Constraints on Hydrological Climates on Ancient Mars from Formation and Persistence of Crater Paleolakes

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Introduction: Early Mars was a markedly different world than the cold, dry desert we observe today. From the Viking era of the 1970s, detailed images of the Martian surface have shown a complex array of valley networks (VNs), outflow channels, and other surface features, which indicate the flow of liquid, presumably water, across the surface [1, and references therein]. Subsequent observations of sedimentary rock [2-3], minerals that form in the presence of liquid water [4-6], and landforms interpreted as deltas and crater lakes [7-10], among other features, all point to surface runoff in the form of liquid water playing a major geological role on the ancient Martian surface. While the formation processes of fluvio-lacustrine features across the Martian surface indisputably involved water to some extent, two important questions remain unanswered, namely: "For how long did these surface bodies of water (e.g., crater lakes, VNs) remain stable against freezing and/or evaporation?", and "What were the climate conditions under which that stability was maintained?" The results presented here aim to determine the global environmental conditions (e.g., pressure, orbital state, surface water availability) that are consistent with the formation and persistence of VN-fed crater paleolakes up to the Late Noachian/Early Hesperian transition, when many such paleolakes formed.

Background: Eberswalde crater, a well-studied southern highlands location considered as a landing site for both MSL and Mars 2020, is classified as a closed-basin lake [10] having a crater floor at ~-1500 m elevation, but lacking an obvious outflow channel, indicating that evaporative processes were the primary mechanism of water loss from the basin. Early estimates for the age of Eberswalde crater placed it in the Late Hesperian (~3.6-3.4 Ga) [11], though more recent assessment of the crater and the surrounding Holden basin date it potentially to the Noachian/Hesperian boundary when VNs were most active. Heights of the Eberswalde paleochannels (ranging between -1400 and -1350 m) suggest the possibility of multiple episodes of advancing and retreating lake levels [12]. Estimates for the duration of climates conducive to paleolake formation range from 10^4-10^6 years [12-14], when a more vigorous water cycle—one that was, perhaps, intermittent—was capable of balancing evaporation from the Eberswalde crater lake.

In contrast, Jezero crater, site of the Perseverance rover, is classified as an open-basin lake, part of a larger regional VN structure flowing through its rims and into the Isidis basin via an outflow channel [8]. Spectroscopy of interior delta deposits indicates the presence of hydrous minerals such as Fe/Mg-smectite and Mg-rich carbonate [15-19]. Together, the morphology and mineralogy indicate a lacustrine environment with subaqueously formed delta deposits. The estimated volume of the delta fans is ~5-15 km^3 [20-21], which is significantly smaller than the volume of material eroded from the drainage area of the input valleys, suggesting that regional erosion was not continuous, but rather episodic throughout its formation history, where the delta represents only the final depositional episode [22-23]. This is further supported by Perseverance observations of the 'Kodiak' butte, showing layering, associated with the delta's progradation, ~100 m below the elevation of the outflow channel [24]. This indicates that, at the time of emplacement of Kodiak butte, Jezero was a closed-basin lake. Overflow, then, was a threshold event, and not an indication of continuous lake levels. This intermittency suggests the hand of specific, episodic climate drivers at Jezero that are also reflected in the varying lake levels inferred at Eberswalde. Further, it emphasizes the commonality of multiple episodes of wetting, over time, to generate the observed morphology in basins across the planet.

Eberswalde and Jezero reflect conditions during this active transitional period between the Noachian and Hesperian, when fluvial activity was widespread and precipitation seemingly global, but show markedly different morphologies in their closed vs. open nature. There is no obvious difference in the spatial distribution of these two types of lakes (Figure 1) [7-10]. One may use knowledge of the depth limits of putative lakes of each type to probe overall water abundance at the Martian surface.

Climates that are too humid, leading to excessive precipitation, would be incompatible with the aridity constraints imposed by closed-basin lakes. Similarly, climates which are too arid may be incompatible with observations—excessive evaporation might always preclude overtopping of certain open-basin lakes, or insufficient precipitation may extend the filling time to periods that exceed key geological timescales (e.g., obliquity). Further, the recent discovery of 'coupled lake systems'—where an open- and a closed-basin lake are hydrologically connected [25]—allows us to place both upper and lower limits on precipitation simultaneously at a single site, since the precipitation needs to be sufficient to overflow the open basin, but not the adjacent closed basin. In this way, these surface runoff-fed crater lakes, as opposed to groundwater-fed lakes having no VN inlets, offer a window into the early Mars climate, as they directly link surface and atmospheric processes.

