DENSITY VARIATIONS OF SEASONAL CO_2 AT THE PHOENIX LANDING SITE, MARS. C. Mount[1,2] and T. N. Titus[2], [1]Northern Arizona University (cpm42@nau.edu), [2]U.S. Geological Survey (ttitus@usgs.gov).

Introduction: Earth and Mars have nearly the same axial tilt, so seasons on these two bodies progress in a similar manner. During fall and winter on Mars, the primarily CO_2 atmosphere (~95% by volume [1,2]) condenses out onto the poles as ice. Approximately 25% of the entire Martian atmosphere condenses, and then sublimes in the spring, making this cycle a dominant driver in the global climate [1,2]. Because the water and dust cycles are coupled to this CO_2 cycle, we must examine seasonal CO_2 processes to understand the global (seasonal) distribution of H_2O on Mars. The density of the ice may indicate whether it condensed in the atmosphere and precipitated as "snow" or condensed directly onto the surface as "frost" [2-4]. Variations in density may be controlled by geographic location and surface morphology. The distribution and variations in densities of seasonal deposits on the Martian poles gives us insight to the planet's volatile inventories. Here we analyze density variations over time at the Phoenix Landing Site using observational data and energy balance techniques.

Techniques: We calculate the bulk density of surface CO_2 ice by dividing the column mass abundance (the mass of CO_2 per unit area) by the depth of the ice cap at a given location [5,6].

Ice Depth Calculation. We use seasonal rock shadow measurements from High Resolution Imaging Science Experiment (HiRISE) images to estimate ice depth [4]. The length of a rock's shadow is related to its height through the solar incidence angle and the slope of the ground.

From differences in the height of a rock measured in icy vs. ice-free images, we estimate the depth of surface ice at the time of the icy observation [4]. Averaging over many rocks in a region yields the ice depth for that region. This technique yields minimums for ice depth and therefore maximums for density.

Crowning and Moating. Thermal properties of rocks may play an important role in observed ice depths [4]. Crowns of ice may form on the tops of rocks with insufficient heat capacity to inhibit ice condensation, and may cause an artificial increase in shadow length. This increases the apparent height of a rock and thus decreases the apparent surface ice depth. Additionally, moats may form around rocks with sufficient heat capacity to sublime ice as it is deposited. Moating will also artificially increase the shadow lengths (decreasing apparent surface ice depth). We correct for these effects in our depth-estimation technique.

CO_2 Ice Column Abundance Calculation. We balance incoming solar flux with outgoing thermal radiation from Thermal Emission Spectrometer (TES) observations to calculate the column mass abundance. TES thermal bolometer atmospheric albedo and temperature observations are a good proxy to the surface bond albedo and effective surface temperature [5,6]. These parameters are needed to balance the incoming and outgoing flux.

Mars' atmosphere is tenuous so we assume homogeneous radiance from the surface to the top of the atmosphere, no lateral diffusion of heat, and that any excess heat goes into subliming surface ice in our flux balance [5,6]. Using a Monte Carlo model, we integrate the net flux until reaching the time where **C**ap **R**ecession **O**bservations indicate **C**O_2 has **U**ltimately **S**ublimed (the CROCUS date) [5] to obtain the column mass abundance.

Results: We estimate ice depth at a control area (hereafter referred to as Control) and at the Phoenix Landing Site (hereafter referred to as Phoenix). We analyze bulk density only at Phoenix. Control has two post-CROCUS, springtime images, and measuring these frames allows us to test the accuracy of our Crown-Moat (CM) correction technique. Because there is little to no ice in post-CROCUS images, any non-zero depth estimates in these frames are likely due to noise. Ice-free measurements in the control area indicate our CM correction over-estimates average ice depths by 0.05 – 0.10 m. We attribute this "noise" to sub-pixel mixing, i.e., the size of rocks is small compared to ~0.25 m HiRISE pixel scale.

We compare our ice depths with those of [4], who calculated ice depths at Phoenix using a version of this technique that did not account for surface slope or rock thermal effects (i.e., crowns and moats). Our estimates for ice depth are much larger than those estimated by [4], sometimes exceeding double their calculated depths. This implies that dynamic heating properties of rocks and variations in surface slope significantly alter depth estimates.

To further validate our technique, we generate a simple model for ice sublimation. Two cases are explored, one for crowning and one for moating. We find that with each model the ice depth is underestimated, but is still consistent to the estimated values to within 3σ. This agrees with our claim that estimates yield a minimum to the ice depth and maximum to the density.

