A ONE BILLION YEAR MARTIAN CLIMATE MODEL — THE IMPORTANCE OF SEASONALLY RESOLVED POLAR CAPS AND THE ROLE OF WIND.

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Introduction

Wind deflation and deposition are powerful agents of surface change in the present Mars climate regime. Recent studies [1] indicate that, while the distribution of regions of potential deflation (or erosion) and deposition is remarkably insensitive to changes in orbital parameters (obliquity, timing of perihelion passage, etc.), rates of aeolian surface modification may be highly sensitive to these parameters even if the atmospheric mass remains constant. But previous work [2] suggested the atmospheric mass is likely to be sensitive to obliquity, especially if a significant mass of carbon dioxide can be stored in the regolith or deposited in the form of massive polar caps. Deflation and erosion are highly sensitive to surface pressure, so feedback between orbit variations and surface pressure can greatly enhance the sensitivity of aeolian modification rates to orbital parameters.

We used statistics derived from a 1 Gyr orbital integration of the spin axis of Mars, coupled with 3-D general circulation models (GCMs) at a variety of orbital conditions and pressures, to explore this feedback. We also employed a seasonally resolved 1-D energy balance model to illuminate the gross characteristics of the long-term atmospheric evolution, wind erosion and deposition over one billion years. We find that seasonal polar cycles have a critical influence on the ability for the regolith to release CO_2 at high obliquities, and find that the atmospheric CO_2 actually decreases at high obliquities due to the cooling effect of polar deposits at latitudes where seasonal caps form. At low obliquity, the formation of massive, permanent polar caps depends critically on the values of the frost albedo, A_{frost}, and frost emissivity, ϵ_{frost}. Using our 1-D model with values of $A_{frost} = 0.67$ and $\epsilon_{frost} = 0.55$, matched to the NASA Ames GCM results, we find that permanent caps only form at low obliquities (< 10 degrees). Thus, contrary to expectations, the Martian atmospheric pressure is remarkable static over time, and decreases both at high and low obliquity. Also, from our one billion year orbital model, we present new results on the fraction of time Mars is expected to experience periods of high and low obliquity. Finally, using GCM runs at a variety of pressures, we examine the likely role of wind erosion under an early more massive Martian atmosphere.

Seasonal polar cycles and regolith adsorption

For our long-term climate model, we couple the results of the evolution of the obliquity of Mars [3] to a 1 Gyr solar system evolution model [4]. Our 1-D energy balance and regolith adsorption model follows closely that of Fanale and Salvail [2], with one important difference. We use a seasonally resolved 1-D energy balance model matched to the GCM results to compute the surface temperatures and atmospheric pressure throughout the year. The inclusion of the seasonal polar processes has striking implications for the long term results. Figure 1 shows the atmospheric pressure (top) and obliquity (bottom) for the last 10 Myrs. We find that the atmospheric pressure is roughly constant over recent history, and at high obliquities, the atmospheric pressure actually decreases slightly. As seasonal polar caps reach lower and lower latitudes as the obliquity increases, the annual average temperature also decreases at those latitudes. This results in a reduction in the global temperatures, even if the annual average cap temperature increases (Figure 2, bottom plot).

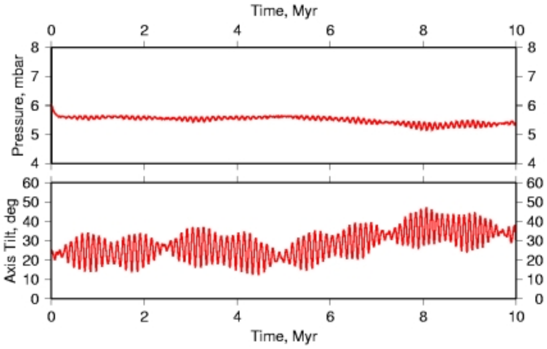

Figure 1: Results for the full climate model over the last 10 Myrs. The upper plot shows the atmospheric pressure as a function of time, the lower plot shows the planet's obliquity variations over the same period. Note the slight decrease in atmospheric pressure at high obliquities. Also, permanent CO_2 caps do not form under the model conditions with $A_{frost} = 0.67$ and $\epsilon_{frost} = 0.55$. The initial slight decrease in pressure at $t = 0$ is the result of the model equilibrating after spinup from the initial regolith temperature profile.

