MARS’ MASSIVE CO₂ ICE DEPOSIT STRATIGRAPHY INDICATES MARS’ EXCHANGEABLE CO₂ INVENTORY IS ≤ 33 MBAR. P. B. Buhler¹, S. Piqueux¹. Jet Propulsion Laboratory, California Institute of Technology (peter.b.buhler@jpl.caltech.edu).

Introduction: CO₂ adsorbed in the martian regolith was discovered over 40 years ago by Viking Lander 1 [1]. Subsequent studies suggested that the adsorbed CO₂ reservoir may be significantly larger than the combined mass of Mars’ 96% CO₂ atmosphere and South Polar Massive CO₂ Ice Deposit (MCID) and, if true, that the process of CO₂ 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 CO₂ 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 CO₂ reservoirs co-evolve. We use a numerical climate model of MCID stratigraphic evolution as a function of Mars’ orbital evolution [4] for various values of mean global thickness of adsorptive regolith $z_{reg}$.

Atmosphere-MCID CO₂ exchange is determined by polar energy balance and vapor pressure equilibrium, according to the methods in [5]:

(Eq. 1) $P_{eq,cap} = P_{eq,0} \exp \left[ -\frac{z_{base} \cdot m_{cap}}{A \cdot \rho \cdot \gamma \cdot \beta} \right]$

Here $P_{eq,cap}$ is the equilibrium pressure at the elevation of the upper surface of the MCID, set by the mean global thickness of adsorptive regolith $z_{base}$ plus the MCID thickness, which depends on CO₂ ice density $\rho$ 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 CO₂ $dm_{reg}$ in each box is calculated based upon $P_{eq,0}$ and temperature $T$ as a function of depth $z$, using [7]:

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

Here $dV_{reg}$ is the regolith volume of a given grid box, $A$ is the specific surface area of the regolith, and $\delta$, $\gamma$, and $\beta$ are values fit to empirical data [7]. The total mass of CO₂ 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, and thermal conductivity of 0.8 W m⁻¹ K⁻¹ [2].

Mars’ total exchangeable CO₂ 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 $\epsilon$. For each $\epsilon$, 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’ CO₂ inventory by interpolating between $\epsilon$ grid points to find the mass of each reservoir for any desired $\epsilon$ (Fig. 2). Eccentricity and longitude of perihelion are set to 0 because the distribution of CO₂ ice is more sensitive to $\epsilon$ than other orbital parameters [3,5].

The MCID stratigraphy of alternating CO₂ and H₂O ice layers evolves as H₂O ice in the CO₂ consolidates into lag layers when CO₂ ice ablates and older ice layers are buried when CO₂ ice accumulates [5].

Methods: We adopt a framework in which changes to Mars’ mean annual latitudinal insolation, due to Mars’ orbital evolution, thermodynamically drive the exchange of CO₂ between the atmosphere, MCID, and regolith. Atmospheric CO₂ is in contact with both the regolith and the MCID, while the MCID and regolith exchange CO₂ indirectly, through the atmosphere. CO₂ exchange between reservoirs is not kinetically hindered on timescales relevant to Mars’ orbital variations [5,6].
evolves over time such that the MCID just barely survives at all orbits, due to the gradual accumulation of H$_2$O ice into the MCID region [5]: 2: $z_{\text{base}}$ is fixed to its current elevation [8], perhaps because the H$_2$O ice beneath the MCID is protected by a dust lag [9]. Scenario 1 is shown in Figs. 1 and 2. In both scenarios, the majority of CO$_2$ is in the MCID at $\varepsilon \approx -15-25^\circ$ (exact value depends on $z_{\text{reg}}$; Fig. 1). Above $\varepsilon \approx 40^\circ$, CO$_2$ starts to migrate to the MCID again because the insolation dependence of Mars’ CO$_2$ albedo [10] leads to decreasing net annual absorbed insolation in this $\varepsilon$ regime [5].

**Stratigraphic Development.** In Scenario 1, where $z_{\text{base}}$ adjusts to an equilibrium elevation over many $\varepsilon$ cycles, increasing $z_{\text{reg}}$ (1) principally decreases $z_{\text{base}}$ of the model MCID (also yielding lower mean pressure because CO$_2$ ice stability is more easily reached at lower elevation; Fig. 2B), (2) modestly increases the mass of the model MCID, and (3) has a minor effect on the mass ratios of the CO$_2$ layers in the model MCID. Models with $z_{\text{reg}} \approx 20$ m yield $z_{\text{base}} < 3$ km—below the lowest observed basal elevation of the MCID [8]—and $z_{\text{reg}} > 60$ m yield $z_{\text{base}} < 1$ km, below even the base of the South Polar Layered Deposits on which the MCID sits [9]. Additionally, values of $z_{\text{reg}} > 100$ m yield model MCID masses $>50\%$ greater than the observed MCID.

In Scenario 2, with $z_{\text{base}}$ fixed to its current observed mean $\sim 4$ km elevation [8], the MCID can totally ablate. If $z_{\text{reg}}$ is sufficiently thick, then at high $\varepsilon$ the low latitude regolith can adsorb enough CO$_2$ such that the cap-atmosphere system has insufficient mass for the atmospheric pressure at $z_{\text{base}}$ to sustain CO$_2$ ice at the temperature set by radiative balance with the insolation. The higher the value of $z_{\text{reg}}$, the lower the $\varepsilon$ at which the model MCID totally ablates. In models with $z_{\text{reg}} > 100$ m, the $\varepsilon$ at which the model MCID totally ablates occurs below $30^\circ$, so the MCID does not survive the 386 kyr $\varepsilon$ maximum, so no CO$_2$ survives beneath the H$_2$O lag horizon and only two (rather than three) CO$_2$ layers are predicted for the present day. Models with $z_{\text{reg}} < 100$ m retain a third (bottom) layer, but the mass of the bottom layer decreases with increasing $z_{\text{reg}}$ because less of the MCID remains at the 386 kyr $\varepsilon$ maximum. Additionally, larger values of $z_{\text{reg}}$ amplify the CO$_2$ mass flux between the regolith and MCID as a function of $\varepsilon$, yielding thicker CO$_2$ layers at the top of the deposit for larger $z_{\text{reg}}$.

**Conclusions:** The MCID (i) mass, (ii) stratigraphy, and (iii) basal elevation $z_{\text{base}}$ provide three observational constraints on Mars’ total exchangeable CO$_2$. Our model best agrees with the observed MCID characteristics for values of $z_{\text{reg}} < 100$ m—regardless of whether $z_{\text{base}}$ is fixed or adjusts—with a preference for $z_{\text{reg}} < 20$ m, which best fits a scenario in which $z_{\text{base}}$ adjusts [5]. This corresponds to a total exchangeable CO$_2$ reservoir of $< 33$ mbar (preferred $< 18$ mbar), similar to or smaller than the 30–40 mbar [7] and 65–514 mbar [2] previously suggested prior to the discovery of the MCID.

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**Fig. 2.** A. Mars’ obliquity history [4]. B. Atmospheric mass. C. MCID mass. D. Adsorbed CO$_2$ mass in regolith. Colors: $z_{\text{reg}} = 0, 0.1, 0.5, 1, 5, 10, 20$ (cyan), 40 (gold), 60 (dark teal), 80 (pink), 100 (brown), 200 (purple), 400 (red), 600 (green), 800 (orange), and 1000 m (blue). Runs with $z_{\text{reg}} < 20$ m are not easily separated at this plot resolution.