CLOUDS IN THE POLAR NIGHT OF MARS: MODELING AND OBSERVATIONS WITH THE MARS CLIMATE SOUNDER. P. Hayne[1], D. A. Paige[1]. [1]University of California, Los Angeles (595 Charles Young Blvd E, Los Angeles, CA 90095; phayne@ucla.edu)

Introduction: Polar "cold spots" – regions of unusually low brightness temperature – affect the Martian climate by reducing the outgoing heat flux, which is balanced by the latent heat of CO_2 sublimation. Since the Viking era, their cause has remained uncertain. Using radiometric observations from the Mars Climate Sounder (MCS) during southern winter, we previously reported that transient cold spots appearing during polar night are statistically correlated with the presence of CO_2 ice clouds [1].

In the present work, we successfully reproduce the MCS observations by employing a radiative transfer model including scattering in a layered, cloudy, dusty atmosphere. Surface emissivity, as well as cloud optical thickness, composition, and altitude are constrained by comparison of the MCS data with the model output. A CO_2 cloud of optical depth ~0.1 – 1.0, near 25 km altitude, is most consistent with the available data.

Theories of Cold Spot Origins: Cold spots with T_b < 148 K are not expected if the CO_2 ice cap is in equilibrium with the gas phase. Nonetheless, they are observed throughout the polar night in both hemispheres (Fig. 1). Three primary explanations have been explored previously [2]:

(1) Depletion of atmospheric CO_2 [3]

(2) Non-unit emissivity of surface CO_2 [4]

(3) Carbon dioxide clouds [5, 6].

Hess [7] demonstrated that *(1)* is feasible only under special circumstances due to dynamical instability. The spectral properties of CO_2 frost and clouds are similar such that it has been difficult to discriminate between *(2)* and *(3)* as viable hypotheses. Rapid variability (time scales of days) observed in some cold spots, as well as morphology and distribution, point toward atmospheric phenomena [11]. In the present investigation, we use radiance measurements of both the atmospheric limb and nadir, along with radiative transfer modeling, to show that *(3)* explains most, if not all cold spots.

Observations of Cold Spots: The Mars Climate Sounder [8] onboard the Mars Reconnaissance Orbiter recorded a series of nadir and limb radiance measurements in nine spectral channels, from ~1–40 μm wavelength. The observations used in this study spanned a range of solar longitude, L_s = 111 to 148, corresponding to southern winter. Radiances are converted to equivalent brightness temperatures using the radiometric response function of each filter and the Planck function. Observations are binned by latitude and longitude (1–5° bins) and L_s, then nadir brightness temperatures, T_b^n, are compared to limb profiles, T_b^l.

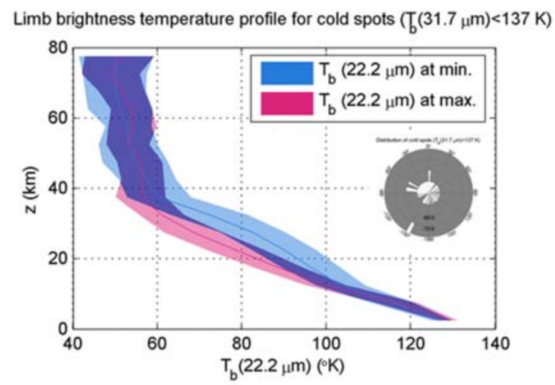

Figure 2: Limb T_b(22 μm) during cold spot activity (blue) and during decreased activity (red). Inset shows cold spot distribution.

Data Analysis: We plotted T_b^l for the A5 channel (22.2 μm) for areas where T_b^n (within three degrees of L_s) dropped below 137 K in the B1 (31.7 μm) channel. Figure 2 compares these limb profiles (blue; shaded area indicates 1σ) to measurements at the same location, but during the period of maximum temperature for that spatial bin (red). During the period when the cold spot is present in the nadir data, brightness temperatures rise significantly at ~20–30 km altitude. This is consistent with a cloud, whose brightness temperature in the nadir may be indicative of the altitude of optical depth ~1, several kilometers above the surface.

Statistical analysis shows that the 22-μm brightness temperatures at ~25 km altitude are inversely correlated (R=-0.55, p<10^{-14}) with nadir 32-μm brightness temperatures (Fig. 2). We show below this is due to the presence of optically-thick clouds, likely composed of CO_2 ice particles.

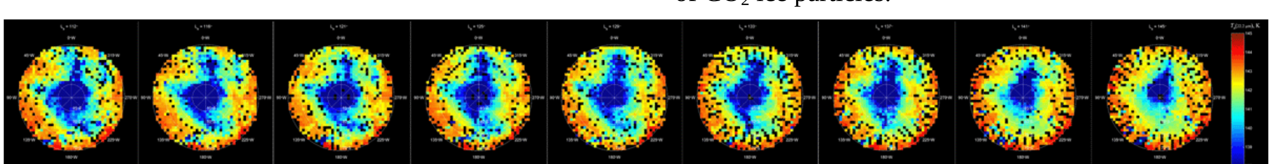

Figure 1: Nadir T_b for the range of L_s = 111° - 149°. Scale: 138 K - 145 K

Modeling:

Method: We employ the δ-Eddington approximation of the radiative transfer equation (RTE), which incorporates a forward peak into the Eddington phase function, accurately representing asymmetric scattering by aerosols. Monochromatic fluxes are calculated rapidly within each layer of an *N*-layer atmosphere, given appropriate boundary conditions and optical properties (ϖ_0, Q_{ext}, g, τ) of each layer. For each wavelength, we integrate the formal solution to the RTE along a desired ray path, and convolve the calculated radiances to the MCS spectral response and FOV. This yields a MCS brightness temperature spectrum for the model atmosphere and viewing geometry.