Permanent cap formation

The formation of permanent polar caps has the potential to remove nearly all of the atmospheric CO_2 reservoir in less than 100,000 years. During periods of low obliquity, decreases in the annual average polar insolation result in the formation of massive polar caps. While massive, these caps tend to cover a relatively small area. In addition, the actual extent and mass of these caps depends on the frost albedo, the frost emissivity, effects due to latent heat transport, dust content, as well as the composition of the polar deposits. Using the seasonal 1-D energy balance model, we track the reservoir of CO_2 that persists during the summer season, and attempt to isolate the effects of at least two of these factors: CO_2 frost albedo and emissivity.

There is a large range of potential values for both the CO_2 frost albedo and the frost emissivity from the literature.

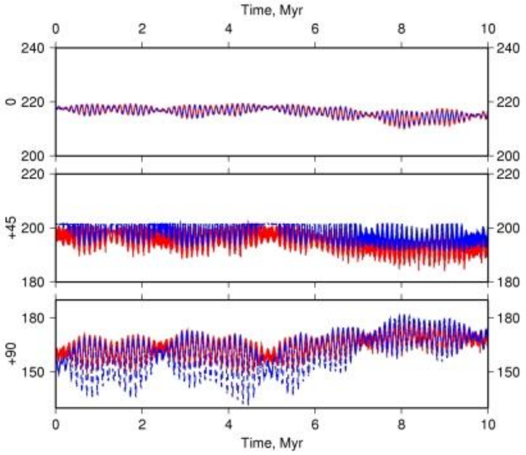

Figure 2: Surface temperature as a function of latitude, results of the full model. The blue dashed lines are derived by using the annual average insolation and the red lines are the annual average temperature calculated from our model with seasonally resolved polar caps. The polar cap extent at high obliquity tends to decrease the annual average temperature, compared to expectations from the annual average insolation. This results in a decrease in annual average temperature at middle and higher latitudes, and a corresponding decrease in atmospheric pressure at high obliquities. The equatorial temperatures, which are not influenced by polar processes, match the temperatures derived from the annual average insolation.

Fanale and Salvail [2], with a model that calculated the annual average insolation to derive surface temperatures as a function of latitude, used the total CO_2 budget in the atmosphere-cap-regolith system as a free parameter, and $A_{frost} = 0.67$ and $\epsilon_{frost} = 0.90$, to develop a model that allowed Mars to form permanent polar caps at a critical obliquity very near to the present value. However, there is some debate as to whether or not the polar deposits on Mars contain any appreciable amounts of CO_2 ice [5].

Detailed theoretical calculations of the albedo and emissivity of CO_2 snow [6] show the range of possible values depending on grain size, snow density, and other factors. Coarse grained CO_2 snow ($\sim 2000\, \mu m$), for example, has a spectrally averaged $A_{frost} = 0.35$ and $\epsilon_{frost} = 0.91$. Fine grained CO_2 snow ($\sim 5\ \mu m$), on the other hand, has $A_{frost} = 0.94$ and $\epsilon_{frost} = 0.39$. The emissivity can also be a function of the snow density, owing to interparticle interference or "near-field effects". This effect is strongest for fine grained CO_2 snow, where a 30 % increase in density (from 0.7 to 1.0 $g\ cm^{-3}$) results in an increase in the spectrally averaged emissivity from 0.40 to 0.52 [6]. The effect is almost non-existent for grain sizes greater than $\sim 500\ \mu m$.

Without detailed information about the state of any permanent CO_2 deposits on Mars, we take a slightly different approach from past studies. We have matched the results of our seasonal 1-D energy balance model to results from the GCM, which in turn has been matched to the Viking lander observations. We find that a frost albedo similar to [2], but a much lower $\epsilon_{frost} = 0.55$, matches the observed Viking data and the seasonal polar deposits in the GCM model quite well. However, using this low value for the emissivity means that Mars does not form polar caps except at obliquities smaller than 10 degrees.