The fact that liquid water was responsible for the formation of Martian paleolakes raises a set of seemingly intractable questions that center on three physical parameters of the early Martian atmosphere—temperature, pressure, and humidity. Sufficiently warm temperatures (273 K for pure water, but possibly 10-20 K lower for plausible brine mixtures) are required to sustain liquid water; this is a necessary, but not sufficient, criterion. A second necessary criterion—a surface pressure above 6.1 mb—is assumed to be satisfied by a thicker atmosphere on early Mars. Finally, the atmosphere must be sufficiently humid to enable precipitation to offset evaporation and fill a crater basin, if precipitation and runoff are, indeed, responsible for the formation of these low latitude paleolakes as the presence of VNs suggest; this is a global requirement. An alternate argument for producing water for many paleolakes emphasizes melting of nearby surface deposits of ice [26-27], though this has its own limitations. Thus, to allow for surface liquid water, we must conceive of an atmosphere that provides the necessary warmth for liquid, and which can sustain sufficiently high humidity for at least the duration of lake development. Final cessation of paleolake activity may be a consequence of lowered temperatures (freezing water), lowered humidity (no precipitation), or both, and may have occurred multiple times through this period of Mars' history. This work aims to provide bounds on surface water abundance, distribution, and duration, by using the aridity of the early Mars climate uniquely derived from hydrologic constraints provided by the global paleolake population.

Method: We leverage the distinct benefits of numerical climate modeling and globally distributed observations as preserved in the geomorphic paleolake record to construct a story of the hydrological cycle of Mars during this critical period of Mars' evolution. A brief summary of each approach is discussed presently.

Climate Modeling: A modified form of the MarsWRF general circulation model is used to generate a full, global water cycle, including evaporation, transport and condensation of water vapor, along with precipitation (as snow or rain) where appropriate. The model includes a simple 'bucket' scheme to track precipitation on the surface (similar to [28]). We have incorporated a version of the Kain-Fritsch 'eta' convective parametrization scheme [29-31] to estimate atmospheric instability, vertical mass flux and convective cloud properties. A five-phase single moment convection scheme (the WRF-single-moment-microphysics class 5 scheme) is employed to track elements of the global water cycle, including water vapor, cloud ice and liquid water, and precipitating snow and rain. Autoconversion of cloud particles to rain/snow is implemented, and the hydrometeors sediment out of the atmosphere, possibly returning to the vapor phase upon descent through sub-saturated model layers.

The MarsWRF GCM includes the ability to create (and, in some cases 'sketch') surface composition—land, ocean, ice, each with unique properties—into a NetCDF input file, greatly facilitating the speed at which distinct modeling cases can be designed and run. This has been particularly useful for the present work which examines multiple different paleo-Mars scenarios. The model has undergone significant testing against other GCMs using well-defined test cases. We have focused our initial efforts on applying the THAI protocol [32], for both land and ocean planets, to our model. Figure 2 shows a comparison of surface temperatures for the 'ben2' THAI scenario (a 1-bar CO_2 atmosphere above a 100% land planet). Comparisons of MarsWRF against the same models for ocean world scenarios (a 1-bar Earth-like N_2 atmosphere above a 100% ocean planet) are ongoing. While not directly relevant to conditions on early Mars, these tests have demonstrated proper working of the water cycle under stressing climatic conditions. Further intercomparisons, including against other paleo-Mars GCMs are ongoing.

Paleolake Hydrology Reconstruction: To investigate the hydrological requirements that allow for paleolakes dominantly sourced by surface runoff to exist on Mars, we use standard hydrological balances and VN-fed paleolake morphologies. Open-basin lakes provide a minimum accumulated water volume and closed-basin lakes provide a maximum; coupled lake systems provide both minimum and maximum constraints. These hydrological reconstructions allow us to quantify the permitted precipitation/evaporation (P/E) values locally from crater morphologies and compare them to the GCM-derived P/E values at those same locations (Figure 3).

Because paleolakes are globally distributed, it provides a widespread distribution of hydrological values that together must be satisfied by a planetwide climate. Interpretations of crater lakes formed in at least modestly arid conditions to those formed in potentially hyper-arid conditions may be a consequence of local circulation patterns at a given time but may also be due to shifts in circulation patterns with change in orbital state or atmospheric mass—essentially allowing us to view precipitation/evaporation as a proxy of time, in addition to location. Although open-basin lake overflow events could have occurred at any point during the Late Noachian/Early Hesperian, this method works to test for the presence or absence of a threshold event—lake breaching—and whether it occurred at any point in early Mars history. In order to satisfy the geologic record, any range of climate conditions must be able to only overflow open-basin lakes, but not closed-basin lakes, regardless of their relative timing.

