Formation of the Martian Polar Layered Deposits: Quantifying Polar Water Ice and Dust Deposition in Present and Past Orbital Epochs with the NASA Ames Mars General Circulation Model

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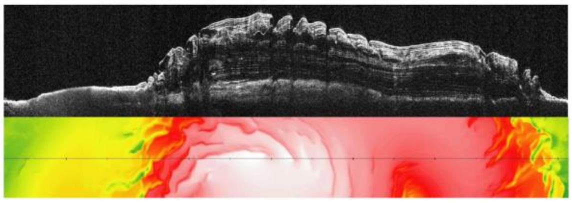
Introduction:

Present in Mars' North and South polar regions are the Polar Layered Deposits (PLD), 2-3 km-thick deposits comprised of alternating layers of water ice and dust in variable mixtures [2]. The stratification of the PLD and the lateral continuity of individual layers over thousands of kilometers implies a sedimentary origin controlled by global-scale processes – likely the gradual accumulation of atmospherically-transported and deposited water ice and dust over the past several millions of years, with average accumulation rates estimated between 10^{-3} – 0.1 cm/yr [2]. Stratigraphic trends are non-random, but rather quasi-periodic, which is interpreted to reflect orbit/precession cycle-forced, climate-driven variation in the relative deposition rates of water ice and dust over the deposits' inferred ~5-10 Myr formation history [2]. Morphological asymmetry in the PLD implies surface accumulation also varied spatially.

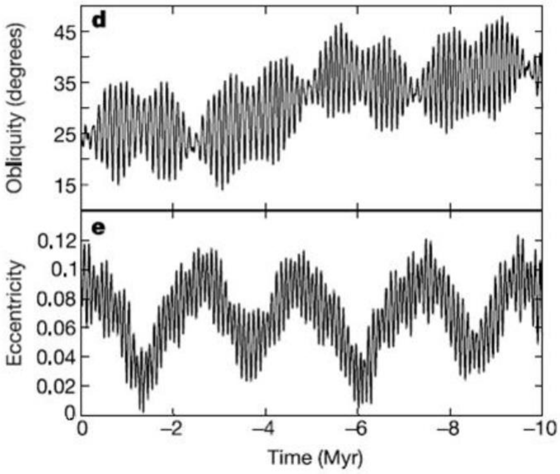
Figure 1: SHARAD cross-section through the north PLD showing vertical variation in radar reflectivity, interpreted as variation in relative dust content



Motivation:

If PLD stratigraphy reflects orbit/precession cycle-modulated climatic variability, then the PLD contain an extensive record of Mars' relatively recent past climate. Reading this record, however, requires 1) Determining how structures and layer properties reflect historical climate conditions and 2) Determining the absolute ages of structures and layers to establish a chronology that correlates features and stratigraphy with geological time. To do so requires retracing the depositional history of water ice and dust, identifying and characterizing the climate forcing mechanisms which determine dust content of annually deposited material, and determining how observed layer properties (albedo, reflectance, etc.) correlate with physical layer properties (composition, density, etc.). Previous modelling investigations quantified the effect of orbital configuration on polar rates of net annual deposition, but generally treated water ice and dust deposition as separate and non-interactive processes. The dust and water cycles are in reality physically coupled by water ice nucleation upon dust (airborne ice crystal condenses onto a suspended dust particle). Models further suggest that PLD growth is enhanced by dust lag formation [2] (ice sublimation produces veneer of surface dust that impedes further sublimation), and dust rich layers may be formed during episodes of 1) high relative dust deposition rates or 2) net ice erosion (as dust lags) [1]. A more complete modeling investigation of PLD formation history therefore requires 1) contemporaneous deposition of water ice and dust and 2) consideration of particle nucleation and dust/ice interaction on the surface. The Ames GCM provides both capabilities, and its 5^{o}x6^{o} latitude-longitude grid additionally enables spatial trends in deposition to be resolved throughout the PLD.

