CHARACTERIZING A WARM AND WET EARLY MARTIAN CLIMATE WITH A 3D GLOBAL CLIMATE MODEL. A. M. Palumbo[1] and J. W. Head[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA (Ashley_Palumbo@Brown.edu).

Introduction: The surface of Mars contains abundant geomorphological and mineralogical evidence that liquid water was stable at the surface during the Late Noachian and Early Hesperian, including widespread fluvial valley networks (VNs) [1], open- and closed-basin lakes [2,3], and aqueous alteration products [4]. Further, Noachian-aged craters have degraded rims and no visible ejecta deposits [5], characteristics which have been attributed to rainsplash-related erosion[6].

Despite this evidence for abundant liquid water activity at the surface, climate models have been unsuccessful in reproducing the continuous "warm and wet" conditions presumed to be necessary for the formation of these features when considering the influence of the faint young Sun [7] and reasonable greenhouse gas concentrations [8–11]. Instead, the models predict a "cold and icy" climate, characterized by mean annual temperature (MAT) far below the melting point of water [12,13], an adiabatic cooling effect [14], and ice distributed across the southern highlands. To explain this conundrum, recent work has suggested that the formation of the VNs and lakes may be explained through transient or punctuated ice melting, surface runoff, and ponding in a "cold and icy" climate [14–16], instead of rainfall in a "warm and wet" climate [6]. Additionally, recent work has suggested that crater degradation and smoothing of inter-crater plains can be explained by transient floods which would be expected to occur due to the climatic influence of basin-scale impact events [17].

In this work, we take the opposite approach: we assume that a "warm and wet" climate was plausible, based on the overwhelming geologic evidence, and force these climatic conditions in a 3D climate model. The combination of our model results and the distributions of the VNs and lakes provides useful insight into the possible formation conditions of these features.

Methods: We employ the 3D Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) for early Mars to simulate a "warm and wet" climate. We consider a 1 bar CO_2 atmosphere, obliquities 25-55° [18], a circular orbit, and 75% the present solar luminosity [7]. Because a plausible combination of greenhouse gases that can continuously increase MAT to or above 273 K has not yet been identified [13], we focus on the lowest temperature end of a "warm and wet" climate and we artificially warm the planet by introducing a gray gas into the model atmosphere. A gray gas characteristically absorbs at all wavelengths with a defined absorption coefficient, κ. We choose $\kappa = 7.5 \times 10^{-5}$ m^2 kg^{-1}, which produces a climate with MAT ~273 K in near-equatorial regions (global MAT ~275 K), where VNs and lakes are abundant (**Fig. 1**).

Our goal is to better understand the characteristics of a "warm and wet" climate. In this analysis, we highlight multiple characteristics of this climate and discuss how these characteristics are consistent or inconsistent with the distribution of the VNs and lakes. We analyze the climate on the basis of the factors deemed necessary to explain the formation of the VNs and lakes. Among these factors are temperatures >273 K, and rainfall. We determine regions of the planet that experience temperatures >273 K and rainfall and how these patterns vary seasonally. Then, we perform a spatial correlation between areas with temperatures >273 K and the distributions of the VNs/lakes, and areas with rainfall and the distributions of the VNs/lakes. The goal of this analysis is to determine if the fluvial and lacustrine features could have been formed in a "warm and wet" climate, or if they appear inconsistent with this climate scenario. In the latter case, we consider that the formation of these features may have required even warmer and wetter conditions or that they formed through punctuated ice melting and runoff in a predominantly "cold and icy" climate.

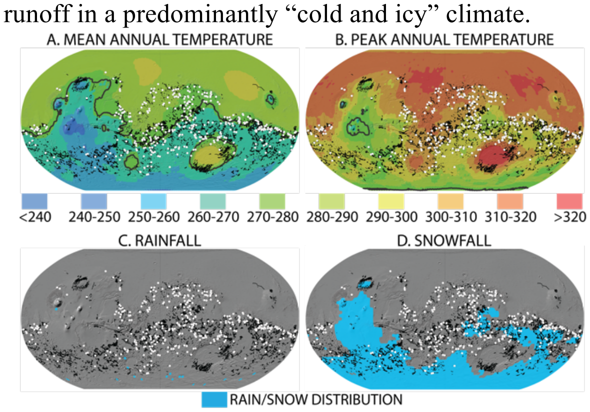

Fig. 1. Results from GCM simulations. (A) MAT, black line is 273 K isotherm, warmer colors represent warmer temperatures. (B) Peak annual temperature. (C) All locations where rainfall occurs throughout the year in blue; only small amounts of rainfall in southern hemisphere. (D) All locations where snowfall occurs throughout the year in blue. VNs are plotted as black lines and lakes as white circles.

