PRELIMINARY THICKNESS MEASUREMENTS OF THE SEASONAL POLAR CARBON DIOXIDE FROST ON MARS.

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Introduction:

The exchange of carbon dioxide between the atmosphere and the polar caps on Mars creates a seasonal cycle of growth and retreat of the polar caps. CO_2, the major component of the Martian atmosphere, condenses in the polar regions of the planet during the winter seasons, precipitating as CO_2 frost. It then sublimates during the spring and summer seasons in response to solar radiation. Nearly 30% of the atmosphere takes part in this seasonal process [1]. While the northern seasonal CO_2 frost appears to dissipate completely, the south pole has a thin, permanent cover of dry ice over the residual cap. The underlying residual caps are believed to contain large quantities of water ice. We have attempted here to quantize the time-dependence, spatial extent, and thickness of the polar carbon dioxide frost through the use of gamma-ray data measured by the Gamma-Ray Spectrometer (GRS) instrument suite on Mars Odyssey. After launch on April 7, 2001, Mars Odyssey reached Mars for orbital insertion and began mapping several months later on February 18, 2002. The study discussed here includes data received from solar areocentric longitude (L_s) 329˚ through 135˚ (February, 2003). Measurements and analyses have been done for the north and south poles, for latitudes poleward of ±65˚, using the hydrogen neutron-capture gamma-ray line at 2.223 MeV.

The concentration of an element within the top few tens of centimeters of the surface is proportional to the flux of the gamma-rays emitted at the element's characteristic energy [2]. Variations in the thickness of the carbon dioxide frost over time can be approximated by observing the attenuation of this signal caused by increases and decreases in CO_2 coverage throughout the Martian seasons.

To first order, we can estimate the seasonal frost thicknesses by assuming that the intensity of hydrogen gamma-rays at the surface of the regolith does not vary with thickness of CO_2 frost above it. This allows us to employ the Beer-Lambert Law, which states that the radiation absorbed per unit length in a medium depends at any wavelength only on the incident radiation intensity:

$$dI(\lambda)/dx = -\mu\, I(\lambda) \quad \textit{or}$$
$$I_t = I_o e^{-\mu t}$$

t: thickness of attenuator (CO_2 polar cap frost)

μ: attenuation/absorption coefficient, dependent on wavelength (from photon cross-section database)

I_o, I_t: initial (incident) and final (transmitted) intensities

The attenuation coefficient (μ) for the 2.223 MeV hydrogen line through carbon dioxide is 0.0420 cm^2/g. Using this value and the gamma-ray flux observed for a frost-free versus CO_2-covered surface, we obtain an approximation of the seasonal polar frost thickness in g/cm^2. (Note that depths are given in terms of the mass abundance of the column of CO_2 above the surface to avoid assumptions regarding the density of the column.) Additionally, we employ a model of the change in atmospheric thickness with time based on the Ames Research Center Global Circulation Model (ARC GCM), and we correct the hydrogen gamma-ray flux for the modeled change in the atmosphere.

The results can be compared to information about the polar environment previously inferred from the ARC GCM and to data accumulated one Martian year earlier by the Mars Orbiter Laser Altimeter (MOLA) aboard the Mars Global Surveyor (MGS) [3].

Data Processing and Analysis:

The process by which we go from counts in the GRS instrument [4] to elemental concentrations on the surface of Mars and then from concentration variations to seasonal carbon dioxide frost thicknesses is somewhat complicated. The flux of gamma-rays (as well as neutrons) depends on the subsurface composition of the regolith, and the signal is detected from a median depth of approximately 20 g/cm^2. Every 19.2 seconds, the GRS returns a gamma spectrum (along with several neutron spectra) collected along 59 kilometers of orbital arc, or one degree of motion, over the surface of Mars. Statistics are improved by binning the data over regions of interest.

