The Last 10 Myr on Mars: Comparing Atmospheric Simulations with Recent Geology Curtis V. Manning[1], Christopher P. McKay[2], Kevin J. Zahnle[2], [1]Department of Astronomy, University of California, Berkeley, CA 94720, manning@astron.berkeley.edu, [2]NASA-Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA.

Introduction: We have devised a fully coupled, obliquity-driven linear model to follow the evolution of Mars' carbon dioxide atmosphere over the last ~ 4.55 Myr [1]. We use parameters and functional representations garnered from the literature to represent the sources and sinks for four main CO_2 inventories – the atmosphere, the ice-cap, CO_2 adsorbed to the regolith, and the carbonates. These include flux terms for juvenile outgassing, impact erosion of volatiles, sputtering and photochemical losses, and weathering, as well as oscillatory fluxes between the regolith, ice-cap and the atmosphere, driven by changes in orbital parameters. We assume a current regolilth capacity of 50 mbar [2].

The constraint that model outcomes must match the present atmospheric pressure has reduced the range of possible models substantially. But there still exists a significant range of parameter values that reproduce the present – primarily due to an uncertainty in the size of the inventory of frozen CO_2. This fact is crucial to understanding the recent climate of Mars. At an obliquity of $\delta \gtrsim 27.5°$, a mere 2.3° larger than at present, all non-seasonal deposits of frozen CO_2 are expected to evaporate, and the atmosphere enters a "runaway greenhouse" [3]. A series of such periods must have occurred between 0.4 and 5 Ma (dotted line in Fig. 1 is $27.5°$).

While recent observations appear to constrain the CO_2 content of the southern ice-cap to about 3 mbar [5], we find that only a small fraction of viable outcomes have such a small ice-cap. Our calibrated greenhouse model provides an upper limit to the greenhouse pressure of $P_{green} \sim 102$ mbar. We suggest that evidence for very recent ponding [6] (or less-recent [7]), are reason enough to ask whether sizeable quantities of CO_2 lie under the north polar cap, where it preferentially forms [8]. The large buried inventories suggested by [9] were followed by the more moderate suggested upper limits [10]. Considering that $\sim 2/3$ of evaporating CO_2 goes to the atmosphere (and the remainder to the regolith), our upper limits for P_{green} are consistent with the ice cap limits of [10]. A long-term high obliquity phase, such as that between 5 and 10 Ma (see Fig. 1) would likely have ablated or melted the north polar cap and caused the evaporation of frozen CO_2. Our models suggest that the pressure during recent greenhouse phases may have been significantly greater than at present.

Viable Models: Viable models are those which reproduce the present; they come in two forms, those that survive the Noachian with some of their initial exchangeable inventory, and those that are totally eroded. The range of initial inventories which produce viable non-eroding models is small; only ~ 700 mbar. Initial inventories for viable models are on order 3 bars. Eroded models come about when initial inventories are

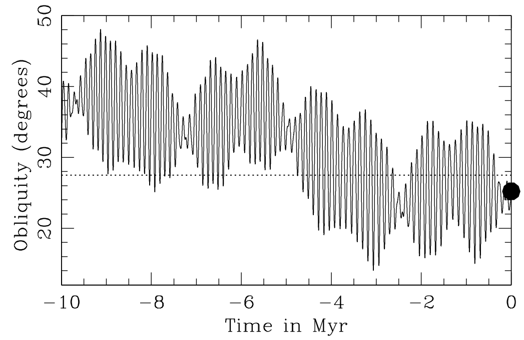

FIG. 1.— The obliquity variations [4] over the last 10 Myr. The dash lined indicates the $27.5°$ obliquity at which the runaway greenhouse phase is thought to begin. Modeling assumes this distributioin of obliquities was repeated in the past.

not sufficient to withstand the early impact erosion and sputtering and photochemical losses. These are viable for all initial inventories less than some non-eroding lower limit (~ 2 to 3 bars, depending on model specifics).

A possible problem for eroded models is that mean pressures (as averaged over 10 Myr bins) are less than the triple point pressure P_t until ~ 2 Ga. Non-eroded models with current CO_2 ice-caps less than ~ 60 mbar have $P_{mean} > P_t$ over the last ~ 3 Gyr [1]. Observations of ponding or lacustrine environments in the Hesperian ([11], [7]) pose problems for these models.

We find that following the Noachian, the prospects for removing large amounts of exchangeable CO_2 from non-eroded models are slight. After 3.5 Ga, sputtering and photochemical losses together account for ~ 100 mbar, and weathering takes perhaps another 20 to 40 mbar. Juvenile outgassing is modeled to vary from ~ 170 to 200 or more mbar. Most viable models have current CO_2 ice-caps larger than about 50 mbar [1].

The Last 10 Myr: The fluctuations in climate produced by recent changes in Mars' orbital parameters will produce disequilibria in the surface distributions of the volatile inventories. Our program currently considers only CO_2, but the equilibria of both CO_2 and H_2O respond to changes in obliquity. Water must move *from* latitudes at which the irradiance has increased, and *toward* latitudes at which it has decreased.

