THE ROLE OF CARBON DIOXIDE SNOWFALL IN THE FORMATION AND ENERGY BALANCE OF THE SEASONAL ICE CAPS OF MARS. P. O. Hayne\(^1\), O. Aharonson\(^1\), D. A. Paige\(^2\), and the Mars Climate Sounder Science Team, \(^1\)California Institute of Technology (MC 150-21, Pasadena, CA 91125, phayne@gps.caltech.edu), \(^2\)University of California, Los Angeles (595 Charles E. Young Drive East, Los Angeles, CA 90095).

**Introduction:** Carbon dioxide snowfall may be an important process in forming the seasonal polar caps of Mars, yet it has no terrestrial analog and probably occurs primarily in the darkness of polar night \([1,2]\). By scattering emitted infrared radiation, snowfall can substantially decrease the effective emissivity of the seasonal caps, altering the polar energy balance and reducing net accumulation of CO\(_2\) during winter \([3,4,5]\). Furthermore, if their granularity persists through the spring and summer, high albedo snow deposits might be preferentially preserved over slab ice \([6]\). The distribution of snowfall may thus have bearing on the location and perennial stability of the south polar residual cap (SPRC).

We investigated the infrared emission behavior of the condensing seasonal polar caps and atmosphere using the Mars Climate Sounder (MCS), as well as seasonal topography variations due to ice accumulation (during an earlier year), using the Mars Orbiter Laser Altimeter (MOLA). The results from MCS suggest that snowfall is an especially important process in forming the seasonal deposits on top of the SPRC, where at least 7 – 15% of accumulation by mass occurs as snowfall originating above ~4 km altitude. Wintertime snowfall rates decrease away from the poles in both hemispheres. Furthermore, initial comparisons between the MOLA and MCS observations suggest that regions of high snowfall also tend to be those with the thickest seasonal deposits.

**Instrumentation and Observations:** Previous infrared investigations have provided evidence that fine-grained surface frost and/or snow particles in the atmosphere substantially reduce the wintertime emissivity of the polar regions, but have so far been unable to convincingly distinguish between the two \([7,8]\). Near-infrared echoes measured in the troposphere by MOLA, however, suggest optically thick clouds do occur frequently in the polar night \([9,10]\). MCS brings the advantage of nearly simultaneous limb and surface observations over the poles, allowing retrieval of cloud optical depth over low-emissivity regions in order to establish or rule out their correlation.

**MCS Instrument and Data Analysis.** MCS \([11]\) is a multispectral infrared radiometer onboard the Mars Reconnaissance Orbiter spacecraft, and consists of two telescopes and nine channels spanning the visible through ~50 \(\mu\)m wavelength, each with a linear 21-detector array. Two independent actuators allow scanning from nadir to ~100 km altitude, with a typical vertical field of view FWHM at the limb of ~4 km. The best low-emission angle nadir observations were acquired during the southern winter of MY28 (following the convention of \([12]\)). Opacity retrievals are performed by iterative relaxation on the limb radiance profiles, and ice cap emissivity is estimated by the ratio of measured nadir radiance to that of a blackbody at the local frost point temperature \([13,14]\).

**MOLA Instrument and Data Analysis.** MOLA is a nadir-looking near-infrared laser altimeter, designed to map global surface topography \([15]\). By calculating residual differences between pairs of crossing ground tracks, \([16]\) and \([17]\) were able to deduce spatial and temporal changes in surface height due to seasonal accumulation and sublimation of CO\(_2\), with errors < 15 cm. Below we present only the “annual” amplitude map, derived by fitting simple sinusoids to the variation over one Mars year \([17]\).

**Results:**

**CO\(_2\) Clouds are Correlated with Low-Emissivity Regions.** Early in the MCS investigation, extensive clouds were observed over the winter pole, which we established to be composed of CO\(_2\) ice \([14]\). We quantified the correlation \((R \approx 0.6)\) between cloudiness and low-emission regions using the entire southern winter dataset. The results establish that while clouds sometimes occur without a corresponding reduction in nadir brightness temperature, the converse situation (i.e. low emissivity without clouds) never occurs at scales > 300 km. This relationship suggests that backscatter by clouds and/or associated snow deposits could be the primary cause of low emissivity regions. Additionally, the distribution of polar CO\(_2\) clouds observed by MCS closely matches the pattern of echoes measured by MOLA in an earlier year.

The brightness temperature contrast \(T_{11} - T_{22}\) (where subscripts denote effective MCS center wavelength) effectively measures the degree of scattering in the 25-\(\mu\)m transparency band of solid CO\(_2\), and is similar to the “cold spot index” used by \([2]\). For surface deposits, this contrast increases for decreasing effective grain size, while for clouds it is a measure of optical depth. Figure 1 shows that the spectral contrast is highly correlated with CO\(_2\) cloud opacity (here expressed as a normalized mixing ratio); this is further evidence that...
clouds and/or snow deposits strongly influence the radiative behavior of the seasonal polar caps, and the nadir spectral contrast can be used as a proxy for cloud opacity at large scales.

**Figure 1.** Variation in cloud fraction and MCS nadir spectral contrast as a function of latitude

**Observed CO₂ Clouds Lead to Substantial Surface Accumulation.** We estimated snowfall rates by 1) retrieved cloud optical depths and theoretical sedimentation velocities, and 2) infrared cooling rates based on retrieved cloud profiles. In both cases, we find that the measured clouds above ~4 km altitude contribute 7 – 15% of the net accumulation of CO₂ ice to the seasonal caps over the SPRC (substantially less at lower latitudes). At lower altitudes, even greater atmospheric deposition is likely to occur, but the finite MCS field of view prevents opacity retrieval this region.

**Cloudy Regions are Correlated with Thick Seasonal Deposits.** We used the spectral contrast $T_{11} - T_{22}$ as a proxy for snowfall (see above), and compared this to maps of seasonal ice cap thickness derived from the MOLA crossovers in the southern hemisphere. Figure 2 shows a striking correlation between these two quantities, suggesting that regions experiencing enhanced snowfall develop the thickest deposits.

**Discussion and Conclusions:** Polar winter limb and surface observations by MCS reveal that CO₂ clouds are correlated with regions of low emission, and substantially alter the spectral contrast in the key wavelength region near 25 μm. Our cooling rate and sedimentation flux calculations based on the MCS cloud opacity retrievals suggest that a substantial fraction of the seasonal deposits occurs as snowfall, especially over the SPRC. The SPRC also shows the thickest seasonal deposits, based on MOLA crossover residuals.

Taken together, these observations and models reveal snowfall to be an important process in forming the seasonal ice caps of Mars, in addition to strongly altering the polar energy balance. In fact, a paradox emerges: How can the cloudiest regions, where emissivity is most reduced, also contain the thickest seasonal deposits? One potential solution is that the deposit thickness is most influenced by the grain size (and hence porosity) of the deposits, which causes snow deposits to be less dense and thicker than ice condensed directly at the surface. Nonetheless, we calculate a ~30% radiative forcing on the energy balance of the SPRC due to the measured wintertime emissivity reduction, which must be counterbalanced by its longer winter accumulation period if its present location is the most stable on interannual timescales.


**Figure 2.** (left) Map of effective grain size / cloud cover from MCS observations; (right) amplitude of topographic seasonal change (1st harmonic) from MOLA crossover residuals.