Since converting from gamma-ray counts directly to surface concentrations is not possible, we perform a series of forward calculations that predict expected gamma-ray counts based on a priori assumed planetary abundances and compare these model results to observed results to derive a measure of elemental concentrations. We use a Monte Carlo Neutral Particle code (MCNPX) to predict the gamma-rays leaving the surface of Mars [5], [6]. These predictive models initially assume that Mars has the composition of the soil measured by the Mars Pathfinder Alpha Proton X-Ray Spectrometer (APXS) [7]. We further assume that the signal comes from a large footprint defined as the circular region on Mars from which 99.9% of the signal would come when approximating the planet as a sphere with uniform atmosphere and no topography. Within each footprint, a grid of 0.5 degree cells is defined over the surface to allow the specification of various compositions, altitudes, and atmospheric thicknesses. On the order of 10,000 cells are processed for each spectrum yielding expected gamma-ray counts. We then compare measured counts to predicted counts and determine relative concentrations for various elements as functions of latitude and longitude on the planet.

From the concentration profiles, attenuation effects due to the seasonal CO_2 frost can be investigated. Although we can obtain approximations from the basic Beer-Lambert Law calculations mentioned above, the effect of the CO_2 can increase the flux of thermal neutrons [3], and we cannot necessarily assume that the flux of gamma-rays under the frost does not vary with the frost thickness. Incorporating various models for the flux of hydrogen gamma-rays through a range of different thicknesses of CO_2 frost covering the regolith, we can plot the ratio of flux through a range of thicknesses of CO2-frost to that when no CO2 frost is present (i.e. intensity ratio) to obtain the equations below.

Northern model:
Intensity ratio = $e^{-0.042633*\text{thickness}}$ *or*
Thickness (g/cm^2) = -54.0094*log(intensity ratio)

Southern model:
Intensity ratio = $e^{-0.048288*\text{thickness}}$ *or*
Thickness (g/cm^2) = -57.6844*log(intensity ratio)

These models take into account both the efficiency of the detector as a function of angle and the effect of peaking of the emission in the upward direction with thicker CO_2 frost, leading to the given relationships between carbon dioxide thickness and the attenuation ratio. These relationships hold for all thicknesses up to 80 g/cm^2 after which the gamma-ray flux is essentially completely attenuated.

Spatial and Temporal Dependence of the Seasonal Polar CO_2 Frost Caps:

Thickness versus latitude. Preliminary plots incorporating hydrogen gamma-ray (2.223 MeV) flux data binned over 5˚ by 360˚ latitude bands at both north and south poles are plotted in Figures 1a and 1b using the aforementioned procedure. Column density in g/cm^2 is plotted for latitudes poleward of approximately ±60˚. Lower limit values, given by the triangular data points, are employed when error bars become excessively large due to near total attenuation of the transmitted gamma-ray signal and signify the lowest value within the two-sigma range of calculated CO_2 seasonal frost thickness.

For the north pole, a weighted average of the hydrogen gamma-ray flux seen during the northern summer (L_s = 90° - 135°) is taken as the basis for minimal/no frost coverage. The corresponding maximum 2.223 MeV line strength creates the basis for all attenuation ratio calculations. Similarly, a weighted average of data in the time interval: L_s = 345° - 15° during the southern summer creates the frost-free basis for all southern CO_2 frost thickness measurements.

As sublimation of carbon dioxide to the atmosphere occurs on one pole, the growth of the CO_2 cap occurs on the opposite pole. During the time period of this study, the retreat of the northern seasonal polar frost is observed, as the southern CO_2 cap continually grows. Retreat/growth takes place at a fairly constant rate as the seasons progress. As expected, greater frost depth is observed at increasingly poleward latitudes for both hemispheres.

For low values of column density, the most sensitive measurements are obtained from gamma-ray studies. As the thickness increases and the signal approaches full attenuation, epithermal neutrons provide the most effective frost measurements (see [3] for detailed CO_2 frost depth analysis using neutron data). In any event, the maximum frost depth inferred from GRS data before encountering this limit is approximately 75 g/cm^2 in the north, and 65 g/cm^2 in the south (lower bounds).

