ARIDITY ENABLES WARM CLIMATES ON MARS. M. A. Mischna[1], E. S. Kite[2] and L. J. Steele[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA (michael.a.mischna@jpl.nasa.gov), [2]University of Chicago, Chicago, Illinois, USA.

Introduction: A key unknown in the search for habitable planets is the minimum insolation for sustained surface liquid water. Despite receiving just 30% of the Earth's present-day insolation, Mars had water lakes early in its history due to an unknown warming mechanism. Most proposed mechanisms fail to match the geologic record of $\gg 10^2$ yr-long lake-forming climates that persisted as late as < 3 Ga [1,2]. A possible exception is warming by water ice clouds [3,4], but this cloud greenhouse has proven difficult to replicate, and has been argued to require unrealistically high-altitude optically thick clouds [5,6]. Here we use a global climate model (GCM) to show that a cloud greenhouse can warm a Mars-like planet to an area-averaged temperature $T_a > 290$ K from a cold dry start, and stay warm for centuries or longer, but only if the planet is arid.

Methods: To test the cloud greenhouse hypothesis we use the MarsWRF GCM, modified to include radiatively active water ice clouds [7,8]. We use a 40-layer vertical grid (extending to ~80 km), with a horizontal resolution of 5.625°×3.75° in longitude and latitude. A thermal inertia of 250 J m^{-2} K^{-1} $s^{-1/2}$ is used, with surface albedo set to 0.2, or 0.45 in locations where substantial water ice exists. Our reference early Mars simulation uses Mars Orbiter Laser Altimeter topography, a faint young Sun (70% of modern solar luminosity), a modal cloud particle radius of 5 μm, and a 1 bar CO_2 atmosphere. (These values, along with surface ice reservoirs, were varied in sensitivity tests.)

We use a dynamic water cycle, including sedimentation of ice particles, rapid snow-out above an autoconversion threshold, and exchange with surface water ice. Humidity is buffered to $\lesssim 1$ by rapid condensation of cloud particles. Cloud particles undergo Stokes settling with a Cunningham slip correction. Ice particles collide within cirrus clouds to form fast-settling snow. This process is efficient above a cloud particle number density threshold. In order to conservatively represent the cloud-depleting effect of mass transfer from slow-settling cloud particles to fast-settling snow (autoconversion), we increase the settling velocity to a fast value (1 m s^{-1}) when the cloud particle density exceeds a conservatively low threshold (0.03 g kg^{-1}).

Results: We initially compared our GCM results to previous 1D simulations by imposing static cloud distributions in the GCM, with specified optical depths and cloud heights. Our results are consistent with other studies [6,9], with maximum warming occurring when the cloud optical depth is ~5 and clouds are high (~30 km altitude).

Next we allowed clouds to form using a dynamic water cycle. Results are shown in Figs. 1 and 2. For a cold, dry initial condition with surface water ice restricted to the south pole and on high ground at Alba Mons, initially $T_a < 240$ K, with tenuous low-latitude water ice clouds at altitudes of 15-20 km. As more water vapor is injected into the atmosphere, T_a rises, surface humidity drops, the condensation level above which clouds can form moves to higher altitude, and the water vapor injection rate increases. Water vapor is horizontally well-mixed, so the cloud cover is global, and the average cloud thickness builds up over time. After 24 years of simulation, $T_a > 273$ K occurs (Fig.

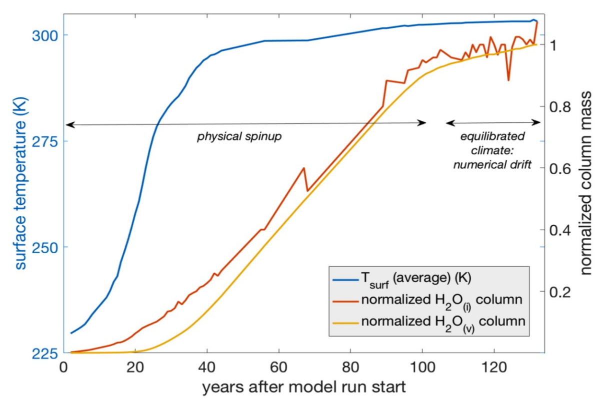

Fig. 1 *GCM spin-up for a cold/dry initial condition. The column masses are normalized to values of 120 pr-μm for ice and 5×10⁴ pr-μm for water vapor.*

