” climate (fig 2b); the difference between these two ice distribution maps portrays the areas in which snow/ice would be melted during the change from cold to warm conditions during a punctuated heating event (fig 2c). Note that we make the reasonable assumption that the punctuated conditions are akin to the simulated “warm and wet” climate.

Fig. 2. GCM results for a long-lived “cold and icy” climate with punctuated heating for 25° (top) and 45° (bottom) obliquity. Shaded in blue are (a) areas where snow/ice is present year-round in a “cold and icy” climate, (b) areas where snow/ice is present year-round in the punctuated (“warm and wet”) climate, and (c) areas of predicted melting.

We then compare the distribution of VNs and lakes with the model-predicted distribution of meltwater to estimate the percentage of VNs and lakes that could have formed through snow/ice melting and runoff during a period of punctuated warm conditions in a long-lived “cold and icy” climate. For the simulation with 25° obliquity, we find that 57% of VNs and 39% of lakes are located in areas where meltwater production is predicted (fig 2c, table 1). For $45^\circ$ obliquity, we find that 72% of VNs and 61% of lakes are located in areas where meltwater production is predicted (fig 2c, table 1).

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<tr>
<th>Obliquity</th>
<th>RAINFALL</th>
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<tr>
<td>45°</td>
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Table 1. Percentage of VNs and lakes that are located in areas of model-predicted rainfall or snow/ice melting for all GCM simulations and climate scenarios considered in this work. The scenario with the highest percent of VNs and lakes located in areas of predicted fluvial activity is highlighted in blue.

Conclusions: Recent climate modeling studies have shown that fluvial activity in the LN-EH would have been dominated by melting of snow/ice, not rainfall, regardless of whether the climate was “warm and wet” or “cold and icy” with punctuated heating [9,10]. In this work, we analyzed GCM results and the distribution of VNs and lakes in order to determine whether the distribution of model-predicted snow/ice melting is more consistent with the distribution of the VNs and lakes for the scenario of (1) melting of surface snow/ice during the summer season in a long-lived “warm and wet” climate or (2) melting of surface snow/ice during a punctuated heating event in a long-lived “cold and icy” climate. Our results show that ~20-30% more of the VNs and lakes are in areas of predicted meltwater for the scenario of a long-lived “cold and icy” climate with one or more periods of punctuated heating than for the scenario of a long-lived “warm and wet” climate (table 1).

These results are consistent with the hypothesis that (1) the long-lived background Noachian climate could have been “cold and icy”, characterized by widespread cold-based glaciation in the highlands and little-to-no fluvial activity, and (2) one or more periods of punctuated heating could have led to relatively short-lived “warm and wet” conditions in the LN-EH, characterized by abundant widespread snow/ice melting, runoff, and formation of the VNs and lakes.

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