The Early Martian Climate: Effects of Airborne Dust, CO_2 Ice Cap Albedo, and Orbital Obliquity on Atmosphere Collapse.

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Introduction: The stability of the early Martian atmosphere against collapse into permanent surface CO_2 ice reservoirs is fundamentally important for understanding the evolution of Mars' atmosphere and surface throughout its history. The existence of gaseous CO_2 in the atmosphere requires enough energy, distributed planet wide, to stave off the formation of permanent CO_2 caps that leads to atmospheric collapse. Estimates of atmospheric mass loss predict that between 50 and 90% has been lost to space through ion sputtering and photochemical escape since the late Noachian[1]. Based on this predicted range of atmospheric masses, we focus initially on 80 mbar atmospheres. We will broaden our investigation in the near future to include atmospheric masses between 80 and 500 mbars.

Simplified energy balance arguments predict that a clear thick 80 mbar atmosphere is unstable and will collapse when the current orbital parameters are considered. The presence of a "faint young sun" that was likely about 25% less luminous than the sun is today exacerbates the problem. Although greenhouse warming becomes more efficient as the mass of a CO_2 atmosphere is increased, warming due to a CO_2 greenhouse has been shown to be weak for the atmospheric masses considered here[2,3].

Dust that enters the atmosphere can affect CO_2 condensation and sublimation by altering the thermal and dynamical state of the atmosphere and by modifying the albedo and emissivity of the polar ice caps when it returns to the surface. Thus, it is possible that the dust cycle could play a important role in preventing atmospheric collapse, especially if it was more active on early Mars.

Sagan and Bagnold [4] first hypothesized that the efficiency of wind erosion could be linked to the variable nature of surface pressure on Mars. One viable mechanism for dust lifting from the Martian surface is through momentum transfer from the atmosphere to the surface by near-surface winds. The momentum imparted to the surface by winds is governed by the surface stress (τ): $\tau=\rho u_*^2$, where ρ is the near-surface atmospheric density and u_* is the surface friction velocity. This relationship dictates that for a given surface friction velocity, the momentum transferred to the surface increases linearly with atmospheric density (or similarly, surface pressure). Thus, the dust cycle may have been more active on early Mars.

Methods: The NASA Ames Mars General Circulation Model (MGCM) is used to explore the effects of three parameters—dust loading, CO_2 ice cap albedo and orbital obliquity– on the CO_2 cycle and atmospheric collapse.

Thirty-six simulations were designed and executed for 5 Martian years with a circular orbit (Table 1). The model is initialized with 80 mbars of CO_2. The quantity of atmospheric dust varies by simulation but within a simulation, dust is assumed to be constant in time and space with a vertical distribution defined by a Conrath-ν prescription. The model uses a broad-band polar cap albedo at visible wavelengths, which is set to a user-defined constant value when CO_2 ice is present on the surface.

Dust Optical Depth	CO_2 Cap Albedo	Obliquity
0.3	0.3	25°
1.0	0.5	30°
5.0	0.7	45°
		60°

Table 1: Parameters used in the MGCM study.

Results: The main results of this study are:

1. 80 mbar CO_2 atmospheres are difficult to maintain. Of the 36 simulations conducted, only 10 resulted in a stable atmosphere (i.e., permanent CO_2 ice caps did not form; Fig. 1).
2. Increasing the dust loading can either accelerate or decelerate atmospheric collapse, depending on the CO_2 ice cap albedo. Increased atmospheric dust only stabilizes the atmosphere at very high obliquity (Fig. 2).

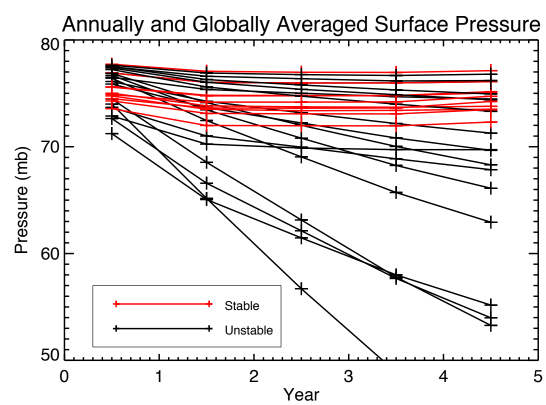

Figure 1: 5 years of annually and globally averaged surface pressure for all simulations in this parameter study. Red lines denote runs that are stable, and black lines indicate runs that result in collapsing atmospheres.

Cap Growth. In all albedo and obliquity cases, increasing the dust loading decreases the total amount of CO_2 condensed and results in a CO_2 cap that is smaller in latitudinal extent. This occurs because dust increases the atmospheric heat transported to the latitudes near the edge of the forming cap and reduces the net radiative loss at the top of the atmosphere in the polar night (Fig. 3).

