The Cirrus Cloud Greenhouse on Early Mars:

an explanation, the explanation, or no explanation for rivers and lakes?

Edwin S. Kite[1], Liam J. Steele[1,2], Michael A. Mischna[2] 1. University of Chicago (kite@uchicago.edu) 2. JPL/Caltech.

THE UNIVERSITY OF CHICAGO

P51F-2942

main result: Aridity enables warm climates on Mars

H_2O ice exposed only near coldest points → arid, high clouds → T_{ave} > 290K

extent of surface water ice

lag deposit formation, H escape-to-space, e.t.c. ← → *ice at >+1 km; frozen ocean; e.t.c.*

climate result

(r_{cloud} = **5μm**)

extensive surface H_2O ice → humid, low clouds → T_{ave} < 250K

Summary. Despite receiving just 30% of the Earth's present-day insolation, Mars had water lakes early in the planet's history, due to an unknown warming mechanism. Most proposed warming mechanisms fail to match the geologic record of individually >10^2 yr-long lake-forming climates that persisted as late as 3 Ga [1]. A possible exception is warming by water ice clouds [2-3]. But this cloud greenhouse has proven difficult to replicate, and has been argued to require unrealistic cloud lifetimes and cloud coverage [4-5]. Here we use a Global Climate Model (GCM) to show that **a water ice cloud greenhouse can warm a Mars-like planet to area-averaged temperature (T) >290K from a cold start, and stay warm for centuries or longer in equilibrium with a quasi-infinite surface ice reservoir, but only if the planet is arid.** Stable warm arid climates involve vapor equilibrium with surface ice only at locations much colder than the planet-average, so that the high altitudes of clouds elsewhere maximize warming. In warm and arid climates, lakes could be fed by infrequent storms associated with mesoscale processes that are not resolved by GCMs (e.g. 6), by wicking of groundwater from deep aquifers to the surface [7], or transiently by melting of preexisting ice following a cold-to-warm transition. Thus our result closes the gap between GCMs and the warm and arid climate favored by interpretation of geologic data [8-10]. Unexpectedly, partial drying-out of Mars' surface may have been the pre-requisite for the planet's habitability.

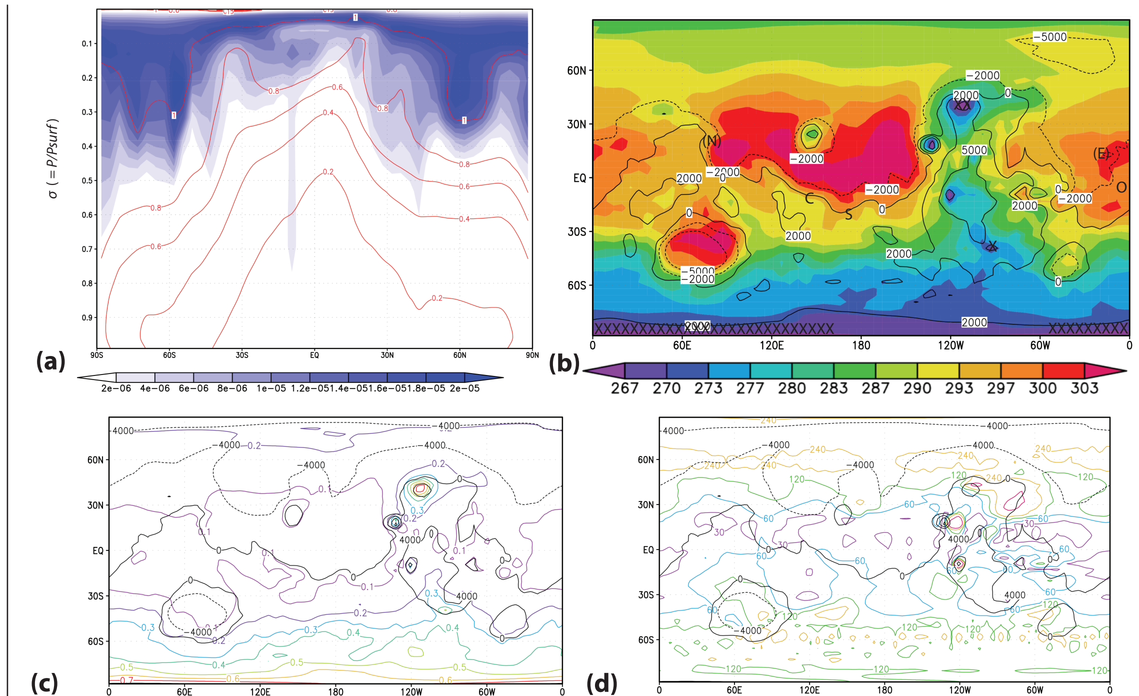

Fig. 1. Warm, arid climate output. **(a)** Zonally-averaged, annual-average cloud water ice mass mixing ratio (kg ice: kg air; color shading), and zonally-averaged, annual-average relative humidity (red contours). Y-axis uses terrain-following σ coordinates. **(b)** Average surface temperatures (K; color shading). "X" marks stable surface water ice locations. Rover sites are marked by letters. **(c)** Relative humidity for the lowest model atmospheric layer (near-surface $H_2O_{(v)}$ mixing ratio is near-uniform). **(d)** Water ice cloud column (pr μm).

