CO_2 Glaciers on the South Polar Layered Deposits of Mars. I. B. Smith[1,2] (ibsmith@yorku.ca); N. Schlegel[3]; E. Larour[3]; I. Isola[1]; P. Buhler[2]; N. E. Putzig[2]; R. Greve[4]; [1]York University, Toronto, Ontario, [2]Planetary Science Institute, Denver, Co; [3]Jet Propulsion Laboratory, Pasadena, Ca; [4]Hokkaido University, Sapporo, Japan

Introduction: Data from the Shallow Radar (SHARAD) instrument on MRO were used to determine that massive CO_2 deposits are buried beneath the surface of the SPRC [1] (Figure 1). Using geophysical arguments and layer geometry, [1-3] determined that CO_2 ice up to 1000 m thick are deposited in the spiral depressions of the SPLD. A total of 16,500 km^3 is likely stored there, having been deposited in three distinct periods [3].

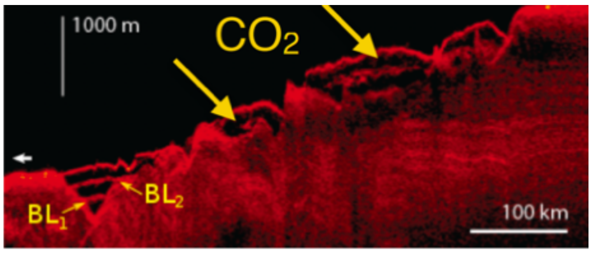


Figure 1: *SHARAD observation showing CO_2 deposits up to 1 km thick at the south pole of Mars.*

Some modeling work has been able to predict climatic periods that make CO2 deposits at the south pole, but they cannot reproduce the observed three-dimensional distribution (Figure 2a), leaving a mystery [4, 5]

Laboratory experiments have determined that CO_2 ice can be much less viscous than water ice (with a stress exponent, n, of 8 rather than 3) at temperatures relevant to the south pole of Mars, 150 to 170 K [6]. This is strong indication that the thick CO_2 ice deposits flow as glaciers, and we test that hypothesis here.

Model Input: We use geometry of the current surface [3] and mapping by the SHARAD instrument [3] to provide geometric inputs that feed the model. Additionally, we use physical constants of CO_2 ice (Table 1), including the newly obtained flow law parameters [6], as inputs into a three dimensional glacial model. For our simulations, the surface temperature is locked at ~150 K (the sublimation temperature of CO_2 at Mars' pressure), and a very high friction coefficient was chosen to prevent basal sliding because CO_2 glaciers are dry based.

Modeling: To model these deposits, we employ the Ice-sheet and Sea-level System Model (ISSM) [8]. ISSM successfully simulates glaciers and ice sheets on Earth and can be adapted to Mars by changing parameters for the planet (e.g. geothermal flux, gravity) and for the type of ice (eg. rheological parameters, thermal conductivity) (Table 1). Full thermal conduction and advection is included with the model. This provides a foundation to run a steady state simulation that calculates the vertical temperature profile of the deposits and then all of the stresses and strains of the present-day features. We choose a Glen's law behavior using this equation and input from [6]:

$$\dot{\varepsilon} = A\sigma^n e^{(-Q/RT)}$$

Where $\varepsilon^{\cdot}$ is strain rate, A is a material constant (A= $10^{13.4}$ MPa^{-n}/s), Q is the activation energy (Q = 68.2 kJ/mol), R is the gas constant (R_{gas} = 8.3144598 J/K/mol), and n is the laboratory derived stress exponent (n=8).

To evolve the CO_2 deposits, we begin with the basal topography from [3] and no ice. During a forward run (transient) that begins at 600 ka we supply the surface mass balance (SMB) of ice each year as modeled by [4] and deposit it equally over the accumulation zone.

To test the accumulation zone influence, we vary the size of the domain and find the ratio of SMB that provides an equal total SMB over the varying areas. Additionally, we varied the geothermal flux (10 and 25 mW/m^2) to see if that affected the outcome.

Results: We find that during 600 kyrs of alternating accumulation and sublimation, the ice accumulates everywhere and flows fastest on the higher slope regions. These regions point into basins, where the ice accumulates to thicknesses of 100s of meters. During sublimation periods corresponding to higher obliquity,

Table 1: Model Inputs.

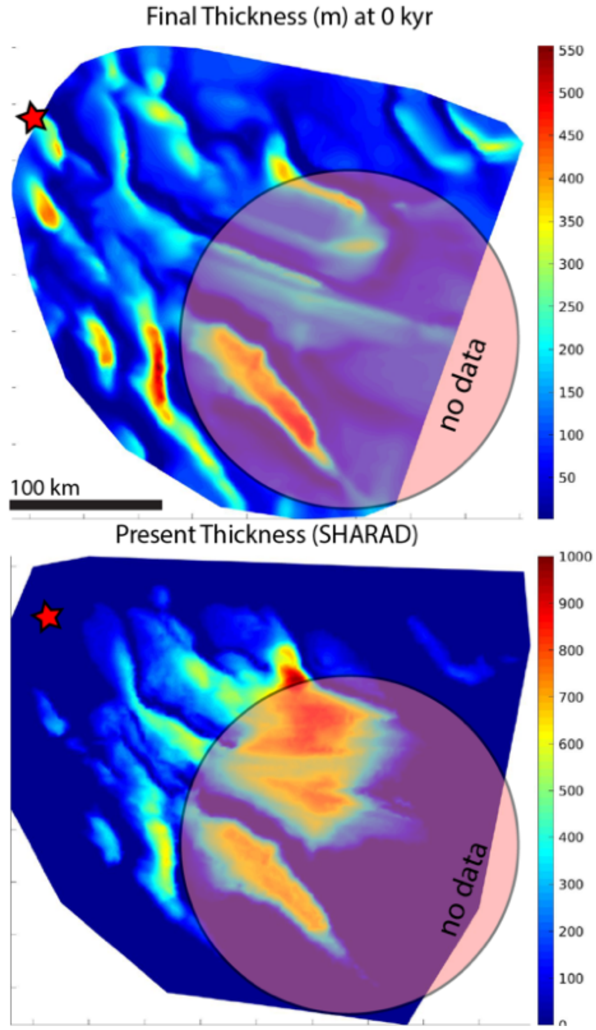
Heat Capacity CO_2	700 J/K
Thermal Conductivity	0.4 W/m/K
Geothermal Flux	0.025 W/m^2
Current Surface Temp	150 K