When the dust loading is high, the CO_2 ice albedo has little effect on the amount of CO_2 condensed or the latitudinal extent of the CO_2 cap. This is true because the increased heat transport due to dust works to confine the CO_2 cap to latitudes high enough that the sun is never above the horizon. Thus, to first order the CO_2 ice albedo is not important.

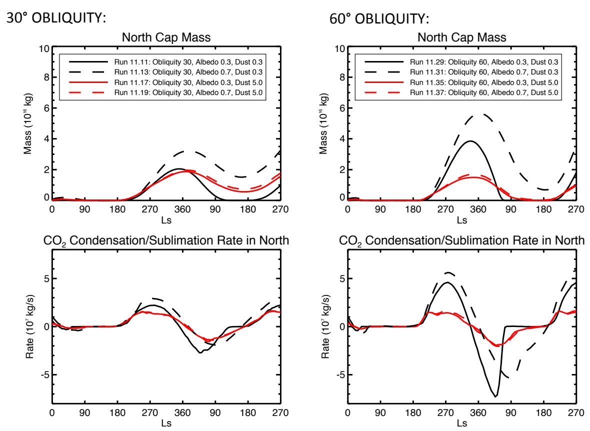

Figure 2: Total cap mass (top panels) and condensation/sublimation rates (bottom panels) in the north for simulations at 30° obliquity (left panels) and 60° obliquity (right panels).

When the dust loading is low, increasing the CO_2 cap albedo has a significant effect on the amount of CO_2 condensed and the latitudinal extent of the CO_2 cap. With weaker midlatitude atmospheric heat transport, CO_2 starts to condense at lower latitudes where the sun still rises. Thus, the higher the albedo of the CO_2 ice, the more CO_2 condenses at lower latitudes.

Cap Recession. In all albedo and obliquity cases, increasing the dust loading decreases the seasonally averaged CO_2 sublimation rate during northern spring and summer (Fig. 2 bottom panels). This occurs because only modest quantities of dust at high zenith angles are required to reduce the net flux at the surface, cool the surface, and reduce the sublimation rate.

Increasing the CO_2 ice cap albedo decreases CO_2 sublimation in all cases because a higher albedo decreases the solar flux absorbed by the surface. This effect is more prominent when the dust loading is low. It is important to note that the total amount of CO_2 sublimation during spring and summer is somewhat dependent on the amount and location of condensed CO_2 during fall and winter. When the atmosphere is relative clear, the cap extends to lower latitudes where, as described above, the effect of albedo is more substantial.

Summary: The net effect of dust on atmospheric stability depends on the combined effects of dust on the growth and recession. The results of this study show that increasing atmospheric dust loading ***does not have a monotonic effect on the stability of the atmosphere***. Dust increases stability when the cap albedo is high because it suppresses CO_2 condensation more than it impedes CO_2 sublimation. Conversely, dust decreases stability when the cap albedo is low because it impedes CO_2 sublimation more than it suppresses CO_2 condensation.

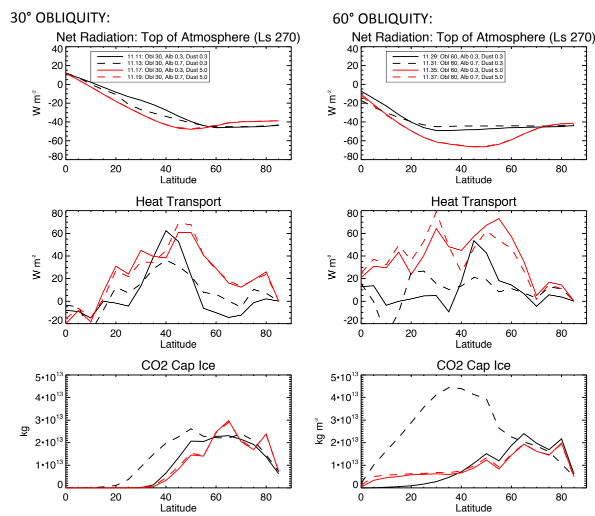

Figure 3: Zonally averaged net radiation at the top of the atmosphere (top panels), heat transport (middle panels) and CO_2 ice cap mass (bottom panels) as a function of north latitude at Ls 270 for simulations at 30° obliquity (left panels) and 60° obliquity (right panels).

References: [1] Jakosky et al., 1994, Icarus, 111, 271-288. [2] Pollack et al., 1987, Icarus, 71, 203-224. [3] Kasting, 1991, Icarus,, 94, 1-13. [4] Sagan and Bagnold, 1975, Icarus, 26, 209-218.

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