MARS' OBLIQUITY-DRIVEN MOBILE CO2 INVENTORY DERIVED FROM POLAR STRATIGRAPHY.
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Introduction: CO_2 adsorbed in the martian regolith was detected over 40 years ago by Viking Lander 1 [1]. Subsequent studies suggested that the adsorbed CO_2 reservoir may be significantly larger than the combined mass of Mars' 96% CO_2 atmosphere and South Polar Massive CO_2 Ice Deposit (MCID) and, if true, that the process of CO_2 adsorption in the martian regolith could significantly affect Mars' pressure—and therefore climate—evolution over obliquity cycles [2]. Nevertheless, due to its poorly known mass and spatial extent, the adsorbed CO_2 reservoir is often ignored in martian climate investigations [3]. However, because the evolution of Mars' atmosphere, regolith, and MCID are intimately coupled, the climate record stored in the stratigraphy of the MCID provides a record of how these three exchangeable CO_2 reservoirs co-evolve. We use a numerical climate model of MCID stratigraphic evolution as a function of Mars' orbital evolution [4] to determine the mass of the mobile CO_2 inventory participating in exchange between the regolith, MCID, and atmospheric CO_2 reservoirs over obliquity cycles (Fig. 1).

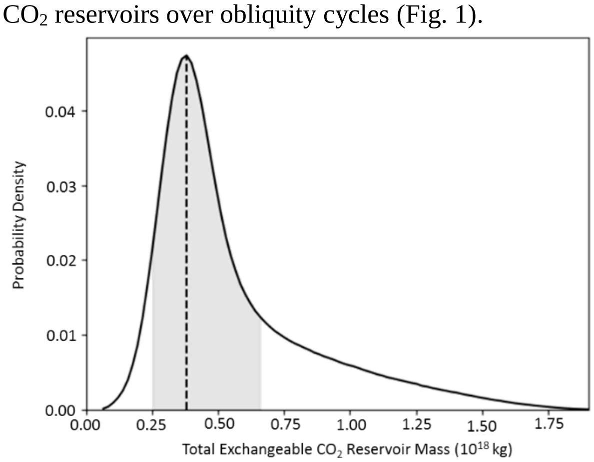

Fig. 1: Model-derived probability distribution for mobile CO_2 inventory participating in exchange between regolith, MCID, and atmospheric CO_2 reservoirs over obliquity cycles.

Methods: We adopt a framework in which changes to Mars' mean annual latitudinal insolation, due to Mars' orbital evolution, thermodynamically drive the exchange of CO_2 between the atmosphere, MCID, and regolith. Atmospheric CO_2 is in contact with both the regolith and the MCID, while the MCID and regolith exchange CO_2 indirectly, through the atmosphere. CO_2 exchange between reservoirs is not kinetically hindered on timescales relevant to Mars' orbital variations [5,6].

Atmosphere-MCID CO_2 exchange is determined by polar energy balance and vapor pressure equilibrium, according to the methods in [5]:

(Eq. 1) $$P_{eq,cap} = P_{eq,0} \exp\left[-\frac{z_{base}+\frac{m_{cap}}{A_{cap}\times\rho}}{H}\right]$$

Here $P_{eq,cap}$ is the equilibrium pressure at the elevation of the upper surface of the MCID, set by the MCID base elevation z_{base} plus the MCID thickness, which depends on CO_2 ice density ρ and MCID mass m_{cap} and area A_{cap}. $P_{eq,0}$ is pressure at the zero-elevation datum, which is also the mean elevation of the regolith surface.

The regolith is divided into a grid of latitude and depth. The mass of adsorbed CO_2 dm_{reg} in each box is calculated based upon $P_{eq,0}$ and temperature T as a function of depth z, using [7]:

(Eq. 2) $$dm_{reg} = dV_{reg} A_S \delta P_{eq,0}^{\gamma} T(z)^{\beta}$$

dV_{reg} is the regolith volume of a given grid box, A_S is the regolith specific surface area, and δ, γ, and β are values fit to empirical data [7]. The total mass of CO_2 adsorbed in the regolith m_{reg} is the integral over all the dm_{reg} elements. Temperature is calculated from a 1-dimensional energy balance model that accounts for incoming absorbed insolation energy flux, outgoing emitted thermal energy flux, and the energy flux conducted to the subsurface. Subsurface temperature is calculated using the diffusion equation [5] with a regolith heat capacity of 837 J kg^{-1} K^{-1}, density of 2000 kg m^{-3} [2].

Mars' total exchangeable CO_2 is $m_{tot} = m_{atm} + m_{cap} + m_{reg}$, a conserved quantity in our model. We model how m_{tot} partitions between m_{atm}, m_{cap}, and m_{reg} for various obliquities ϵ. For each ϵ, we iteratively compute atmosphere-MCID and atmosphere-regolith equilibria until the mass of each reservoir is within 0.1% of the mass from the previous iteration (Fig. 1). We then construct the temporal evolution of the partitioning of Mars' CO_2 inventory by interpolating between ϵ grid points to find the mass of each reservoir for any desired ϵ (Fig. 2). Eccentricity and longitude of perihelion are set to 0 because the distribution of CO_2 ice is more sensitivity to ϵ than other orbital parameters [3,5].

The MCID stratigraphy of alternating CO_2 and H_2O ice layers evolves as H_2O ice in the CO_2 consolidates into lag layers when CO_2 ice ablates and older ice layers are buried when of CO_2 ice accumulates [5].

