MARS AT LOW OBLIQUITY: PERENNIAL CO_2 CAPS, ATMOSPHERIC COLLAPSE, AND SUBSURFACE WARMING.
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Introduction: At low obliquity the polar regions of Mars receive less annual insolation and can reach a point where the total CO_2 sublimation at the pole becomes less than the total condensation – forming a perennial CO_2 ice polar cap. Below this critical obliquity the mass of the CO_2 polar cap(s) increases at the expense of the atmosphere, potentially leading to atmospheric "collapse". Recent radar evidence for a massive buried deposit of CO_2 ice within the south polar layered deposits presented by Phillips *et al.* (2011) [1] has bolstered the case for this scenario. An important consequence of this pressure drop is that it can cause a significant decrease in the thermal conductivity of uncemented porous regolith materials [2]. This effect can lead to increased subsurface temperatures as the planetary heat flow becomes trapped below a more insulating upper layer [3]. The degree of subsurface warming depends strongly on the minimum atmospheric pressure reached, as well as the assumed heat flow, but has the potential to produce episodic liquid water by melting deep ground ice or dewatering of hydrated minerals. Even in the absence of melting, this warming could have significant geomorphic effects by increasing flow rates of buried ice such as lobate debris aprons. At the very least, it would cause the loss or vertical redistribution of as much as 5000 kg/m^2 of ground ice (or ~25 m of 20%-porosity-filling ice) during each low obliquity period.

While the precise magnitude of atmospheric collapse at low obliquity is uncertain, the fact that a significant decrease in atmospheric pressure can occur is a robust conclusion for a wide range of realistic values of CO_2 frost albedo (A_f) and emissivity (ε_f). Values of A_f and ε_f obtained as best-fits in models of the seasonal pressure cycle may not be representative of the entire seasonal CO_2 polar cap because the atmospheric mass is most strongly affected by the lower latitude portions (50°–70°) where they have the greatest surface area [4], and where they are more likely to be affected by dust storms. Observational studies have shown that the central portions of the seasonal polar caps can be much brighter than the outlying portions, with springtime A_f values as high as 0.83 and ε_f close to unity [5] .

Model: We have performed seasonally-resolved calculations of the evolution of Mars' atmospheric pressure over the past 1 Myr using a model [3] that includes subsurface heat conduction and the latest calculations of Mars' orbital and axial variations [8]. The zonally-symmetric model calculates the amount of surface CO_2 condensation or sublimation 12 times per year at 23 latitudes (clustered near the poles) based on a surface energy balance using daily average insolation rates. Subsurface heat conduction is computed using a semi-implicit numerical scheme (~2nd order accuracy) using 40 vertical gridpoints divided into 2 layers with differing thermal properties (Chebyshev spacing in each layer with flux matching at interface). Zonally-averaged Viking IRTM soil albedo and thermal inertia values were used for the upper layer at each latitude, with zonally-averaged MOLA topography to calculate local atmospheric surface pressure and CO_2 frost temperature [3]. We found that for values of A_f = 0.60,

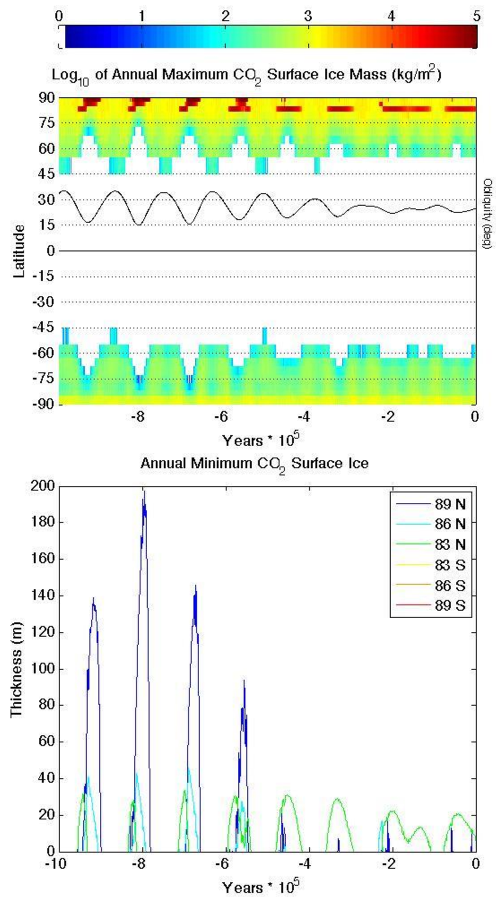

Figure 1 (A) Colors indicated the annual maximum mass (per unit area) of CO_2 ice as a function of latitude and time for the past 1 Myr. The black curvy line indicates obliquity for reference. Areas colored red generally correspond with locations of perennial CO_2 ice. (B) Annual min. thickness of CO_2 ice predicted at several polar latitudes, calculated assuming a solid ice density of 1600 kg/m^3.