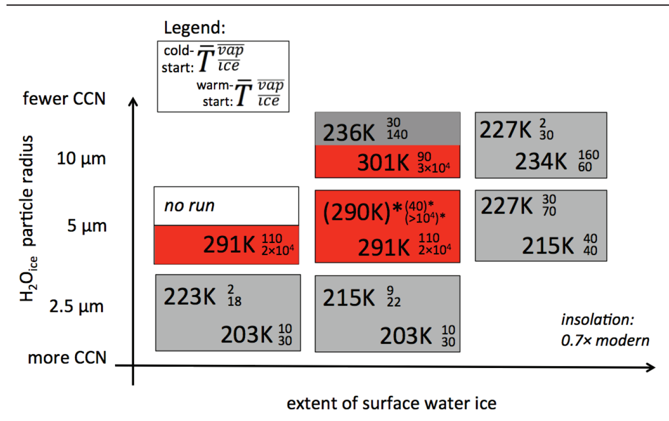

Fig. 2. Control of Mars climate by aridity and cloud particle size. Warm solutions are shown in red, cold solutions in gray. Within each box, cold-start run outcomes are shown in the top left, and warm-start (initial T ≈ 290K, initial $H_2O_{(v)}$ column ≈ 2 × 10^4 pr μm) outcomes in the lower right. Shown are average temperatures (T , K), average vapor columns (pr μm), and average cloud ice column (pr μm). As expected [5], we found cold climates for water ice grain radii 2.5 μm, because 2.5 μm only inefficiently absorbs upwelling thermal IR. There is also an upper limit to cloud particle size for a warm climate. Increasing insolation to 0.8× modern, which is appropriate for 3.0 Ga, also produces warm climates. ()* = run not yet converged: however, the 0.8x modern insolation cold-start run for these conditions is converged, at 303K / 5x10^4 pr μm vapor / 120 pr μm ice.

References. [1] Haberle et al., chapter in Haberle et al. (eds), "The Atmosphere & Climate of Mars", C.U.P., 2017. [2] Segura et al. JGR-E 2008 [3] Urata & Toon Icarus v.226, p. 229-250, 2013 [4] Wordsworth, AREPS 2016 [5] Ramirez & Kasting Icarus 2017 [6] Scanlon et al. GRL 2013 [7] Andrews-Hanna et al. Nature 2007 [8] Grotzinger et al. Science 2015 [9] Ramirez & Craddock Nat. Geosci. 2018 [10] Bishop et al. Nat. Astron. 2018 [11] Mischna et al. JGR-E 2013 [12] Richardson et al. JGR-E 2007.

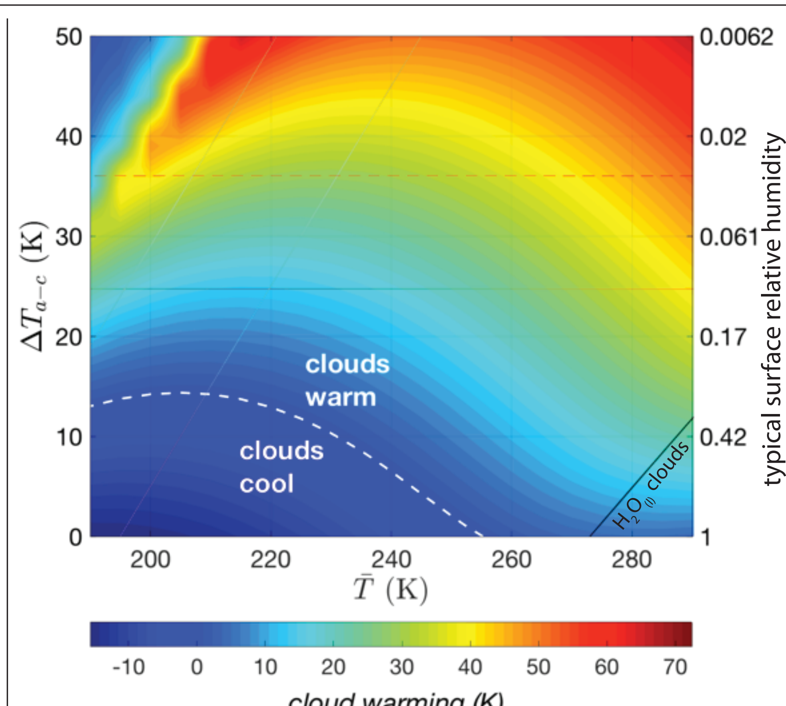

Fig. 3. Warming map for a toy model of the cloud greenhouse (all atmospheric constituents radiatively inert except for clouds). Cloud structure is set by a length scale (updraft speed × autoprecipitation timescale), here 300m, and a maximum cloud ice content, here 10^{-5} kg/m³. Warming increases as the temperature difference (ΔT_{a-c}) between typical surface temperature T_a and cold trap surface temperature T_c increases. This is because, for lower surface relative humidity (at fixed surface temperature), moisture must be lifted higher to condense and form clouds. As a result, total cloud optical depth is less, and more sunlight reaches the surface. However, so long as the cloud has IR optical depth τ_{IR} > 1, the greenhouse effect remains strong.