Results: Initial results focus on the sensitivity of precipitation to the distribution and volume of surface water (as oceans, seas, and lakes) during the LN/EH period. A series of simulations has been run looking at varying shorelines for a putative northern ocean between -4.5 to -2.0 km under both a 1-bar and 0.25 bar CO_2 atmosphere. Here, our approach is to use a fixed 42° mean obliquity (the long-term value determined by [33]) in these simulations. In those scenarios where local temperatures do not support a liquid water ocean, we implement a simple gray gas radiation scheme to augment CO_2 warming with a uniformly mixed gray absorber having an abundance sufficient to bring the northern hemispheric temperatures above the freezing point.

In addition to simulations of a possible northern ocean, we examine similar, but colder, scenarios having a frozen, rather than liquid, northern ocean with a correspondingly reduced amount of water vapor in the colder atmosphere. Lastly, we examine the 'cold and icy' case where icy highlands serve as the global source of water on early Mars.

For all cases, we establish steady state evaporation/precipitation rates across the planet. These rates can then be extrapolated to determine the length of time required to fill each crater, either to a minimum level for open-basin or a maximum level for closed-basin lakes, and to establish whether a particular climate scenario produces patterns of precipitation consistent with the aridity estimates of the crater database as collected by [34].

A second set of simulations explores the role of orbital state on the global precipitation cycle, varying obliquity from 10-60°, and looking to find 'best fit' scenarios to the observed distribution of open- and close-basin crater lakes while fixing global atmospheric surface pressure to either 0.25 or 1 bar. As part of this task, we are also examining potential paleotopographic differences in surface topography, under the assumption, in [35], that VN formation was more contemporaneous with latter-stage Tharsis formation, meaning the full extent of the Tharsis megastructure was not emplaced at the time of crater lake formation. These simulations account for the resulting true polar wander and changed position of a northern lowland ocean relative to the spin axis [36].

Conclusions: The combination of numerical modeling with global observational data promises to be a useful tool for constraining the climate of Mars during the Late Noachian/Early Hesperian transition. By identifying the climate/orbital state which yields a hydrological cycle most consistent with the global crater lake population, we can narrow down the conditions under which these crater lakes were formed. From our model results, we may determine whether precipitation amounts at each crater fall within a suitable range and rate (not too much precipitation to avoid overflowing closed-basin lakes, but sufficient precipitation to overflow open-basin lakes) after one or more obliquity cycles and, from that, semi-quantitatively establish the frequency and duration of lake formation. Here, it might be that open basin lakes fill and overspill every obliquity cycle, or even several times within. Conversely, regions where our model shows sparse precipitation may only see amounts falling within the estimated precipitation range after multiple cycles. These regions might see open-basin lakes overspilling only after the most extreme conditions (e.g., the brief periods of optimum obliquity, surface pressure and global humidity). Our desired result will be a timeline of the global climate during the Noachian/Hesperian transition that reveals the frequency and duration over which the precipitation-fed, open- and closed-basin lakes were formed, providing an independent, geology-controlled constraint on key climate conditions of the early Mars atmosphere.

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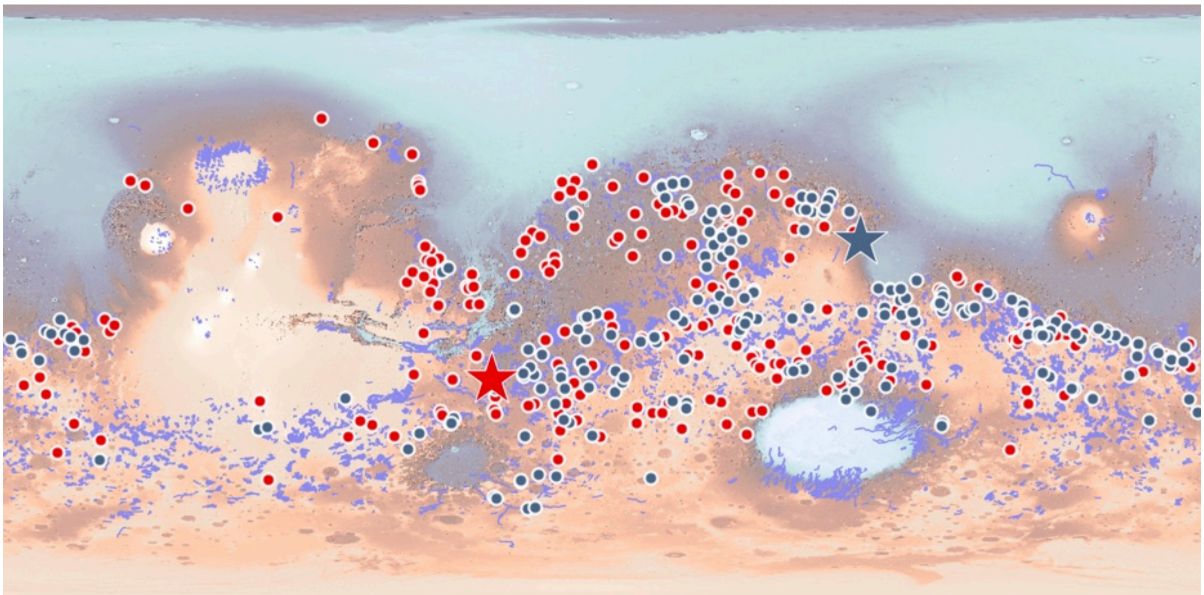