Figure 2: Obliquity and Eccentricity from 10 Ma – present (Laskar 2002) [2]



Methods:

Models. With the Ames GCM, a set of models will be configured with combinations of obliquity eccentricity, and longitude of perihelion that incrementally span minimum and maximum values in those parameters from 10 Ma-present, as well as models with 'present', 'reverse perihelion', and other historical configurations investigated previously by

[3, 4, 5]. All models utilize an identical interactive dust lifting scheme dependent on three parameters – wind stress lifting efficiency threshold, and dust devil lifting efficiency, drawing from an infinite surface dust and water ice reservoir (water is sourced from the North residual cap). Suspended dust is allowed to radiatively interact with the atmosphere.

Quantifying Deposition in Each Configuration. In a given configuration, over the GCM's 2D surface grid, layers will be accumulated in ~5 sol increments over at least two consecutive years to quantify seasonal and annual changes in deposit thickness and deposit dust content. These quantifications will directly build on the results of previous GCM-based investigations. Additionally, comparison of seasonal layering trends with GCM-calculated insolation, temperature, opacity, and wind fields could link depositional behavior to climate conditions and forcing mechanisms.

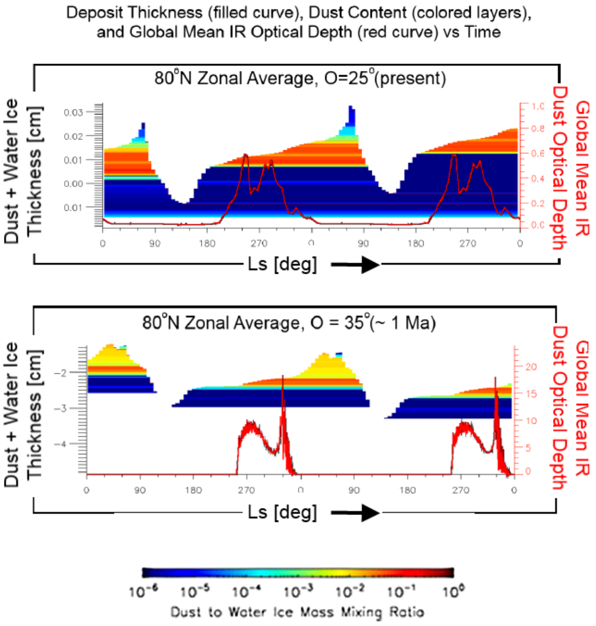
Modelling PLD Formation History. With the results described above, a parameter space will be constructed in which annual deposition rate and annual deposit dust content may be interpolated for an arbitrary orbit configuration. Mars' orbital solution will be sampled in ~10^5 time intervals from 10 Ma-present, quantities interpolated at each interval, and a time-marching integrating model applied to simulate long-term deposit formation while retaining a chronological record of spatial and vertical structure.

Preliminary Results:

Effect of Obliquity. Initial simulations have investigated seasonal and annual changes in water ice and dust deposition in the North PLD resulting solely from variations in obliquity.

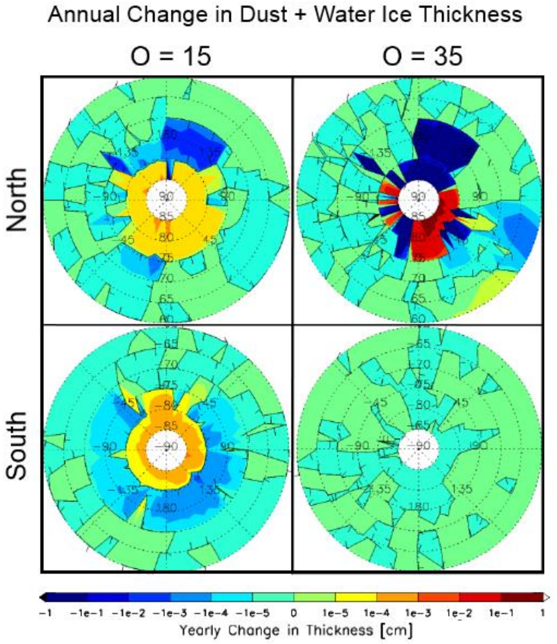
Seasonal/Interannual variability and climate forcing. Under all obliquity scenarios, the dust-to-ice mixing ratio of deposited material and total deposit thickness varies seasonally over model years, with inter-annual repeatability in this seasonal behavior. The deposition of the most dust-rich layers loosely coincides in time with southern hemisphere summer peak in global mean IR dust opacity, corresponding to local winter in the north. At low obliquity (25°), averaged over the 80° N latitude band [Fig. 4, top], a gradual increase in mean deposit thickness is observed over multi-year timescales, with a net accumulation of ~0.01 mm/year. At high obliquity (35°) [Fig. 4, bottom], however, a gradually decreasing trend is observed, with net removal of ~0.1 cm/year. Seasonal accumulation begins in the late summer season, prior to the onset of CO2 ice accumulation (CO2 ice thickness not shown). Deposit thickness increases until shortly before the following summer solstice, when water ice thickness rapidly declines in response to the sublimation and total depletion of surface CO2 ice. In net annual accumulation scenarios [Fig 5., top], a subset of deposited layers survive summer erosion. Future analyses will quantify the mean dust-to-ice mass mixing ratio of the layers comprising the annual residual for each configuration. In net annual removal scenarios [Fig. 5, bottom], no deposited layers survive summer erosion. Significant ice sublimation is expected to not only excavate previously deposited material, but also produce a thin lag of surface dust with a mass mixing ratio of 1 (pure dust), after this capability is implemented into the model.