Regionally averaged ice depth at Phoenix varies seasonally from ~0.40 m in early spring to ~0.14 m shortly before CROCUS. Noise from subpixel mixing and "patchiness" of surface ice may account for the relatively large ice depth in late spring. Figure 1 illustrates density over time for one sub-region at Phoenix. The regionally averaged density is also plotted in Figure 1. Density estimates are consistent across all five sub-regions to within 1σ. All sub-regions suggest a nearly constant sublimation rate and a slight de-densification throughout the sublimation period. At L_s ~11° the regionally averaged density is ~400 $kg \cdot m^{-3}$. This reduces to ~100 $kg \cdot m^{-3}$ by L_s ~37°. Slab CO_2 deposited by direct condensation would yield densities of approximately 1600 $kg \cdot m^{-3}$. The low density at Phoenix suggests atmospheric deposition, i.e., CO_2 snow [3,6].

We normalize the observed densities in two ways. Assuming sublimation begins at the vernal equinox (L_s= 0°), we weight the initial density in the data set with respect to the CROCUS date at that location. In this way we normalize the density to the percentage of the sublimation season that has passed before our first measurement. We also time average the density curves using a Riemann sum over time. This discrete integral has a normalization coefficient that accounts for the season in which a measurement was taken relative to the CROCUS date. We find that the normalized initial density indicates atmospheric condensation as the primary depositional mechanism at Phoenix. The time-averaged density at Phoenix is consistent with numerous studies of northern seasonal deposits on Mars [7-12] that suggest low-density deposits are widespread across the Northern Seasonal Cap.

CO_2 snow is thought to be relatively fine-grained [2,3]. Thus, we should expect atmospheric deposits to be visibly bright [3-5]. This is because the mean free path of light is small for these deposits. [13] and [14] showed that fine-grains will anneal into slab over a short time period. As the snow sinters, the path length of light will increase and the ice will become darker over the sublimation season. It is thought that this is accompanied by densification of the ice [13].

Table 1 shows regional red-band albedo estimates during sublimation. These were calculated from HiRISE I/F radiances using a Lommel-Seeliger photometric function. Early in the sublimation period, the ice is homogeneously bright. As sublimation progresses, the ice heterogeneously brightens then subsequently darkens, as would be expected for snow annealing into slab. However, Figure 1 indicates de-densification over sublimation. We propose that as the ice sinters, it leaves gaseous vesicles in the ice sheet. Since the surrounding ice brings the CO_2 in the vesicles to thermal equilibrium, the gas will recondense leaving the vesicle in vacuum and consolidating grains into larger particles [14]. This will cause the ice to preferentially forward scatter light, making it darker. As the ice receives more solar energy it fractures, reducing the density.

Summary and Conclusion: The seasonal CO_2 cycle is the dominant driver of the global climate on Mars. Time dependent density variations of seasonal CO_2 ice constrain this cycle's behavior. Bulk density was analyzed at the Phoenix Landing Site. We used seasonal rock shadow measurements from HiRISE images to estimate surface ice depths. We used TES thermal bolometer albedo and temperature observations to calculate column mass abundance. The effects of crowning and moating were corrected for and we found these to significantly alter ice depth estimates. Calibration against a control region indicated that our ice depths were overestimated. We attributed this overestimate to be "noise" from subpixel mixing. Calibration against a simple sublimation model indicated our technique underestimated ice depths. Seasonally normalized initial and time-averaged densities suggested that atmospheric condensation was the primary deposition mechanism at Phoenix. Surface brightness observations, when combined with CO_2 ice density estimates, indicated that these snow-like deposits sintered into highly porous slab ice that fractured throughout sublimation.

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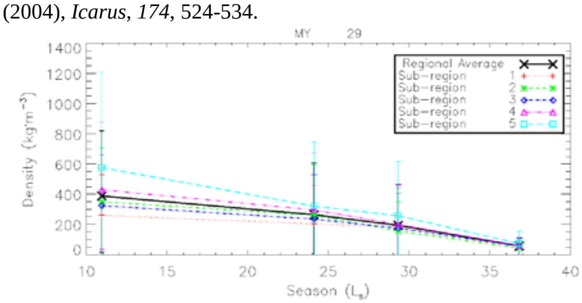

Figure 1. Ice depth vs. season (top) and density vs. season (bottom). The regionally averaged ice depth is initially ~0.40 m and reduces nearly linearly throughout sublimation. The density of ice decreases throughout sublimation, beginning relatively low and ending near zero.

HiRISE Frame	Season (L_s)	Albedo	Error
PSP_001893_2545_RED*	154	0.294	±0.088
PSP_006706_2485_RED	11	0.566	±0.170
PSP_007062_2485_RED	24	0.702	±0.211
PSP_007207_2485_RED	29	0.627	±0.188
PSP_007418_2485_RED	37	0.536	±0.161

Table 1. Red-band (0.55-0.85 µm) albedos calculated from HiRISE I/F radiances. * Indicates reference (ice-free) frame. The bare soil image has an albedo consistent with a dust covered surface. The early-spring albedo is relatively high, indicating the presence of ice. The ice brightens then subsequently darkens. Albedo measurements indicate the presence of ice as late as L_s ~37°.