SUSTAINING MARS SURFACE HABITABILITY: CLIMATE AND CLIMATE EVOLUTION.

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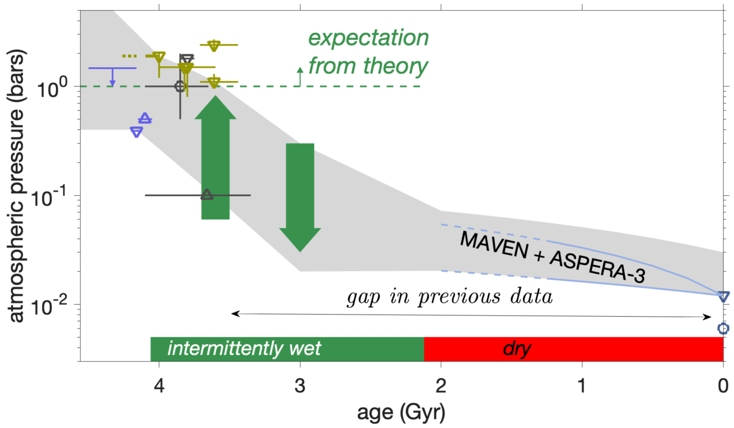

Fig. 1. Atmospheric evolution of Mars. Thick green arrows: New estimates of average pCO_2 from the shifting spatial distribution of water flow on Mars, in the context of independent estimates on paleo-atmospheric pressure on Mars (symbols) and expectations from theory (green dashed line). Wet-to-dry transition age from [*13*]. Purple symbols: constraints from analysis of meteorite data [*14-15*]. Gold triangles: upper limits from embedded-crater method [*16*]. Dark gray symbols: constraints from analysis involving rover data (e.g. [*17*]). Sky-blue lines: extrapolation of present-day CO_2 escape-to-space rate from MAVEN and ASPERA-3. Modern-era value (blue triangle) includes both the present-day atmosphere (blue circle) and also CO_2 in polar ice deposits.

Introduction: Earth has been continuously habitable since ≥3.5 Ga; Mars' surface habitability has varied. Early in Mars history, multiple lake-forming climates lasted individually up to >10^2 yr (potentially longer), but lake-forming climates were intermittent ([*1*], and references therein). These constraints, plus improved modeling (e.g. [*2-3*]), exclude many models for Hesperian through Amazonian wet climates [*1*]. Remaining hypotheses include warming by H_2-CO_2 Collision-Induced Absorption (CIA) [*4-5*], and warming by high-altitude water-ice clouds [*6-7*]. These hypotheses make distinct predictions for the true duration and atmospheric pressure (≈pCO_2) of the lake-forming climates. (i) H_2-CO_2 CIA requires pCO_2 ~1 bar to make lakes [*5*], whereas the cloud greenhouse can lead to warm climates at much lower pCO_2 [*6*]. (ii) During the Hesperian through Amazonian average H_2 production rates are low, so if H_2-CO_2 CIA caused warm climates, then those climates would have been intermittent, individually lasting 10^4-10^6 yr (due to the 10^5 yr H_2 escape timescale) ([*4*], but see also [*8*]). By contrast, the cloud greenhouse could generate wet climates over a wide range of timescales. These predictions enable tests: if pCO_2 was < 1 bar when lakes filled, or if individual lake-forming climates lasted less than 10^4 yr or more than >10^6 yr, then the H_2-CO_2 CIA hypothesis is disfavored relative to alternatives such as the high-altitude water-ice cloud greenhouse.

Analysis of late-stage lake-forming climates (geology and GCMs): We analyzed an existing database of Late Noachian / Early Hesperian (LN/EH) valley networks [*9*] and our new database of mostly Late Hesperian / Amazonian (LH/A) alluvial fans and deltas [*10*], correcting both for postfluvial resurfacing. We found that the LN/EH valley networks formed preferentially at high elevations, with a modest equatorial preference, consistent with the latitudinal and elevation trends in temperature and snowpack stability predicted at ≳0.1 bar pCO_2 by our GCM (MarsWRF; [*11*]) and other GCMs [*12*]. By contrast, the latitude-belt distribution and frequent location at low elevation of mostly LH/A alluvial fans and deltas, compared to GCM output,

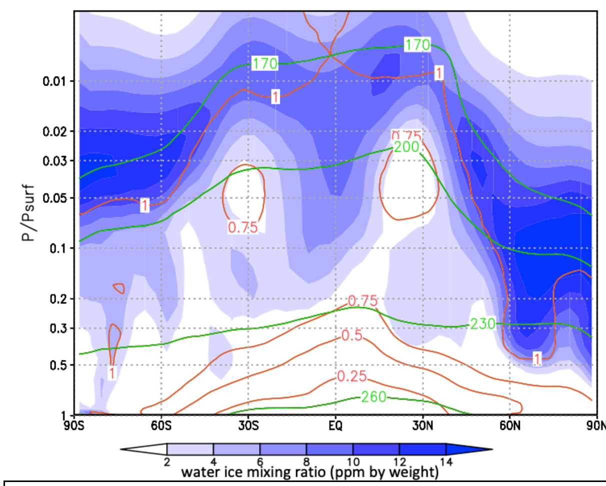

Fig. 2. Latitude-elevation slice through results from cloud greenhouse simulation showing warm, arid, stable early Mars climate. Zonally averaged, annual-average output for water ice mixing ratio (blue shading)**,** atmospheric temperature (K, green contours), and relative humidity (red contours). Y-axis uses terrain-following σ coordinates ($\sigma = P/P_{surf}$). Nonzero average ice abundances occur in areas with average relative humidity < 1 due to weather, e.t.c. Our GCM does not spatially resolve the deep craters explored by *Curiosity* and *Perseverance*, but taking into account the local anti-correlation between elevation and average surface temperature $\bar{T}$, our model implies $\bar{T} \geq 273$ K for all rover landing sites. Surface water ice is at <-75°S and at Alba Patera. This run is for a circular orbit, and zero obliquity. Increasing eccentricity to 0.1 and increasing obliquity to 25°, similar to Mars' present-day parameters, causes a 100-day interval with $\bar{T}$ >273 K to occur every year between 30°S and 50°N at all elevations (excepting only Tharsis).

instead indicates ≲0.1 bar pCO_2 (in Fig. 1, we conservatively include a factor of 3 "safety factor" to this upper limit).

