ENTOMBR: AN ENERGY BALANCE MODEL FOR EXPLORING THE SEQUESTRATION OF THE MASSIVE MARTIAN BURIED CO_2 ICE DEPOSIT.
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Introduction: Large variations in Mars' obliquity over secular timescales drive drastic climate change [1]. Different obliquity-driven insolation conditions cause the atmosphere to collapse and reinflate and surface volatile reservoirs to grow, shrink, and migrate between the poles and the equator. A particularly striking expression of this climate variability is the recently discovered massive reservoir of CO_2 ice entombed within the south polar H_2O ice cap that has a mass equivalent to the modern atmosphere [2, 3]. Although models have shown that large deposits of CO_2 build up during periods of low obliquity, the critical question of how the CO_2 becomes entombed and stabilized under periods of high obliquity remains unresolved [3]. Here we introduce and perform initial validation of EnTOMBR (Energy Transfer On Mars Balancing Routine), an energy balance model designed for exploring the sequestration of the buried CO_2 deposit in the style of Leighton & Murray [4]. Model development is ongoing and additional findings will be presented at the conference.

Methods: EnTOMBR has a grid of latitudinal bands with 2 degree binning from 40 degrees latitude to the poles and 5 degree binning between 40 degrees and the equator, similar to Wood & Paige [5]. For model validation, we vary six parameters: ground thermal conductivity k, frost emissivity ϵ_{CO_2}, and frost albedo A_{CO_2} in each hemisphere. The ground albedo and emissivity are kept constant (0.25 and 0.95, respectively) and the product of the ground heat capacity and density is held at 10^6 in mks units, as in [5]. The total CO_2 budget is 3.05 x 10^{16} kg. The pressure (and therefore CO_2 frost point) at each time step in each band is determined based its average Mars Orbiter Laser Altimeter elevation.

Energy balance is calculated at each time step according to:

$$(1)\quad m_f c_p \frac{dT}{dt} = S_0(1-A) - \epsilon\sigma_B T^4 + L\frac{dm_f}{dT} + k\frac{dT}{dz}$$

Here m_f is frost mass, c_p is CO_2 heat capacity, T is temperature, S_0 is solar normal flux, A is albedo, ϵ is emissivity, σ_B is the Boltzmann constant, L is latent heat of sublimation, k is thermal conductivity, and z is depth. For initial model validation (Fig. 1) presented here, S_0 is the incoming flux at the top of the atmosphere (i.e. atmospheric scattering is neglected). However, atmospheric effects can be enabled in EnTOMBR and are implemented using a two stream Delta-Eddington approximation with a reflective surface boundary condition. Atmospheric effects are validated by reproducing the insolation function published by Pilorget et al. [6] (Fig. 2).

EnTOMBR models subsurface heat transfer using a vertical grid with 35 cells that enlarge exponentially with depth down to three annual skin depths. The one-dimensional heat conduction equation, with temperature-independent thermal diffusivity:

$$(2)\quad \frac{dT}{dt} = \frac{k}{\rho c}\frac{d^2T}{dz^2}$$

is solved numerically at each time step. The lower boundary condition is set to match the martian geotherm [cf. 6]. EnTOMBR adaptively scales the subsurface grid spacing depending on the thermal conductivity to maximize resolution while maintaining computational stability (Fig. 3).

During validation (Fig. 1), the model is evaluated 35 times per sol (every ~40 min) in order to capture the diurnal thermal cycle and run for 4 years to ensure convergence. Even though sub-diurnal resolution increases runtime, sub-diurnal resolution is needed because emitted power is proportional to T^4 and so emitted power is underestimated if diurnal-averaged temperature is used.

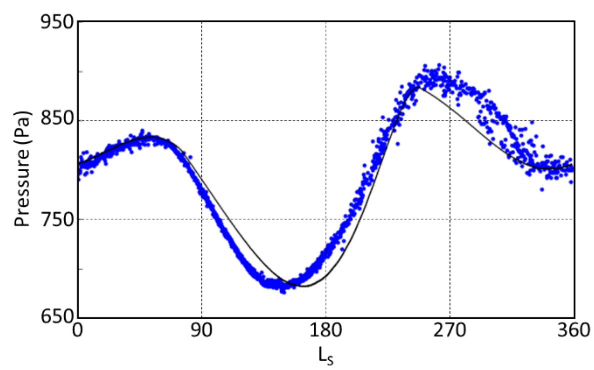

Fig 1. EnTOMBR model output (black curve) compared to day-average Viking 1 lander pressure observations (blue dots). The model curve is scaled to match the elevation of the Viking 1 lander. Dust storms and incomplete daily coverage in southern summer (around L_S 270) are likely responsible for the higher Viking Lander pressure observations in that season as compared to the EnTOMBR output, as also seen by [5].

Results: We validate EnTOMBR's atmospheric parameterization (Fig. 2), subsurface heat transfer routine (Fig. 3), and ability to reproduce the martian seasonal pressure curve (Fig. 1). The pressure curve is best reproduced using k = 0.15 W m^{-1} K^{-1}, ϵ_{CO_2} = 0.8, and A_{CO_2} =

0.5 in the south and k = 2 W m^{-1} K^{-1}, ϵ_{CO_2} = 1, and A_{CO_2} = 0.59 in the north.

Discussion: EnTOMBR is similar in form to the model of Wood and Paige [5], but also includes topography and atmospheric scattering effects that are not included in [5]. EnTOMBR successfully reproduces the Viking 1 Lander seasonal pressure observation, except for an offset near southern spring (Fig. 2, L_S 180). This offset may be due to time-varying physical properties, the non-inclusion of atmospheric scattering effects, or regional second-order effects [e.g. 7]. Additional model results including exploration of these effects, the apparent need for dichotomous k in each hemisphere, and the inclusion of H_2O deposition and secular timescale simulations will be presented at the conference.