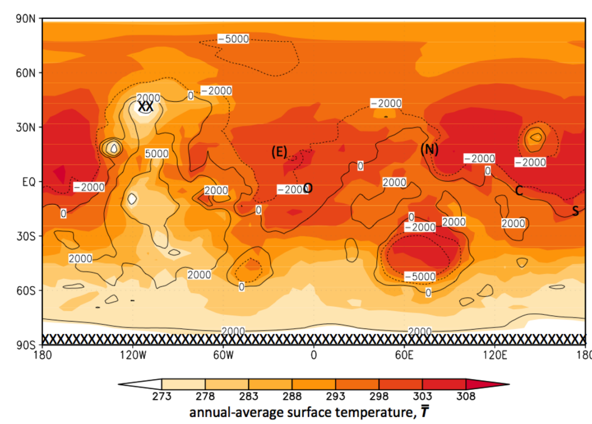

Fig. 2 *Annual-average surface temperatures (shading, K) and topography (contours, m) from a cloud greenhouse simulation showing a warm, arid early Mars climate. "X" marks stable surface water ice locations. Landing sites are shown for (O)pportunity (S)pirit and (C)uriosity, and the next (N)ASA and (E)SA rovers.*

1). After high altitude clouds become optically thick, water vapor continues to build up for a further ~80 years before asymptoting. Increasing water vapor warming is offset by the increasing albedo of thicker (but no higher) ice clouds during this stage, so that little further warming occurs.

Fig. 2 shows a warm-climate steady-state in equilibrium with surface water ice. The global-average cloud water column is 100 pr-µm, which is the same as for modern Earth but provides much more positive radiative forcing because the early Mars clouds are much higher (centered at ~40 km in the tropics) than on modern Earth. Similarly, the peak cloud ice mass mixing ratio in our early Mars model is the same as observed in modern Mars' low-latitude clouds [10], but provides much more positive radiative forcing because the early Mars clouds are much more optically thick and are higher on average. In contrast to previous models that could not generate sustained high surface temperatures at +1 km elevations, here T_a > 290 K for almost all paleolake locations on Mars [11], and also for all rover landing sites.

Fig. 2 shows T_a after equilibrium has been reached for a seasonless orbit. Sensitivity tests show that the warm, arid climate is little-affected by increasing the obliquity to 25° and the eccentricity to 0.1, adding a water vapor injection flux corresponding to a 10^5 km^2 'lake' at the equatorial Mars Science Laboratory landing site, or removing the high-topography Olympus Mons and Tharsis Montes. The clouds are in equilibrium with surface water ice where surface relative humidity reaches unity (~90°S and at high ground ~40°N). These cold trap locations have T_a < 270 K. With ice at these locations, warm steady-state climates result from both warm- and cold-atmosphere initial conditions (Fig. 3). Cold climates (T_a < 235 K) result from more extensive initial surface water ice distributions, due to optically thick, low-lying clouds that produce little or no net warming. These results, while different from previous 3D models of melt-permitting climates on Mars, are consistent with geologic data that suggest early Mars had an arid climate [12,13].

Conclusions: Arid, warm, stable 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. Cloud coverage is close to complete because ice sublimates as fall streaks, allowing modest updrafts to sustain tenuous but optically thick clouds. 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 close the gap between GCMs and the warm and arid climate favored by interpretation of geologic data [13-15]. Unexpectedly, partial drying-out of Mars' surface may have been a pre-requisite for the planet's habitability under the Faint Young Sun.

Acknowledgements: We acknowledge financial support from NASA (NNX16AG55G, NNX15AH98G), and use of University of Chicago Research Computing Center resources. A portion of this work was performed at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration. E.S.K. conceived the research, E.S.K. and L.J.S. designed the research, and L.J.S. and E.S.K. carried out the research. M.A.M. wrote the water ice cycle code (with modifications by L.J.S.) and developed other physical parameterizations used in MarsWRF.

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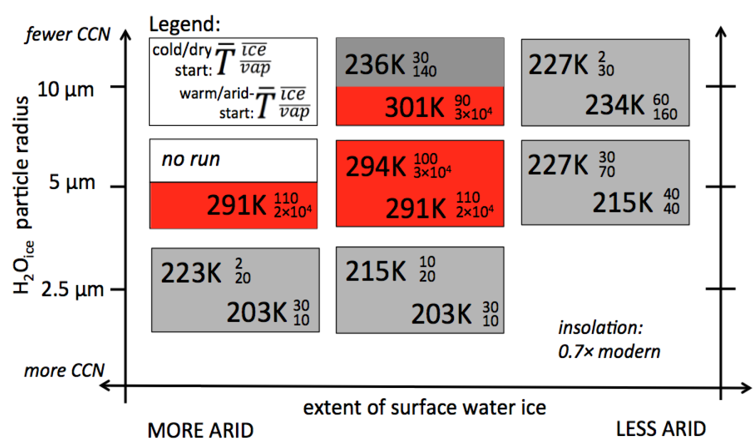

***Fig. 3** Control of Mars' climate by aridity and cloud particle size. (Warm, cold)-climate equilibrated outcomes are colored (red, gray). Shown are average temperatures, vapor columns and cloud ice columns. Within each box, cold/dry-start outcomes are shown in the top left, with warm/arid-start outcomes in the lower right.*