Thickness versus L_s. The growth and retreat of the seasonal carbon dioxide frost can also be plotted at specific latitudes as a function of L_s. Figures 2a and 2b show CO_2 thickness plotted for latitudes from ±62.5° poleward. Once again, triangular data points represent the lower limit within error bars of seasonal frost thickness, corresponding to near total attenuation of the H gamma-ray signal. Note that we reach this limit at lower column density values in the northern hemisphere than in the southern due to greater atmospheric thickness and attenuation over the northern lowlands.

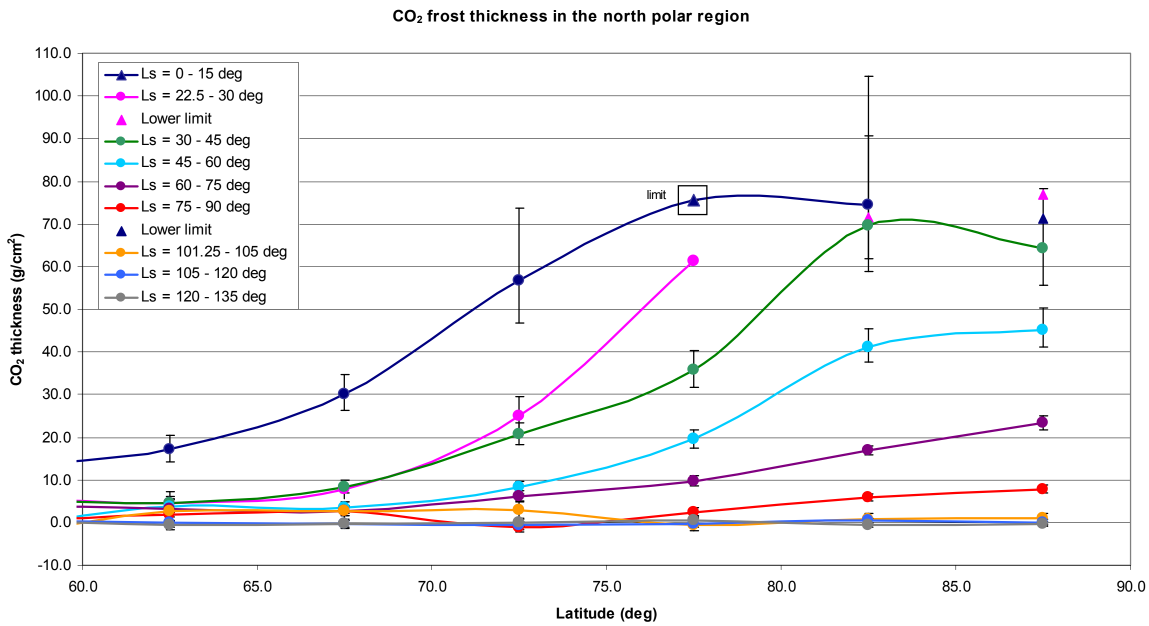
As shown in the previous plots, frost depth at any given date increases as we move poleward. In addition, the CO_2 cap coverage continually decreases (increases) over time for any specific latitude band beginning at approximately L_s = 0° in the north (south) pole.