References: [1] Laskar, J. et al. (2004) *Icarus 170*, 343-364 [2] Phillips, R. et al. (2011) *Science 332*, 838-841 [3] Bierson, C. et al. (2016) *GRL 43*, 4172-4179 [4] Leighton, R. & Murray, B. (1966) *Science 153*, 136-144 [5] Wood, S. & Paige, D. (1992) *Icarus 99*, 1-14 [6] Pilorget, C. et al. (2011) *Icarus 213*, 131-149 [7] Martinez, G. et al. (2017) *Space Sci Rev 212*, 295–338

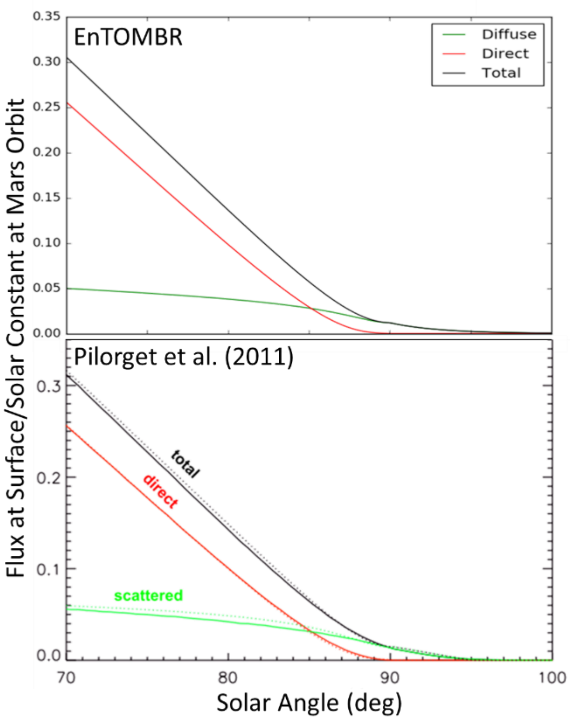

Fig 2. Validation of two stream Delta-Eddington atmospheric scattering model. Top panel is output from EnTOMBR, bottom is from Pilorget et al. [6]. Plots show the fraction of flux that reaches the surface as compared to the solar constant at Mars' orbit as a function of solar zenith angle. Red line is the direct component, green is the scattered component, and black is the total flux.

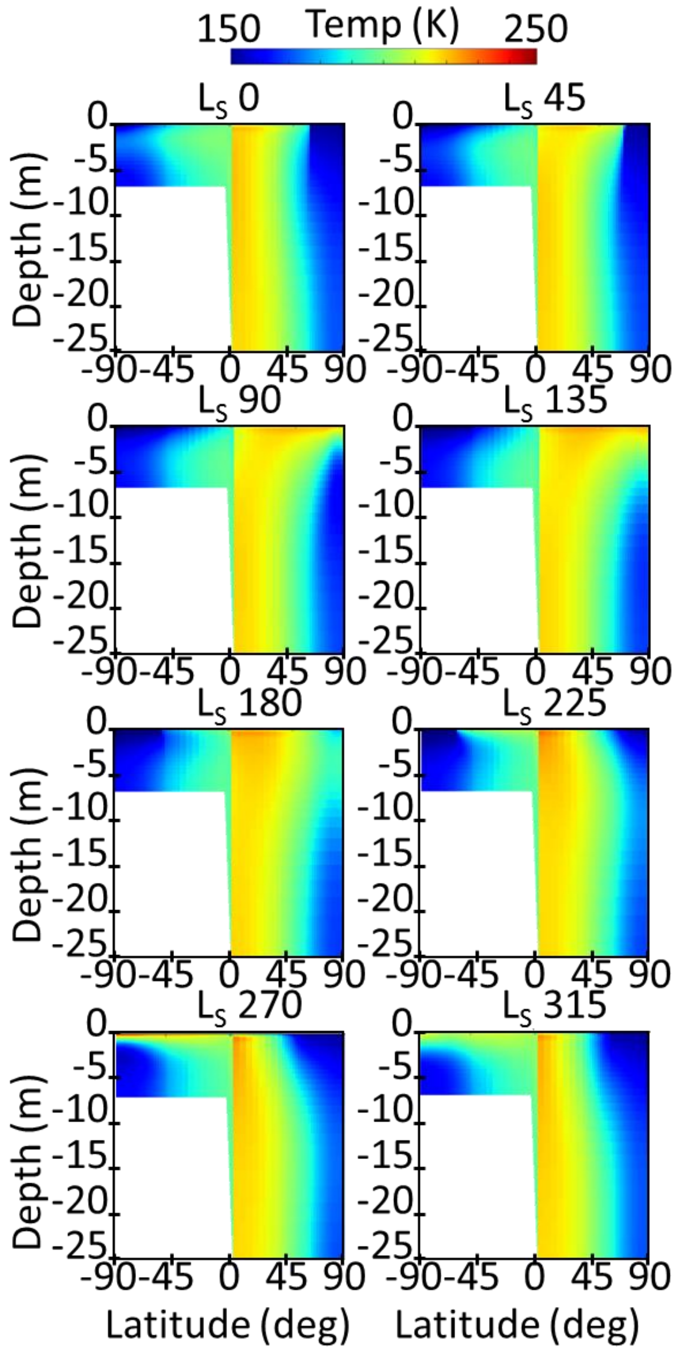

Fig 3. Temperature evolution of the subsurface over a martian year. Each panel shows the temperature profile at midnight every 1/8th of a year and is labelled with its solar longitude (L_S 0 = N spring). The temperature dichotomy and difference in grid depth across the equator is due to differing model subsurface thermal conductivity in each hemisphere.