

Introduction: The abundance of evidence that liquid water flowed on the surface early in Mars’ history strongly implies that the early Martian atmosphere was significantly more massive than it is today [1]. While it seems clear that the total CO₂ inventory was likely substantially larger in the past, the fundamental question about the physical state of that CO₂ is not completely understood. Because the temperature at which CO₂ condenses increases with surface pressure, surface CO₂ ice is more likely to form and persist as the atmospheric mass increases. For the atmosphere to remain stable against collapse, there must be enough energy, distributed planet wide, to stave off the formation of permanent CO₂ caps that leads to atmospheric collapse. The presence of a “faint young sun” that was likely about 25% less luminous 3.8 billion years ago than the sun today makes this even more difficult.

Several physical processes play a role in the ultimate stability of a CO₂ atmosphere. The system is regulated by the energy balance between solar insolation, the radiative effects of the atmosphere and its constituents, atmospheric heat transport, heat exchange between the surface and the atmosphere, and latent heating/cooling [2,3]. Specific considerations in this balance for a given orbital obliquity/eccentricity and atmospheric mass are the albedo of the caps, the dust content of the atmosphere, and the presence of water and/or CO₂ clouds.

Forget et al [4] show that, for Mars’ current obliquity (in a circular orbit), CO₂ atmospheres ranging in surface pressure from 500 hPa to 3000 hPa would have been stable against collapsing into permanent surface ice reservoirs. Soto et al [5] examined a similar range in initial surface pressure to investigate atmospheric collapse and to compute collapse rates. CO₂ clouds and their radiative effects were included in [4] but they were not included in [5]. Here we focus on how CO₂ clouds affect the stability of the atmosphere against collapse.

Model Description: We use a version of the NASA Ames Mars GCM that has recently been modified for early Mars simulations. We have upgraded our two-stream, correlated-k radiative transfer scheme to incorporate the effects of CO₂ collision-induced absorption (CIA; [6,7,8]) and to include the CO₂ far line absorption assuming sublorenzian line shapes [9]. We have added a simple CO₂ cloud microphysics that is similar to the one described in [4], whereby atmospheric CO₂ condenses onto a specified spatially and

temporally constant number of ice nuclei. The nominal number mixing ratio of ice nuclei is 10⁵ #/kg, but we vary this number to understand its sensitivity since it is not well constrained. The CO₂ clouds are radiatively active. We have also included processes appropriate for a water cycle (see Steakley et al., this conference), but these are not utilized here.

Simulations. Two 1000 hPa simulations are presented to demonstrate the importance of CO₂ clouds in maintaining the atmosphere against collapse on early Mars. The first simulation includes CO₂ cloud formation as described above. The second simulation does not explicitly include CO₂ clouds. Instead, any condensed atmospheric mass that would form clouds when the temperature drops below the saturation temperature is instantaneously deposited onto the surface. In the first case, atmospheric condensation only leads to surface ice accumulation when the cloud particles reach the surface through gravitational sedimentation, while in the second, all atmospheric condensation leads to surface ice accumulation. Once CO₂ ice reaches the surface via either method, the surface albedo is reset to 0.5.

Results: The two end member simulations show very different behavior: the simulation that explicitly includes CO₂ clouds is stable, while the simulation without CO₂ clouds collapses into permanent surface CO₂ reservoirs.

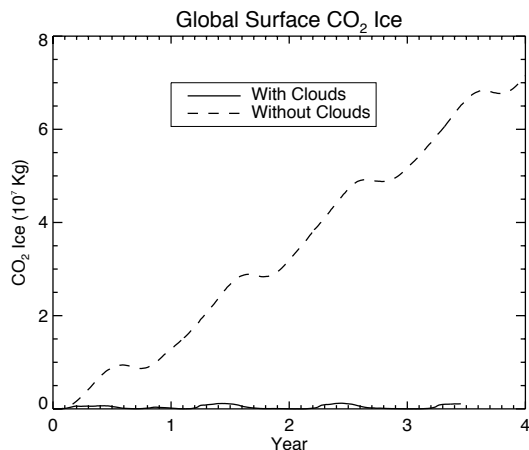


Figure 1: Global surface CO₂ ice inventories as a function of simulated year for the simulations with (solid line) and without (dashed line) CO₂ clouds.

Figure 1 shows the global surface CO₂ inventory for the two simulations. The amount of surface CO₂

ice grows and shrinks seasonally when CO₂ clouds are included but increases almost monotonically when CO₂ clouds are not included. The total amount of CO₂ ice on the surface is significantly less in the simulation with clouds than the simulation without.