Could the spatial distribution of alluvial fans and deltas record melting at high pCO_2 of snow that was deposited at low pCO_2? This is not ruled out by our data. However, it would require atmospheric collapse/reinflation cycles. The maximum total CO_2 consistent with atmospheric collapse/reinflation is 0.6 bar or less, according to models [*18*]. Could the LH/A alluvial fans and deltas record very short-lived lake-forming climates, for example post-impact rainout? Based on models, this is not very likely because of the relatively small size of LH/A impacts [*19*]. Moreover, we analyzed the hydrology of hundreds of LH/A paleolakes, finding evidence for an arid but essentially Earth-like hydrologic cycle at least intermittently during the LH/A (consistent with the results of smaller-scale studies, e.g. [*20-21*]). For example, if wet climates were brief, then because small sinks fill quicker than big sinks, paleolake levels should be higher for small craters. We found the opposite trend, disfavoring the scenario in which late-stage lake-forming climates were powered by the greenhouse forcing from a single volcanic eruption, or the energy of a distant impact. In summary, our results are simply explained by, and suggest, < 1 bar pCO_2 at the time of lake-forming climates in the LH/A.

Improved modeling of the high altitude water ice cloud greenhouse: What could generate warm climates at < 1 bar pCO2? Previous work has shown that the water ice cloud greenhouse can lead to warm (global and annual average $\bar{T}\approx$265K) climates at 0.25 bar [*6*]. However, assumptions underlying this result have been questioned [*22*], and other investigations of the water ice cloud greenhouse have also reached pessimistic conclusions [*5*, *23*]. In 1D and quasi-1D radiative-convective simulations, everyone agrees that high-altitude water ice clouds with ice particle radius ≥10 µm can provide strong warming. We found that the 3D disagreement can be explained by the dependence of the steady-state climate outcome on the extent of atmosphere-exchangable surface water ice (Fig. 3). When surface water ice is extensive (e.g., Late Noachian Icy Highlands), low clouds form and the cloud greenhouse effect is weak. When surface water ice is less extensive, in our model at 0.6 bar pCO_2 high clouds can form (Fig. 2) and the cloud greenhouse effect can be strong. Results from new simulations will be presented at the conference. Warm, stable climates involve vapor equilibrium with surface ice at locations much colder than the planet average, so that the high altitudes of clouds at locations horizontally distant from the surface cold traps maximize warming. Radiatively significant clouds persist because ice particles resublimate as they fall, moistening the subcloud layer so that modest updrafts can sustain clouds. The resulting climates are arid (area-averaged surface relative humidity ≈25%). In a warm, arid climate, lakes could be fed by groundwater upwelling, or by melting of ice following a cold-to-warm transition. Our results assume no H_2-CO_2 CIA, although the water ice cloud greenhouse might also provide a positive feedback on H_2-CO_2 CIA. Our results are consistent with the warm climate favored by interpretation of geologic data [*24*, *25*] and support the cloud greenhouse hypothesis.

Tests, extensions: This is not a complete explanation: the runs shown in Fig. 2, while at lower pCO_2 than for the H_2-CO_2 CIA hypothesis, are still too high-pCO2 to be consistent with the LH/A pCO_2 constraint in Fig. 1. Nevertheless, it is testable. At Jezero's deltas (likely Hesperian or Amazonian in age, [*26*]) and at Gediz Vallis, we can further test warm-climate models by looking for constraints on past pCO_2 (such as pH-sensitive detrital minerals), and on the duration of lake-forming climates (such as interbedded impact craters). Our work also suggests possible explanations for why Mars eventually dried out, which we will discuss at the conference.

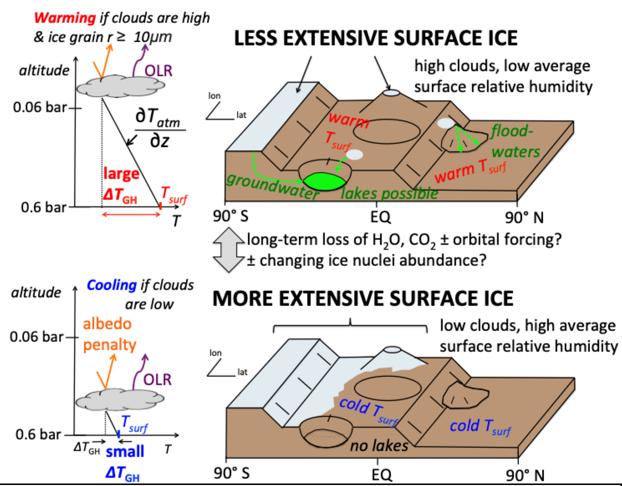

Fig. 3. Cartoon summary of the physical basis for results presented here, and possible links to the geologic record of intermittent paleolakes. OLR = Outgoing Longwave Radiation.

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