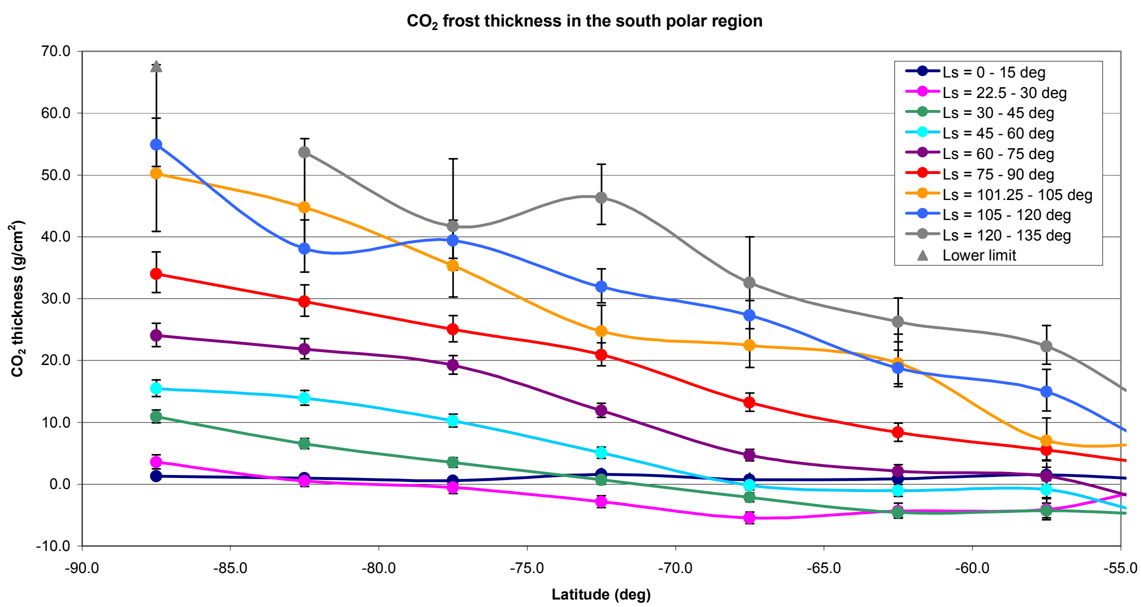
Future work:

The data shown here represent our understanding and evaluation of the seasonal polar CO_2 frost cycle at the time of abstract submittal. By the July conference date, we expect to have accumulated and analyzed three more months of GRS data.