Head et al. ([12]) suggested that recent higher obliquity phases at $t \lesssim 4$ Ma correspond to ice-ages for the mid-latitudes. We revisit this issue. Figure 2 shows the trend in atmospheric pressure during the last 10 Myr for our baseline model [1]. It predicts a current ice-cap pressure-equivalent of ~ 60 mbar. The inset shows the last 1.5 Myr; the blue line is the CO_2 ice-cap, black is the atmospheric pressure, orange is the total carbonate inventory, and red is the regolith capacity. The pressure

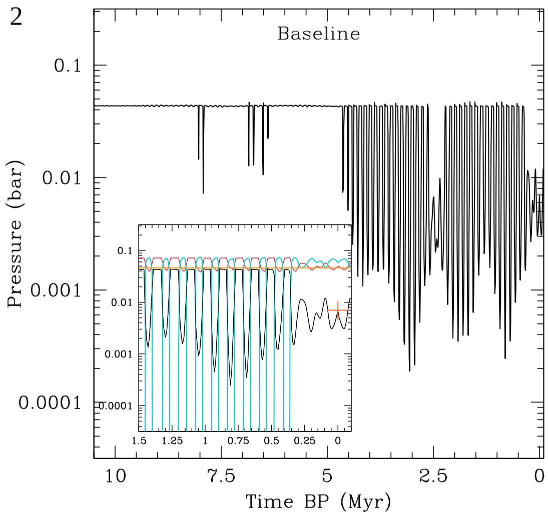

FIG. 2.— Atmospheric pressure for the baseline model in the last 10 Myr. The inset shows the change in other inventories (see text) for the last 1.5 Myr. The present is marked in the inset by the orange "+" sign.

during runaway greehouse phases $P_{green} = 43$ mbar. There are ~ 36 episodes of ~ 55-70 kyr duration in which the "permanent" CO_2 ice-caps disappeared and a greenhouse phase ensued. Each obliquity cycle moves water and CO_2 on the planet. Notice also that the last ~ 350 kyr has experienced a low variability in its obliquity (Fig. 1); water ought by now to have achieved a near-equilibrium state.

The trend in the obliquity of Mars during the last 10 Myr (Fig. 1) is one of a decline from high obliquity ($\delta \simeq 38^\circ \pm 8^\circ$) to a low obliquity ($\delta \sim 25^\circ$). The high obliquity period before 5 Ma would have driven water from the polar caps toward the mid-latitudes. The more recent low obliquity periods would have driven it back. What appears to be a remnant rock glacier on the Northwest flanks of Arsia Mons [13], and its the knobby and ridged facies, suggest that large equatorial glaciers once existed. The obliquity trends suggest they could have been formed between 5 and 10 Ma. The outermost glacial manifestations are the ridged facies, which consist of parallel ridges identified as the drop morains of a cold-based glacier whose gradual ablation was periodically stalled, producing depositional caustics [13]. The fluctuations in the glacier withdrawal rate could occur during a period of low mean obliquity with large obliquity variations. This facies could thus have been formed in the period ~ 5 Ma to 350 ka. The evenness of the ridged deposits along their length suggests that it consists of dust deposited from the atmosphere and entrained in the glacier. At a higher altitude, the knobby terrain appears to correspond with a period of pure, unmitigated ablation of the glacier. We identify this period as the last 350 kyr of small obliquity fluctuations.

Ponding: We now consider possibile ponding on Mars (eg, [6], [7], [11]). To sustain a pond, the local daily average temperature must exceed 273 K [14]. Pollack et al. show that when the eccentricity is at a maximum, large excursions of the daily average temperature from the yearly mean may occur [15]. During periods of high eccentricity, some areas on the planet may experience a flux up to 1.89 times the mean planetary flux [15]. This is based on a maximum eccentricity $e = 0.14$ [16], and a factor of 1.4 for the excess ratio of the flux at the sub-solar latitude over the planetary mean [17]. The most recent estimates of e [4] find the eccentricity does not get larger than ~ 0.11 in the last 10 Myr. The maximum flux enhancement in this case is 1.76.

The mean radiative equilibrium temperature at Mars is $T_{eq} = 194(S/0.7)^{1/4}$ K. For $S = 1.76$, $T_{eq} = 244.3$ K. A functional fit to modeling of [15] is given by [14], with a correction for greenhouse warming of approximately $\delta T = 20\sqrt{P}(1 + S)$ K, where P is in bar. For a pressure of 6.8 mbar (or 100 mbar), the correction is $\delta T = 4.6$ K (or 17.5 K), hence maximum daily averaged temperatures are 248.9 K (261.8 K); short of 273 K. With $e = 0.14$, temperatures are 253.5 K (267.0 K).

According to these calculations, ponding cannot occur. Temperatures *could* reach 273 K if $P_{green} \approx 238$ mbar. At such a large P_{green}, our model would not allow the freezing of CO_2 on the poles at the current obliquity, without changing our albedo or ice-cap extent parameters. Perhaps special circumstances can be claimed. For instance, a large day-time temperature may produce ponded water with temperatures exceeding freezing by enough to survive the night. Some ponding may be explained by hydrothermal outflows if ambient temperatures are not very far below freezing.

It is likely that observations of features strongly suggesting fluvial action can provide firm, albiet model-dependent, lower bounds to the atmospheric pressure when the permanent CO_2 ice-cap has evaporated. Our results show that large CO_2 ice-caps, or alternatively, large runaway greenhouse pressures, are likely to be required to explain ponding and other fluvial features.

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