REVIEWING AND ASSESSING SOURCES OF TRANSIENT HEATING IN A "COLD AND ICY" EARLY MARTIAN CLIMATE. A. M. Palumbo[1] and J. W. Head[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence RI 02912 (Ashley_Palumbo@Brown.edu).

Introduction: Late Noachian-Early Hesperian (LN-EH) aged valley networks (VNs), lakes, and degraded craters imply that the early climate may have been "warm and wet", with global mean annual temperature (GMAT) above freezing and abundant liquid surface water [e.g. 1,2]. Climate modeling studies have attempted to reproduce these "warm and wet" conditions. However, due to the faint young Sun, models instead predict that the long-lived background climate was "cold and icy", with GMAT ~225 K and surface water trapped as ice in the highlands [3–5]. In an ambient "cold and icy" climate, fluvial and lacustrine activity does not occur. Ages of VNs and lakes imply that this "warm and wet" climate may have actually been relatively short-lived [e.g. 6], persisting for 10^4-10^6 years at the LN-EH boundary. If the background climate was "cold and icy", then such a "climatic optimum" requires a period of LN-EH transient heating to be reconciled with climate models [7].

Here, we (1) assess many transient heating mechanisms to determine whether short-lived "warm and wet" conditions could persist in an ambient "cold and icy" climate, and (2) identify remaining questions that could bridge the gap between the geology and models.

Assessing sources of transient heating: Multiple LN-EH transient heating sources have been proposed.

Impact cratering-induced heating. When a projectile collides with the surface, large volumes of projectile and target material are melted, ejected from the crater, and vaporized. The vaporized component would consist of vaporized silicate-rich material and water vapor. For basin-scale impacts, the vapor plume expands globally and can cause significant short-term climate change [8,9]. As the atmosphere cools from its initially very hot post-impact state, the silicate material will first condense and fall out globally, forming the equivalent of a terrestrial spherule layer. Then, after continued atmospheric cooling, the water vapor will condense into hot rain [8,10].

Researchers have suggested that impact-induced rainfall could be responsible for VN formation [8]. However, recent work has shown that (1) impact-induced rainfall is only global following basin-scale impacts [9] and Hellas, Isidis, and Argyre pre-date the VNs [6], (2) the resultant rainfall is short-lived, lasting only tens of years [11], and (3) predicted rainfall rates are too high to explain VN-like fluvial activity [9,11]. Thus, although impact-induced rainfall was not responsible for the LN-EH fluvial activity [6,9,11], it inevitably influenced the surface in the Early-to-Mid Noachian, when Hellas, Isidis, and Argyre formed.

Volcanism-induced heating from sulfur-based gases. Sulfur-based gases, such as SO_2, are strong greenhouse agents in the martian atmosphere because they have absorptions in the IR atmospheric window [12]. Also, ~30% of Mars was resurfaced by LN-EH flood volcanism [13,14]. Thus, volcanism was an active process in the LN-EH, which has led researchers to study volcanism-induced heating as a mechanism for increasing GMAT >273 K and producing transient "warm and wet" conditions [e.g. 12,15–19].

There are two phases of atmospheric SO_2 distribution following a volcanic eruption [19]. Phase 1: SO_2 is focused near the volcanic edifice and spreading through a latitudinal band. For 10 ppm SO_2 released into a 1 bar atmosphere, phase 1 lasts ~45 days; the duration is likely to be dependent on atmospheric pressure and amount of SO_2. Phase 2: SO_2 is spreading poleward and becomes globally distributed. Eventually, the sulfur-based gases condense onto atmospheric water vapor and dust and form aerosols, which are cooling agents, and the greenhouse period ends.

In phase 1, localized heating occurs, but, for reasonable gas amounts, local temperatures are unlikely to be above >273 K unless an eruption occurs at local summer [19]. In phase 2, global heating occurs, but GMAT is unlikely to be >273 K for reasonable gas amounts [e.g. 15,17,18]. Some summertime melting is possible in phase 2 [18], but conversion to aerosols and transition to atmospheric cooling is so rapid that heating may not last for more than one year [e.g. 15,16]. These observations suggest that volcanism-induced heating from sulfur-based gases was not an important LN-EH heating mechanism.

Spin-axis/orbital variations and summertime melting. Variations in spin-axis/orbital parameters can cause climate change [e.g. 20] and researchers have hypothesized that significant summertime melting could occur during periods of optimal obliquity and eccentricity. Although potentially not the canonical "warm and wet" rainfall-dominated conditions [1,2], glacial meltwater production could lead to runoff and ponding in topographic lows, which could explain the VNs and lakes [e.g. 21]. Palumbo et al. [22] used a 3D GCM to explore the possibility of summertime melting in the Noachian, considering the full range of plausible obliquity and eccentricity values [23]. For the conditions of a CO_2-H_2O atmosphere, summertime melting is negligible for the majority of possible spin-axis/orbital parameter combinations and melting does not occur in all regions where there are VNs, only at edges of the predicted ice sheet. Thus, this mechanism may not be capable of explaining the VNs and lakes.