0.65, and 0.70 (with ε_f = 1.0 in all cases), the minimum pressures reached were 113 Pa, 69 Pa, and 45 Pa, respectively. Results for this model with A_f = 0.65 and e_f = 1.0 for CO_2 surface ice are shown in **Fig. 1**.

Insolation-dependent CO_2 frost albedo: Guo et al. (2010) [12] performed simulations of the seasonal CO_2 cycle with a Mars GCM using an insolation dependent CO_2 frost albedo based on Viking IRTM observations. They found that including this effect produced a stable perennial CO_2 south polar ice cap near the south pole for the present orbital configuration, similar to what is actually observed on Mars, because the albedo effect outweighs the elevation effect described above. Guo et al (2010) also point out that an insolation-dependent A_f can also lead to stable perennial CO_2 caps at high obliquity as well. This effect is also seen in our model simulations (**Fig. 2**).

Atmospheric Inflation?: The total mass of buried CO_2 ice recently discovered near the south pole is estimated to be ~80% of the present global atmospheric mass [1]. If this reservoir was released into the atmosphere, perhaps during a favorable high obliquity period in the past 1 Myr, then it would nearly double the global mean surface pressure which could have significant climatic effects related to aeolian transport and liquid water stability among others [1]. In order to explore its potential effects on past atmospheric collapse and subsurface warming, we performed some model simulations with a doubled CO_2 inventory (400 kg/m^2 global). An example of our results is shown in **Fig. 2**, for a case in which we also used an insolation- and hemisphere-dependent CO_2 frost albedo (linear fits in Fig. 7). Although the albedo effect resulted in thick perennial CO2 caps during some high obliquity periods, there were several times when the atmospheric pressure reached 1000-1200 Pa followed by a rapid drop to <100 Pa, which could produce a greater degree of subsurface warming than our previous estimates. Finally, we note that this model also produces perennial CO2 ice deposits at the south pole comparable in thickness to the buried deposit recently detected [1].

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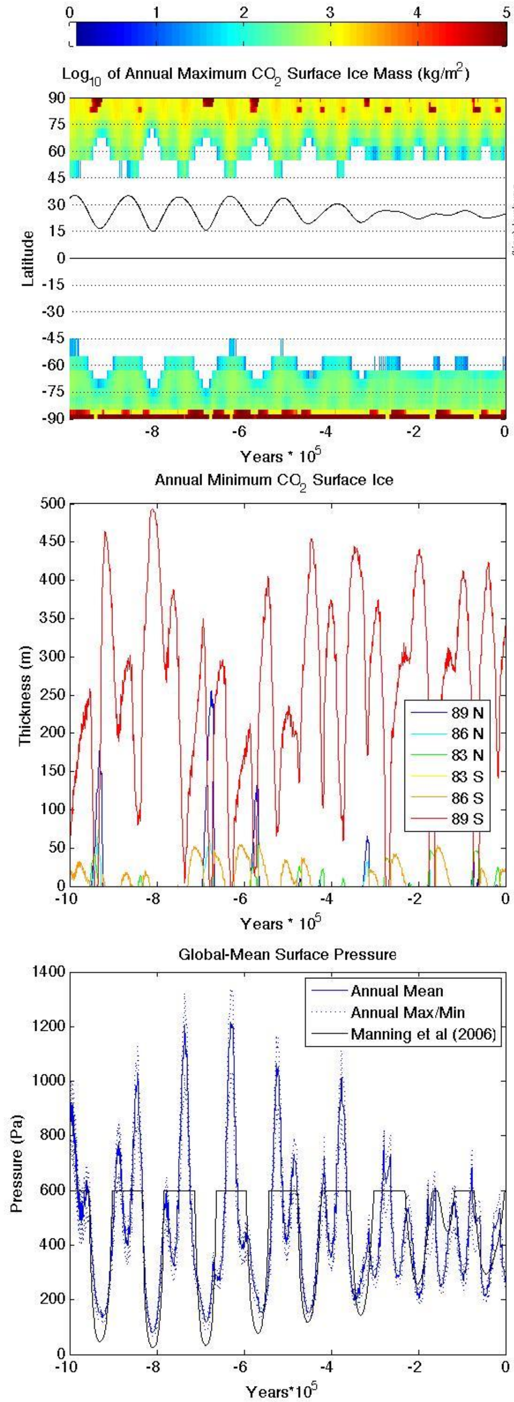

Figure 2 – (A,B) Same as Fig, 1, but for case with doubled CO_2 inventory and insolation-dependent A_f. (C) Corresponding model-calculated variations in annual mean surface pressure (blue solid line) as well as the range of seasonal variations (dotted blue lines).

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