Results and Discussion: Under the influence of an atmosphere much thicker than current, the atmosphere and surface thermally couple and temperature becomes dominantly altitude dependent [12,15]. Thus, higher altitudes act as cold traps for water and ice becomes stable at high altitudes year-round. In the typical "cold and icy" climate scenario, ice is distributed across the highlands because of this effect. In this "warm and wet" simulation, the highest altitude region, the Tharsis rise, and the south polar region are consistently below 273 K and some water is trapped in these regions as ice (**Fig. 1**).

The global MAT is above the melting point of water (~275 K), but the altitude dependence of temperature leaves vast portions of the southern highlands with MAT <273 K (**Fig. 1**). Areas with abundant VNs and lakes and MAT >273 K include Arabia Terra and regions near the dichotomy boundary. In total, ~33% of the VNs mapped by [1] are located in regions with MAT ≥273 K.

Seasonal temperature variations increase temperatures above 273 K in the warmest parts of the summer season, producing peak annual temperatures >273 K for most of the planet (**Fig. 1**). However, these temperatures are relatively short-lived. As a result, most precipitation occurs as snowfall instead of rainfall. The distribution of locations that experience rainfall is very limited, with only a few locations in the southern highlands (**Fig. 1**), and none of these regions are correlated with areas with MAT >273 K, where a significant percentage of the VNs are located. Thus, the distribution of VNs and lakes is inconsistent with rainfall in this "warm and wet" climate. However, widespread snowfall occurs across most of the southern highlands. In low latitudes and near-equatorial regions, the snowfall distribution is consistent with many VNs and lakes. Specifically, ~41% of the VNs mapped by [1] are located in regions where snowfall occurs at some point in the year (**Fig. 1**). When temperatures increase above 273 K in the summer season, melting of the snow accumulation and subsequent runoff and ponding would be expected. It is possible that snow melting and runoff could have been responsible for incision of VNs and filling of lakes, instead of rainfall.

Thus, based on temperature and precipitation distributions, the formation of the VNs and lakes appears broadly inconsistent with rainfall in the simulated "warm and wet" climate, but may be explained through seasonal snow/ice accumulation and melting in the southern highlands. Further, the climate produced in this study is inconsistent with rainfall as the driving mechanism for crater degradation [6] due to the fact that snowfall dominates precipitation. Thus, the observed crater degradation requires an alternate explanation, possibly transient flooding [17].

In summary, despite the "warm" MAT, the fluvial and lacustrine features and observed crater degradation cannot be explained through rainfall in this climate scenario. We have offered possible alternative explanations for these features and characteristics, but the explanations are inconsistent with formation through rainfall [6,19]. Thus, we next consider whether an even warmer climate could explain these features through rainfall.

Previous studies have simulated warmer climate scenarios, with MAT ~285 K [14], in which precipitation is dominated by rainfall. For reference, the MAT of present day Earth is ~288 K. In this mars climate scenario, although there is abundant rainfall, the distribution of the VNs is inconsistent with the distribution of rainfall in many regions [14]. Thus, increasing temperatures even further does not appear to offer a rainfall-related explanation for VN and lake formation. It is important to note, however, that under these warmer conditions rainfall is widespread and offers a rainsplash-related explanation for degraded crater rims and interiors.

Conclusions: Using a 3D GCM, we have simulated the coldest possible "warm and wet" climate (MAT ~275 K). Rainfall in this climate is limited, precipitation is dominated by snowfall, and temperatures in the southern highlands are <273 K for the majority of the year. We find that this climate is broadly inconsistent with the formation of VNs and lakes through rainfall and associated runoff. Further, analyses of warmer climates [14] suggest that, even when precipitation is dominated by rainfall, the distribution of rainfall is not well-correlated with the distribution of the VNs.

For these reasons, we explore if the VNs and lakes could have formed through snow/ice accumulation and subsequent melting. It is possible that such a process was occurring on the annual scale, such as in the simulations shown above. Alternatively, it is possible that the climate was "cold and icy" and ice melting and runoff occurred by (1) small annual amounts of summertime melting at the edges of the ice sheet [16], (2) punctuated melting events from volcanism-induced heating [20,21], or (3) punctuated melting events from impact cratering-induced heating [22]. Previous studies have shown that the VNs appear to be better correlated with the distribution of snow accumulation in a "cold and icy" climate than the distribution of rainfall in a "warm and wet" climate [14], and that the lakes are distributed near the edges of the predicted ice sheet in a "cold and icy" climate. Thus, the VNs and lakes appear consistent with formation through punctuated or transient ice melting in a "cold and icy" climate [15].

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