We then run the climate model over a range of regolith albedo (0.2 - 0.3) [3], thermal conductivity (0.08 - 2.0 $Wm^{-1}K^{-1}$), regolith specific surface area ($10^2 - 10^5$ $m^2\,kg^{-1}$) [7,9], and regolith thickness (1 m – 1 km) [2,7]. For each parameter set, we obtain a model-derived stratigraphy. This work focuses on how varying regolith parameters affects MCID stratigraphy, so we do not explore the effect of varying model parameters relating to the polar CO_2 ice, but rather adopt values from [5]. We also do not vary regolith emissivity (set to 1.0) or the geothermal gradient (0.03 $W\ m^{-2}$ [10]), because these parameters are degenerate with albedo and thermal conductivity, respectively.

Finally, we perform Markov Chain Monte Carlo analysis to compare the model-derived stratigraphy for a particular parameter set to observations in order to determine the likelihood of the mass of the mobile CO_2 inventory participating in exchange between the regolith, MCID, and atmospheric CO_2 reservoirs over obliquity cycles (Fig. 1). We use observed volume fractions of the CO_2 layers in the MCID of: top, 77%; middle, 21%; bottom, 2% [8,11, I.B. Smith per. comm.].

Results: Models in which the total accessible mobile inventory of CO_2 on obliquity timescales is 100^{+80}_{-34} mbar $(3.8^{+3.0}_{-1.3} \times 10^{17}\ kg)$ yield stratigraphies that are most consistent with the observed MCID stratigraphy (Fig. 1).

In general, larger CO_2 inventories lead to larger top layers and smaller bottom layers, and vice versa. This is because, when regolith adsorptive capacity is larger, the variation in MCID mass extrema are larger, meaning that proportionally less CO_2 survives obliquity maxima. Likewise, the upper layers are thicker because more CO_2 fluxes back onto the cap during the recent lower obliquity periods. CO_2 mass in the atmosphere, cap, and regolith are shown as a function of obliquity in Fig. 2.

Discussion and Conclusions: Previous attempts to model Mars' exchangeable CO_2 inventory on obliquity cycles [2,7] did not have the benefit of comparison to the record of CO_2 exchange stored in the MCID stratigraphy. Instead, they relied on the best observations of the time, which indicated that Mars had an insignificant polar CO_2 ice deposit. As a result, the task of identifying Mars' total CO_2 inventory was under-constrained and required previous investigators to select their preferred value of regolith adsorptive capacity. Fortunately, the MCID provides a geologic record of CO_2 exchange between the atmosphere, MCID, and regolith [5,8]. The modern observations of the MCID available to our study (the ratio of multiple MCID layers rather than the binary presence/absence of a polar CO2 ice deposit) sufficiently constrain statistical determination of the best-fit parameters, eliminating the need to select regolith adsorptive capacity as a model input.

The best-fit exchangeable CO_2 inventory on obliquity cycles determined in our model is intermediate between previous estimates: 30-40 mbar [7] and 65-514 mbar [2].

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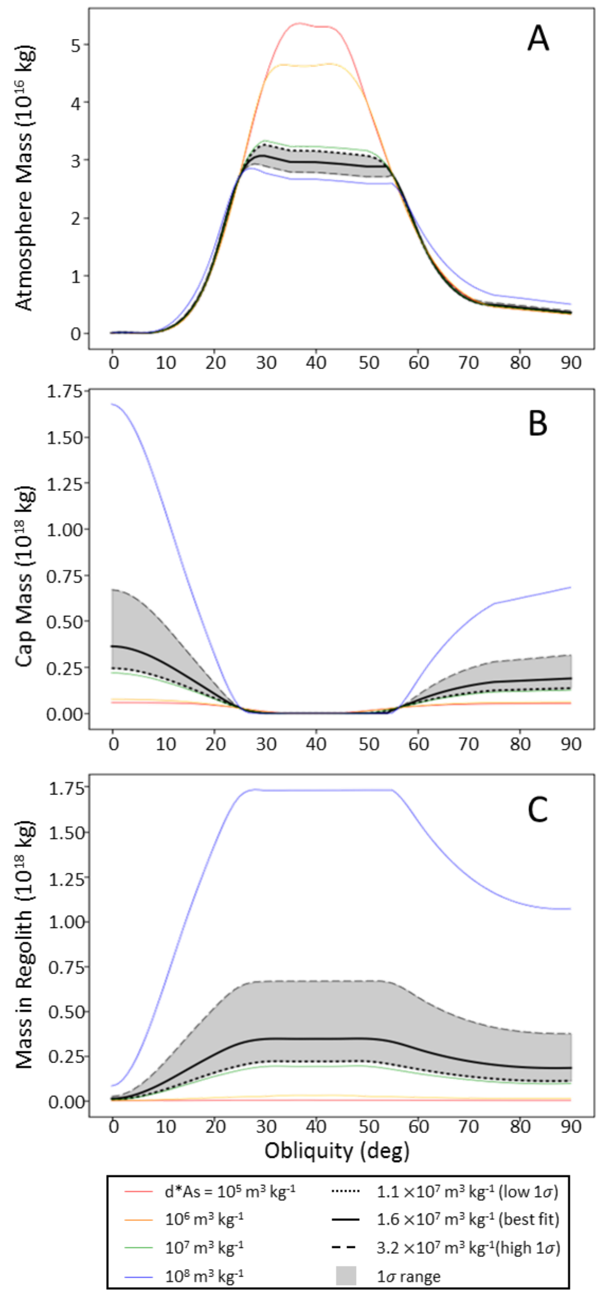

Fig. 2. The mass in each reservoir (A. Atmosphere, B. Cap, C. Regolith) as a function of obliquity for various values of regolith adsorptive potential (depth × specific surface area).