Figure 4:



Net annual deposition and spatial variability. Quantifying the annual change in deposit thickness at all northern and southern grid points [Fig. 4], considerable spatial variability in depositional behavior is apparent in all configurations, but net polar accumulation is generally favored at low obliquity (15°) [Fig. 5, left panels] while net removal is favored at high obliquity (35°) [Fig. 5, right panels]. A set of grid points from 80° poleward exhibit net accumulation regardless of obliquity, with accumulation rates enhanced at increased obliquity. Presently, these models incorporate initial surface properties characteristic of the polar caps at present. Since these grid points coincide with regions of high initial thermal inertia and albedo (not shown), depositional behavior appears to be strongly biased by initially-prescribed surface properties.

Figure 4: Polar plots of change in deposit thickness between consecutive summers at low and high obliquity in the north and south



Comparison to Observation and Implications

Chronology. Pattern matching between modelled stratigraphy and observed stratigraphy would provide a direct PLD chronology from the modelled time record. Wavelet analysis of modelled columns may reveal dominant orbital cycles recorded in layering, providing ages of layer packets.

Composition. Mean dust-to-ice mixing ratios will provide estimates of PLD dust content vs depth and bulk dust content. Comparison to visible and radar imagery may relate dust content to albedo and radar reflectivity.

Past Climate. Correlating seasonal depositional behavior with GCM temperature, opacity, and wind fields may reveal atmospheric conditions which force, and are thus recorded, in layering.

Age. Integrated ice reservoir history implies deposit age (when did the poles begin accumulating?)

Morphology. Spatial variation in the model may reveal ages and evolution of large-scale morphological features, and the climatic conditions which forced formation and subsequent growth of those features.

Ongoing Work and Future Considerations:

Model Tuning. Current efforts are focused on tuning the current version of the NASA Ames GCM (v2.3) to reproduce present pressure, temperature, dust, and water cycles, as measured and derived from multi-year observations by the Thermal Emission Spectrometer (TES) on board Mars Global Surveyor (MGS).

Initial conditions. The Ames GCM is configured to simulate present surface and climate conditions by default, with modern ice cap topography, albedo, and thermal inertia initially prescribed. Preliminary results reveal a resultant bias on the distribution and magnitude of water ice and dust deposition in the polar regions. Past configurations will require different initial and unbiased prescriptions. Design of appropriate initial surface ice reservoirs for different configurations will draw from previous modelling results, which investigated the effect of orbital configuration on the global stability and distribution of surface ice [3, 4].

Dust-Water ice interaction. The Ames GCM’s microphysics routine simulates water ice nucleation upon dust, affecting the sedimentary cycle of both tracers and enabling their co-deposition. The presence of CO2 on the surface realistically inhibits dust lifting, but the code must be modified to extend this capability to surface water ice. The Ames GCM will also be modified to account for the formation and effect of dust lags, a process suspected to have influenced layer formation and ice evolution, particularly during high-obliquity epochs conducive to sublimation of polar water ice.

References:

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