Figure 1: Distribution of open-basin (blue) and closed-basin (red) lakes adapted from [9-10] showing widespread distribution mainly across the southern highlands. Eberswalde and Jezero are shown as diamonds. Underlying valley network global distribution is shown as purple lines. Data overlain on MOLA topography.

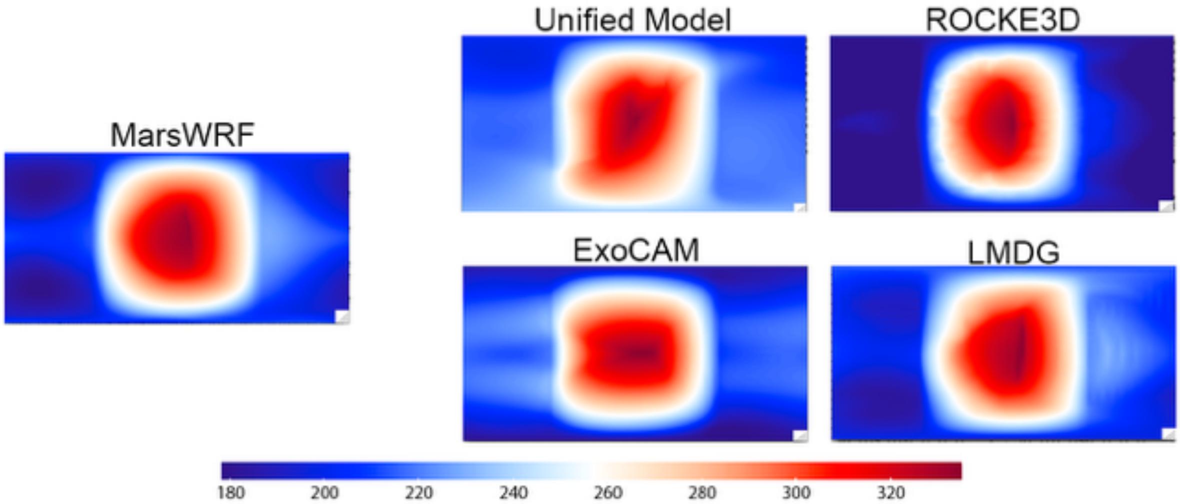

Figure 2: Surface temperatures for the THAI 'ben2' scenario between the MarsWRF GCM as modified for this work (left) and four other community models, following the THAI v1 protocol.

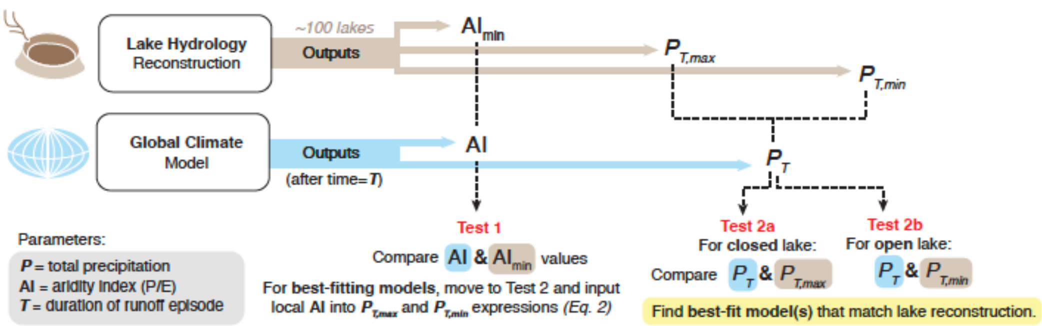

Figure 3: Flowchart illustrating the process of integrating the GCM with the hydrological reconstructions. Given outputs from both sources we compare GCM results to the hydrological reconstruction for each crater (Tests 1, 2a/2b). AI_{min} = minimum aridity. PT = precipitation (note minimum vs. maximum, as constrained by closed or open lakes [see 34]. We select best-fitting models and discard the choice of GCM conditions that have poor fits as unacceptable for each crater. Then, where model precipitation is most consistent with the bounds of the hydrological reconstruction, we can accept the model(s) as consistent with crater lake formation.