Grants: UChicago RCC; NASA (NNX16AG55G, NNX15AH98G).

We used MarsWRF [11-12] Mars GCM, modified to include radiatively-active $H_2O_{(i)}$ clouds. Our reference simulation used (70-80)% of modern solar luminosity, modal cloud particle radius 5 μm, and 1 bar CO_2. Fig. 1 shows results for a run that has reached warm-climate steady-state in equilibrium with surface water ice. Cloud cover is global, with high-altitude clouds with (geometric) optical depth 4-10 over paleolake terrains (Fig. 1a), giving a strong greenhouse effect. In contrast to previous models that could not generate sustained high T at +1 km elevations, T > 290K for almost all paleolakes on Mars, and also for all rover landing sites. Clouds are in equilibrium with surface $H_2O_{(i)}$ at locations around 90°S, and also at high ground at both 40°N and 40°S. These cold-trap locations have T < 270K. With ice at these locations, warm steady-state climates result from both warm-atmosphere and cold-atmosphere initial conditions. The Mars simulation is as warm as modern Earth, but ~10 times more arid. This matches geologic data that suggest an arid climate on early Mars [e.g. 7,9]. The warm, arid climate is little-affected by increasing obliquity from 0° to 25°, increasing eccentricity to 0.1, or removing Olympus Mons.

Aridity is set by the distribution of perennial surface-exposed H_2O (water or ice). H_2O is a greenhouse gas, and $H_2O_{(i)}$ clouds provide strong warming in Fig. 1. Thus it is surprising that more extensive initial surface $H_2O_{(i)}$ distributions lead to <235K (Fig. 2). This is not a surface albedo effect. Instead, cold-start runs initialized with water ice in higher-T locations (e.g. S pole ice extending to 60°S, frozen Northern Ocean, or ice at >1 km elevation) yield low-lying clouds that produce net cooling. Thus, steady-state climate warmth depends on aridity. Aridity is set by the temperature difference (ΔT_{a-c}) between typical surface temperature T_a and the surface temperature of cold-traps, T_c. What sets ΔT_{a-c}? Growth of a tall mountain will create cold ground at high elevation, which may increase ΔT_{a-c}. A thinner atmosphere, or a fall in obliquity, will lead to a steeper equator-to-pole temperature gradient, which can also increase ΔT_{a-c}. Loss of surface H_2O (e.g. escape-to-space, hydration reactions, loss to deep aquifers, or formation of lag deposits) will reduce the tendency of surface ice to be found away from the cold-trap location. Each effect can make the planet more arid, and thus bring a potential for warmer climate.

Details of method: We ran MarsWRF at 5.625°x 3.75° horizontal resolution (40 vertical resolution levels). CO_2 radiative transfer uses the Hadley model modified to use a correlated-*k* scheme. $H_2O_{(i)}$ particle radii are affected by the number density (*n*) of cloud condensation nuclei (CCN). Early Mars *n* depends on the relative efficiency of dust aerosol production by wind erosion versus dust aerosol consumption via sediment induration, and is unknown. To take account of this unknown, we considered modal water ice cloud particle radii of 2.5 μm, 5 μm, and 10 μm. (Current low-latitude Mars $H_2O_{(i)}$ particle radii are 3-4 μm). Particles undergo slip-corrected Stokes settling. To represent mass transfer from slow-settling cloud particles to fast-settling snow (autoconversion), we increase settling rate to 1 m/s when cloud particle density exceeds 3 × 10^{-5} kg/kg. In our runs, cloud particles are destroyed by downwards advection and particle settling that leads to the particles re-evaporating as fall streaks, typically 30 km above the surface. Surface thermal inertia is constant (250 J m^{-2} K^{-1} $s^{-1/2}$) and surface albedo is set to 0.2, except where substantial water ice exists, for which surface albedo is set to 0.45. During the run, which can last for ~10^2 simulated years (for cold-start runs), the location of the surface $H_2O_{(i)}$ can shift. A large surface $H_2O_{(i)}$ source is prescribed at t=0; its location varies between runs and is a major control on the climate outcome. Such equilibrium with a quasi-infinite surface water source is a requirement for any habitable warm-Mars climate mechanism.