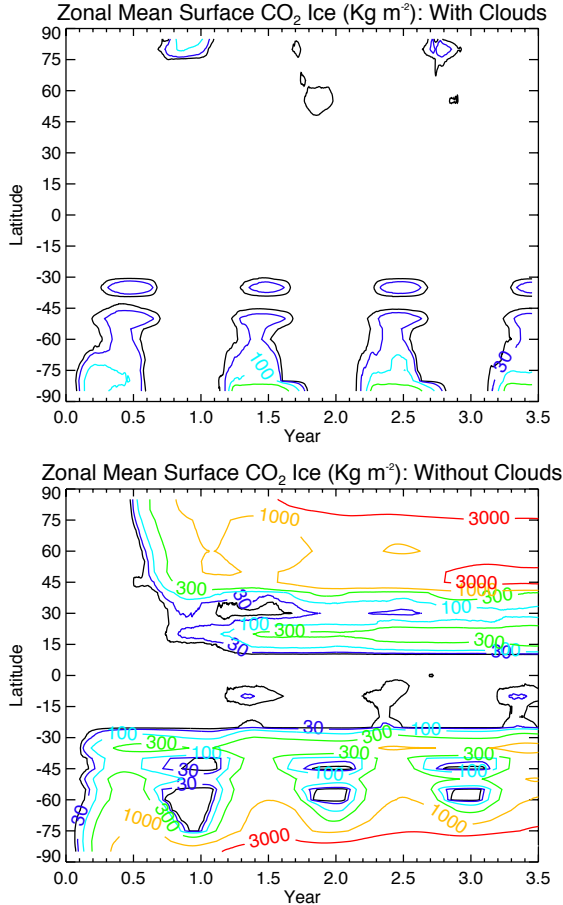


Figure 2: Zonal mean surface CO₂ ice inventories as a function of simulated year for the simulations with (top panel) and without (bottom panel) CO₂ clouds.

Figure 2 shows the latitudinal variation in surface CO₂ ice as a function of time for the two simulations. When clouds are included, seasonal CO₂ ice caps grow and recede at high latitudes. When clouds are not included, permanent reservoirs of surface ice accumulated at high and middle latitudes.

Discussion: The striking difference between these two cases illustrates the important role of CO₂ cloud microphysical processes. In both cases, significant atmospheric condensation is occurring in the atmosphere throughout the year. This condensation occurs at nearly all latitudes, particularly in the regions of large topographic features (e.g., Olympus Mons). In most cases, the condensing region is disconnected from the surface. In the case without CO₂ clouds, all atmos-

pheric condensation (even if it occurs at altitude) leads directly to the accumulation of surface ice, whereas in the case with CO₂ clouds, there is a finite settling time-scale for the cloud particles. Depending on this time-scale and the local conditions, the cloud particles could stay aloft or sublimate as they fall toward the surface. In the case with CO₂ cloud formation, thick CO₂ clouds cover a good portion of the planet in the middle of the atmosphere (Figure 3).

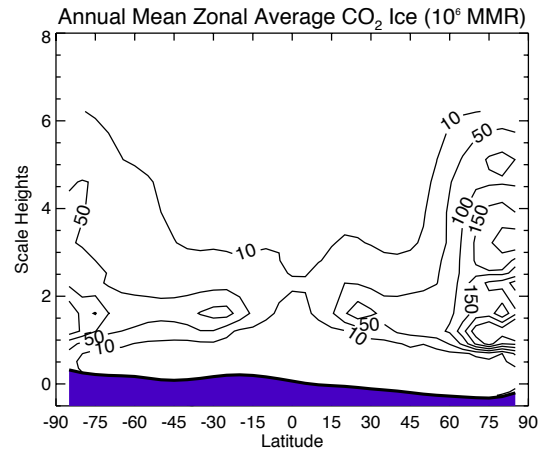


Figure 3: Annual and zonal mean cross-section of CO₂ cloud mass mixing ratio for the CO₂ cloud case.

Conclusions and Future Work: Cloud microphysical processes appear to be of vital importance to the question of atmospheric collapse on early Mars. We have shown that assumptions made regarding how atmospheric condensation and CO₂ clouds are handled in the model have a significant impact on the predicted atmospheric stability against collapse. In particular, the settling timescale controls how much of the condensation that occurs in the atmosphere will lead to surface ice accumulation, which is an important part of determining whether the atmosphere will collapse or not. The settling timescale depends, in turn, on cloud particle size, which will be sensitive to microphysical assumptions such as the number of available ice nuclei, etc. We plan to conduct further detailed studies on the sensitivity of these processes to microphysical parameters in order to better understand the nature of atmospheric collapse on early Mars.

References: [1] Haberle et al (2017), in *The Atmosphere and Climate of Mars*, Cambridge Univ. Press. [2] Haberle et al (1994) *Icarus*, 109, 102-120. [3] Nakamura and Tajika (2002) *JGR*, 107. [4] Forget et al (2013) *Icarus*, 222, 81-99. [5] Soto et al (2015) *Icarus*, 250, 553-569. [6] Wordsworth et al. (2010) *Icarus*, 210, 992-997. [7] Baranov et al. (2004) *JMS*, 228, 432-440. [8] Gruszka and Borysow (1998) *Mol. Phys.*, 93,1007-1016. [9] Perrin and Harmann (1989) *JSRT*, 42, 311-317.