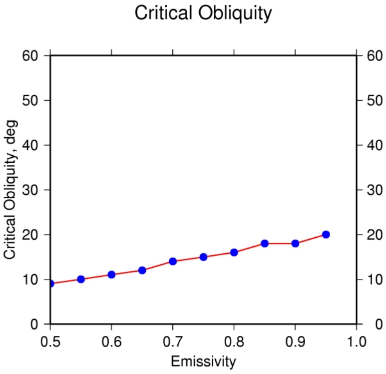

Figure 3: The critical obliquity where cap formation begins as a function of frost emissivity.

We use our seasonal model to predict the critical obliquity of permanent CO_2 cap formation as a function of the frost emissivity and albedo. Using constant orbital parameters, we vary only the obliquity, from 0 – 60 degrees, for values of emissivity and albedo ranging from 0.50 – 0.95. In the models with varying emissivity, we keep A_{frost} fixed at 0.67, and in the models with varying frost albedo, we keep ϵ_{frost} fixed at 0.55. Each model is run for 125,000 years to make sure the seasonal reservoirs, annual reservoirs, and the regolith thermal model come to equilibrium for the obliquity in question. Finally, for each value of the emissivity and frost albedo, we choose the obliquity which shows the smallest non-zero permanent polar deposit (on either pole) as the critical obliquity of cap formation.

Figures 3 illustrates the dependence of cap formation on the emissivity of polar deposits. As we increase the emissivity, the polar cap temperature decreases, facilitating cap formation. We note that the value of $\epsilon_{frost} = 0.90$, chosen by [2], does indeed place the critical obliquity closer to the current value. However, using our value of $\epsilon_{frost} = 0.55$, we find Mars will form permanent caps only during periods of extremely low obliquity of less than 10 degrees, assuming a frost albedo and emissivity of 0.67 and 0.55 respectively. This corresponds to only 1 percent of the orbit during the last 1 Gyr (see Table 1).

Figure 4 shows how changing the value of A_{frost} affects the critical obliquity of polar cap formation. Here, we see a much stronger dependence on the value of A_{frost}. With $\epsilon_{frost} = 0.55$, we see a low critical obliquity of cap formation. However, if the CO_2 albedo increases, the critical obliquity for cap formation also increases.

CO_2 deposits on Mars today may also have lower albedos

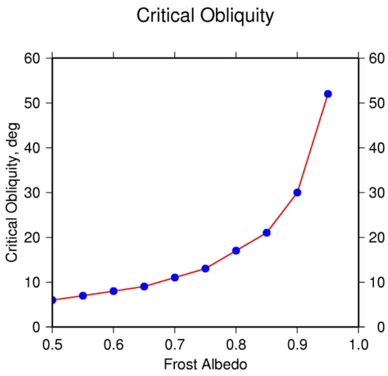

Figure 4: The critical obliquity where cap formation begins as a function frost albedo.

Table 1: Fraction of time spent at values lower than the specified obliquity, with and without Tharsis, for the 1 Gyr orbital model.

θ (degrees)	*Frequency, %* *Tharsis*	*Frequency, %* *No Tharsis*
< 5	0	2
< 10	1	7
< 20	12	30
< 30	48	62
< 40	84	84
< 50	99	99
< 60	100	100

due to dust inclusions in the deposits. The effects of dust on the albedo can be significant, even for small amounts of dust. Work based on dust inclusion in H_2O snow [7] showed that even small concentrations of dust (one part in 1000) can cause the albedo of the deposit to asymptotically approach the dust albedo. In the case of CO_2 on Mars, the frost albedo can be suppressed by modest dust inclusions.

Regardless of the current value of A_{frost}, an interesting scenario presents itself. As we approach the critical obliquity, massive CO_2 caps will form. As the cap formation depletes the atmospheric reservoir, the atmospheric dust will also become depleted. This will initially decrease the frost albedo. However, the final deposits from the relatively dust-free atmosphere will cause the CO_2 albedo to jump sharply, as the final deposits will be composed primarily of pure CO_2. As the obliquity begins to increase once again, these deposits will persist past the previous value of the critical obliquity, causing a delayed release of the permanent deposits. This hysteresis effect may provide an explanation for the persistence of small amounts of CO_2 ice even at high obliquities. It may even provide an explanation for their instability, as observed in the receded pits and scarps in high-resolution images of the south polar regions [8].