Transient greenhouse atmospheres. Researchers explored the influence of many greenhouse gases. However, when considering reasonable concentrations and sources/sinks, most of these gases are incapable of producing sufficient greenhouse warming. However, recent work has shown that, while methane and hydrogen alone are not strong greenhouse gases, the molecules collide with other H_2/CH_4 molecules and CO_2 molecules; the collision induced absorption (CIA) effects lead to new and stronger absorptions [e.g. 24]. Ongoing work aims to constrain the magnitude of associated heating and concentration of these gases required to increase GMAT above freezing [e.g. 24–26].

High-altitude clouds. Given the correct cloud characteristics, including cloud height, clouds can scatter IR radiation back towards the surface, mimicking a greenhouse effect. Researchers have hypothesized that high altitude CO_2 clouds [27] and high altitude H_2O clouds [10,28–30] could have significantly heated the early martian surface. However, 3D GCM simulations have shown that (1) CO_2 ice clouds can only bring sufficient heating if there is ~100% cloud coverage, which is unlikely [3,4], and (2) high altitude H_2O clouds can form and sufficient heating is possible, but they can only form in very arid conditions [31].

Characteristics of a transiently-heated climate: Some transient heating mechanisms, including greenhouse atmospheres and high altitude H_2O clouds, may have been capable of increasing GMAT >273 K in an ambient "cold and icy" climate. Thus, it is important to characterize the climate conditions for greenhouse-heated and high altitude cloud-heated atmospheres. Specifically, do these heating mechanisms produce a transient climate akin to a "warm and wet" climate, with rainfall as the dominant erosive mechanism?

Palumbo and Head [32] simulated a greenhouse-heated atmosphere by using gray gas as a proxy for greenhouse heating. Interestingly, for climates with GMAT ~275 K, highest elevation regions, including parts of Tharsis, are below freezing year-round and act as cold traps. Thus, even in this warm climate, surface water is cold trapped as ice and, as a result, rainfall is negligible. We note, however, that Wordsworth et al. [33] showed that rainfall is possible in this climate scenario if there is an oceanic water source in the lowlands, but the presence of oceans is controversial [34].

Kite et al. [31] used a 3D GCM to explore the formation of high altitude H_2O clouds on early Mars and found that it is only possible in very arid conditions. Even for GMAT ~290 K, the small amount of available water is trapped on Tharsis and rainfall is negligible.

In summary, transient "warm and wet" climates do not appear to be "wet" (rainfall) at all, regardless of the transient heating mechanism. However, significant melting of surface ice is possible (1) as the climate transitions from "cold and icy" to "warm and wet", and (2) because, in these warmer climates (GMAT ~273 K), ice accumulates in the highlands in the winter and melts in the summer. Although this fluvial activity would not be pluvial in origin, it may have been responsible for VN and lake formation. This result is consistent with the observation that many VNs and lakes are distributed at distal portions of the "cold and icy" ice sheet, where runoff and ponding would be expected if the ice sheet were melted [21].

Summary and future research: Geologic features suggest that the LN-EH climate was "warm and wet", with GMAT >273 K, but climate models predict that the background climate was "cold and icy", with GMAT ~225 K and fluvial and lacustrine activity confined to periods of transient heating. We outlined many potential mechanisms for transient heating in the LN-EH. The only mechanisms capable of producing transient conditions with GMAT >273 K that persist for 10^4-10^6 years are greenhouse warming by H_2 and CH_4 and high altitude H_2O clouds. Recent studies used 3D GCMs to simulate greenhouse-warmed and cloud-warmed atmospheres and found that, even for climates with GMAT >273 K, rainfall is negligible. Thus, transient heating in a "cold and icy" climate cannot reproduce "warm and wet" conditions as canonically viewed [1,2]; although temperatures are high, rainfall is negligible.

Remaining questions that should guide future research include (1) Can VNs/lakes be explained by ice melting runoff, instead of rainfall runoff? (2) Is the necessary greenhouse warming possible with reasonable concentrations of H_2/CH_4? What are sustained sources? (3) Is it possible to warm early Mars even further with transient heating, such that there are no cold traps? Would such warmer conditions permit rainfall? (4) Was Tharsis largely built by the LN-EH, and how may pre-Tharsis topography influence the characteristics of these warmer climates?

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