all of the ice in thin regions moves to the atmosphere; however the pooled ice remains, enduring until the following accumulation period. Over the full run, there are multiple accumulation periods that aggregate to make deposits that rival the thickness of our SHARAD measurements (Figure 1).

Discussion: After 600 kyr of uniform deposition, our forward, transient simulations result in surface topography and glacier thickness similar to that observed with radar, within a factor of 2, supporting the hypothesis that the CO_2 deposits reached their present state in large part because of flow and not preferential deposition (Fig 2). An important component of remaining stable even during periods of sublimation is that the ice has to pool in basins, where the thicker column (up to 500 m) can withstand several meters of sublimation that would not persist if the ice didn't pool (Fig 3).

The resulting volume of ice matches that measured by SHARAD, providing a quick check of the hypothesis, but the real value comes with the predicted stratigraphy. Our model, following the accumulation and

Figure 2: *Model thickness (a) against present thickness (b) for a uniform accumulation pattern over the entire region. Ice flowed into the topographic basins, where it persisted during sublimation periods. The final volume is a near perfect match to the measured, even if the final distribution is not exactly the same. "No data" region is where neither SHARAD nor MOLA have data.*



sublimation patterns of [4], would generate three distinct units of CO_2 ice, separated by a lag of H_2O, that resembles the true stratigraphy as mapped by [3], supplying an excellent test of CO_2 flow.

Our modeling results that used various accumulation areas finds that larger areas result in a decrease in correspondence between the model and SHARAD observations. This tells us that the accumulation zone isn't much larger than the current south polar residual cap (SPRC), or there would be ice in more locations, supporting the conclusions of [9]. Additionally, in our modeling experiments that varied geothermal flux, lower values resulted in a slower moving ice; however, in both cases the ice was fast enough to reach the three-dimensional distribution that we observe.

Future Work: Our current modeling results match the gross stratigraphy, volume, and distribution of ice, giving a compelling story of flow to first order. Several details will complete the study, starting with including the stratification and alternating flow laws of H_2O and CO_2 [10]. We also intend to determine the influence of surface crevasses (as mapped by [5]on flow velocity.

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References: [1] Phillips, R. J. et al. (2011) *Science*, *332*(6031), 838–841. [2] Bierson, C. J. *et al.* (2016) *GRL*, *43*(9), 4172–4179. [3] Putzig et al., (2018) Icarus 308, 138–147. [4] Buhler, P.B., *et al.* (2019). *Nat Astron* 1–8 [5] Manning, C. et al., (2019) *Icarus* (317) 507-517 [6] Cross, A.J., et al (2020). *GRL* 47 [7] Smith et al., (2001) JGR 106. [8] Larour, E., *et al.* (2012) *JGR Earth Surf.*, *117*(F1), F01022. [9] Colaprete, A. *et al.* (2005). *Nature* 435, 184–188. [10] Fard, K. et al. (2022) LPSC 53

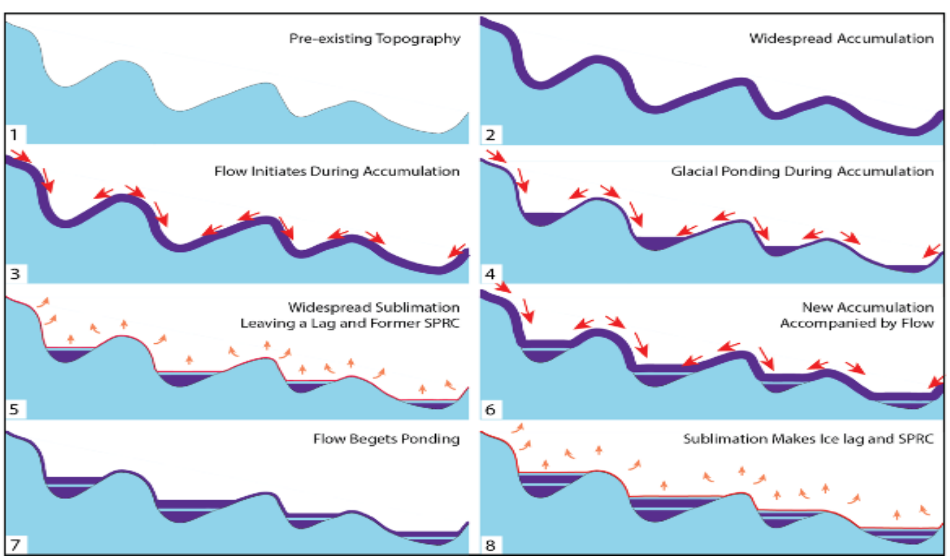

Figure 3: *Heuristic model of the deposition of CO2 ice on the south polar layered deposits of Mars during a cyclical pattern of accumulation and sublimation. The key is that ice accumulated on steep slopes flows into basins where it pools and becomes thicker enough to withstand warmer periods with high sublimation. Between each cycle, a lag layer of H_2O forms [11], leaving stratigraphy by which we can test this hypothesis.*