Results: Figure 3 shows results for a 100-layer atmosphere with a 4 km-thick CO_2 cloud (mode particle radius = 10 μm) at 25 km altitude, for solar optical depths $\tau = 0.1$, 1.0, 2.0, and 10.0. Optical parameters were calculated from Mie theory with laboratory optical constants from Hansen (1997) [9]. Results are consistent with both nadir and limb MCS observations. With a kinetic surface temperature of 148 K, a CO_2 cloud of modest optical thickness results in $T_b^n \approx 130 - 140$ K, with a spectrum consistent with Mariner 9 IRIS data [2]. Limb profiles reproduce the structure of the MCS data, though some work is needed to understand discrepancies in (*i*) the altitude of the cusp, and (*ii*) the magnitude of ΔT_b^l at each level. Forget et al. (1995) [2] found that including a thin H_2O cloud in their model improved the fit to te IRIS data; this may also be the case for the MCS data, though spectral resolution is much more limited.

Discussion: Our analysis implicates carbon dioxide clouds as a cause of Mars' polar cold spots. Brightness temperatures and spectral features from the MCS and earlier datasets are consistent with an optically thick cloud ($\tau \approx 0.1 - 1.0$) near 25 km altitude, which is close to the polar winter tropopause [8]. Calculations of convective available potential energy, based on recent MCS data, also lend credence to the cloud hypothesis [11]. We interpret the statistical correlation between T_b^n and T_b^l of $R < 1$ to indicate some cold spot activity is not related to clouds – this may be due in part to surface emissivity effects.

References: [1] Hayne, P. and Paige, D. A. *LPS XXXIX*, p. 2516. [2] Forget et al. (1995) *JGR 100*, 21,219. [3] Kieffer et al. (1977) *JGR 82*, 4,249. [4] Ditteon and Kieffer (1979) *JGR 84*, 8294. [5] Hunt (1980) *GRL 7*, 481. [6] Paige et al. (1990) *Bull. Am. Astron. Soc. 22*, 1075. [7] Taylor, F. W. et al. (2006) *Adv. in Space Res. 38*, 4, 713-717. [8] McCleese et al (2008) *Nature Geosci.* 1, 745-749. [9] Hansen, G. B. (1997) *JGR* 102, 21569-21588. [10] Heavens, N. et al (2008), *Mars Atm. Modeling Conf.*, Williamsburg, VA. [11] Cornwall, C. and Titus, T. N. (2008) *LPS* XXXIX, p. 1089.

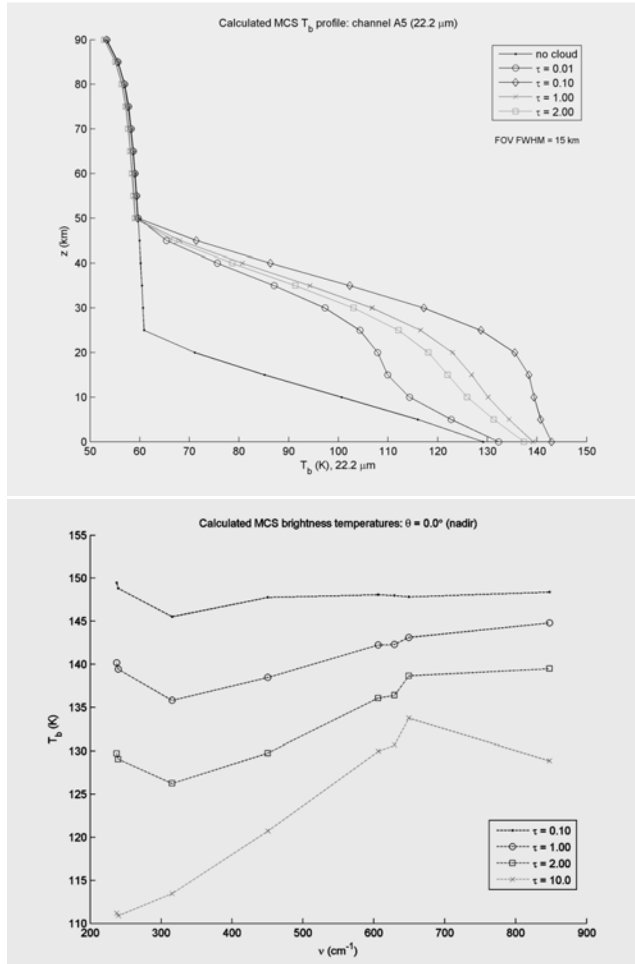

Figure 3: Calculated T_b^n and T_b^l for a CO_2 cloud at 25 km (cf. Fig. 2). **Top** (T_b^l): Total optical depths are 0.01 (circles), 0.10 (diamonds), 1.0 (x's), and 2.0 (squares). **Bottom** (T_b^n): 0.1 (dots), 1.0 (circles), 2.0 (squares), 10.0 (x's).