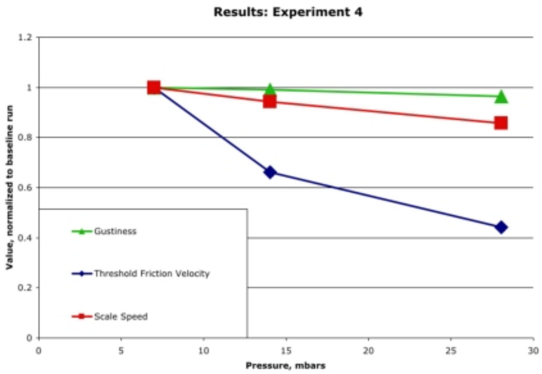

Figure 5: The variations of the planetwide averages of u_t (blue diamond), u_0 (red square), and κ (green triangle) with pressure, normalized to the baseline $P = 7.01$ mbar run. The solid lines and symbols are values derived from the GCM runs. For small changes in pressure, changes in u_t dominate.

Winds on Early Mars

The surface wind stress is capable of liberating material from the surface only if the friction velocity surpasses the threshold friction velocity, u_t. Utilizing the work of [9], we find that for a fixed particle size of 100 μm, the surface friction velocity, to first order, is fit well by a power law

$$u_t = C\rho^{-\alpha}, \tag{1}$$

where ρ is the atmospheric density, C is a constant, and $\alpha \sim 0.5$. Based on this simple relationship, we expect increases in atmospheric density (corresponding primarily to increases in pressure) to reduce the threshold friction velocity for a given particle size.

Results from our long-term climate model suggest that the atmospheric pressure is remarkably constant over time. However, this does not preclude a higher atmospheric pressure early in Mars' history. We used three GCM runs with global mean pressures of 7.01, 14.02, and 28.04 mbars to explore the effect increasing the atmospheric pressure has on the wind speeds. Following previous work [10], we use a Weibull's distribution function to fit the distribution of surface friction velocities on Mars.

$$P(> u_*) = e^{(-u_*/u_0)^\kappa} \tag{2}$$

describes the cumulative probability distribution function (PDF), or the frequency of wind speeds greater than a given surface friction velocity, u_*. The scale speed (approximately the mean value of the wind speed, $\bar{u}_*$, over several sols) is given by u_0 and κ is the "gustiness" factor.

Figure 5 shows the global average in both time and space of u_t, u_0, and κ as a function of atmospheric pressure, normalized to the $P = 7.01$ mbar run. The averages are derived by taking the ratio of u_t, u_0, and κ at each point and performing an annual average over all latitude and longitude bins. The solid lines and symbols are direct averages from the GCM runs.

We see that as the mean pressure increases, on average the scale speed of the distribution decreases. However, while the denser atmosphere has lower wind speeds on average, they also have more frequent high speed winds, as indicated by the decreasing value of κ. Also, we see that for small increases in pressure, the value of u_t decreases dramatically. Therefore, we expect increasing surface pressure to increase potential erosion, at least over this range of pressure change.

Conclusions

By incorporating the seasonally resolved polar cycle into our long term 1-D energy balance model, we have unearthed several important considerations for the long-term climate evolution on Mars. First, the atmospheric budget is roughly constant over time. Also, the formation of permanent polar caps is rare, occurring less than 1 % of the time over the last 1 Gyr. This implies that changes in atmospheric pressure over the last 1 Gyr play a relatively minor role in wind erosion on the surface of Mars. However, topographically induced pressure differences can be very important. Lastly, we expect that a modest increase in pressure on Early Mars, while slightly decreasing the overall wind speeds, will result in enhanced erosion, since the difference between u_0 and u_t becomes more pronounced, while the overall frequency of high speed winds (denoted by smaller κ) increases.

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