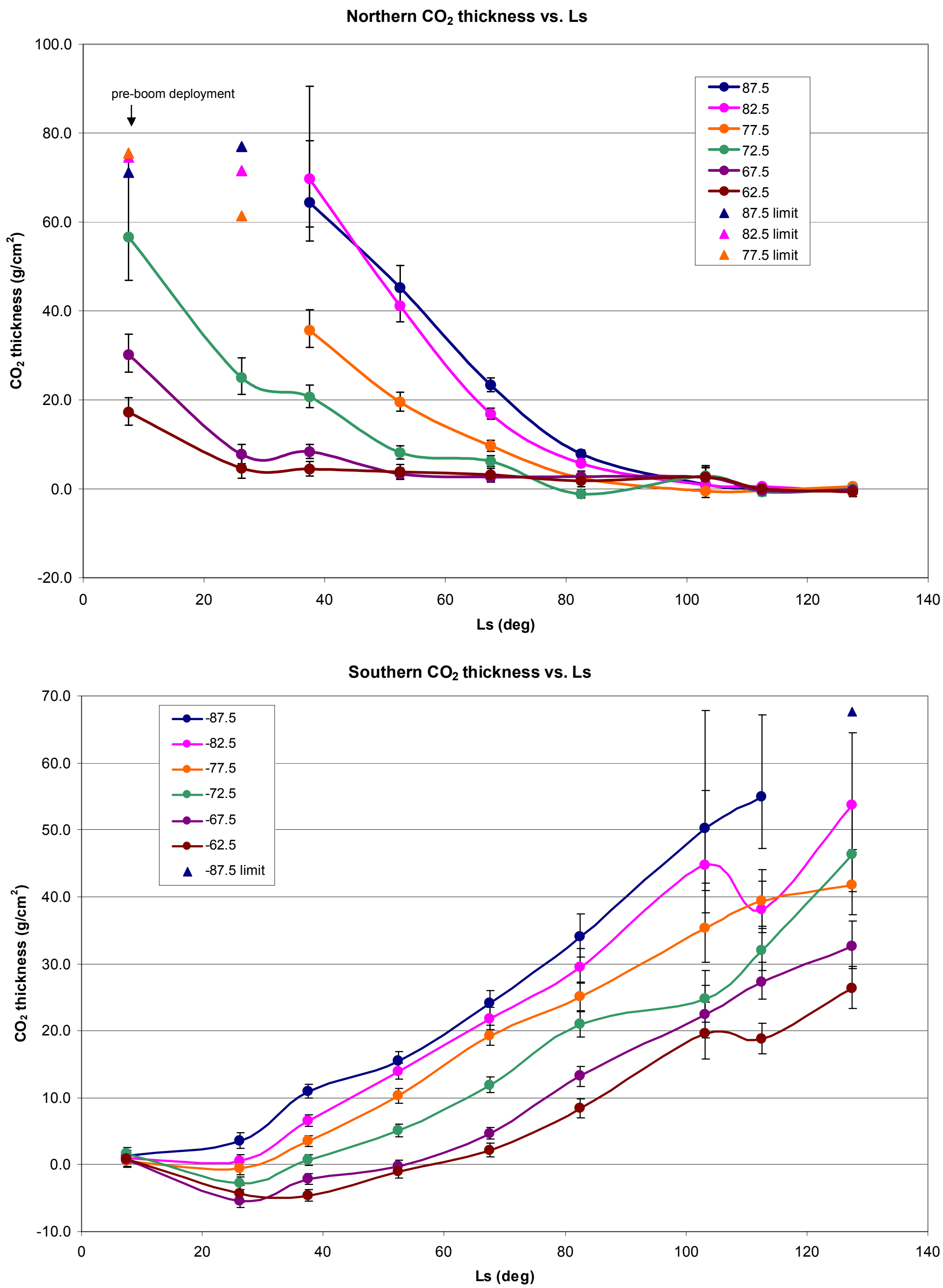
It is currently near the end of the northern summer, so during this time we anticipate observing the growth of seasonal CO_2 frost on the north pole of Mars, as well as the corresponding sublimation of CO_2 from the southern cap.

References: [1] James, P.B. et al, (1992) in Mars, Kieffer, H.H. et al, eds., 934-968. [2] Reedy, R.C. et al, Gamma-rays in a spectrum from the mars odyssey gamma-ray spectrometer, abstract (2003). [3] Feldman, W.C. et al, CO_2 frost thickness on Mars during Northern Winter and Spring, manuscript (2003). [4] Boynton et al, (2003) *Space Sci. Rev.*, in press. [5] Prettyman, T.H. et al, (2002) *LPSC XXXIII*, Abstract #2012. [6] Waters, L.S. Ed., (1999) MCNPX User's Guide, Los Alamos National Laboratory, document LA-UR-99-6058. [7] Wänke, H. et al, (2001) *Space Sci. Rev.*, 96, 317-330.





Figures 1a and 1b. CO_2 seasonal frost thicknesses for various time intervals (Ls = 0º - 135º) as a function of northern (fig.1a) and southern (fig.1b) latitudes. Values are derived from gamma-ray flux data (2.223 MeV) from 5˚ by 360˚ latitude bands. Lower limits designated by triangular data points are employed when uncertainty is large due to near total attenuation of the transmitted gamma-ray signal and represent the lowest thickness values within the error range.



Figures 2a and 2b. CO_2 seasonal frost thicknesses at specific northern (fig.2a) and southern (fig.2b) latitudes for Ls = 0º - 135º calculated from 5˚ by 360˚ latitude bands of 2.223 MeV hydrogen gamma-ray flux data. Lower limits designated by triangular data points are employed when uncertainty is large due to near total attenuation of the transmitted gamma-ray signal and represent the lowest thickness values within the error range.