ON THE MYSTERY OF THE PERENNIAL CARBON DIOXIDE CAP AT THE SOUTH POLE OF MARS.

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Introduction: A perennial CO_2 ice cap has long been observed near the south pole of Mars. The retention of a CO_2 ice cap results from the surface energy balance of the latent heat, solar radiation, surface emission, and subsurface conduction. While models conventionally treat surface CO_2 ice using constant ice albedos and emissivities, such an approach fails to predict the existence of a perennial cap. We explore the role of insolation-dependent ice albedo, which agrees well with Viking, Mars Global Surveyor and Mars Express albedo observations. Using a simple parameterization within a General Circulation Model, in which the albedo of CO_2 ice responds linearly to the solar insolation, we are able to predict the existence of a perennial CO_2 cap at the observed latitude and only in the southern hemisphere [1]. While the single insolation dependent function likely does not capture the full spatial and temporal variations of ice albedo, it provides a demonstration that insolation-dependence of albedo is probably the key factor in the existence of a residual cap. Future work on the microphysical and macrophysical mechanisms of CO_2 ice albedo and emissivity is required, one application of which would be a physically-based parameterization of surface radiative effects of CO_2 ice for climate models.

Insolation-dependent albedo: We use the MarsWRF model, the Martian implementation of the planetWRF model [2]. We calibrate the GCM by tuning the albedos and the emissivities of the seasonal dry ice caps and the total CO_2 inventory in the system to reproduce the VL1 surface pressure cycles. Water cycle and CO_2 cloud microphysics, which are likely aliased to the model parameterization of frost albedo and emissivity, are not explicitly included. At the steady state, the model predicts a pressure cycle that matches the Viking Lander records very closely [3]. The predicted mass of the seasonal caps is consistent with other GCMs and observations[4]. However, like all the other models trying to fit the VL pressure records, a residual CO_2 cap in the south pole is not predicted by MarsWRF with this setup.

The Viking observations suggests that the albedo of the southern residual CO_2 cap changes with time [5] [6]. More usefully, the relationship between the residual CO_2 caps albedo and the incident solar flux is very linear (Figure 1). When we use a least square linear regression method, we obtain an empirical equation that predicts the surface CO_2 frost albedo based on the insolation:

$$A = 0.532 + 8.72 \times 10^{-4} \times F_s \qquad (1)$$

where A is the albedo of the CO_2 ice cap and F_s is the incident solar flux in W/m^2. This linear model fits the Viking albedo observations for the southern residual cap very well, with only several percent of fitting error. In the absence of a proven physical model for the dependence of albedo on insolation or other environmental factors, this empirical relationship is potentially very important for reproducing a perennial cap in a GCM. Larger albedo creates a larger energy deficit that has to be compensated by more surface CO_2 ice condensation or less sublimation. From Equation 1, the albedo is the largest in the summer when the incident solar flux is the most intense, which is ideal for the CO_2 ice to endure the summer.

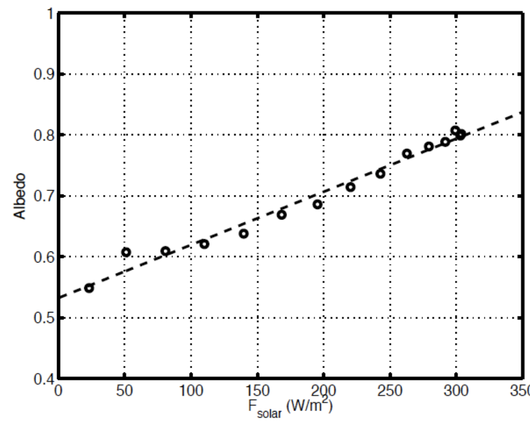

Figure 1: Southern residual cap albedo as a function of incident solar insolation. Open circles: observations from the Viking spacecraft. Dashed line: the line from the linear fitting of the Viking data. Data fit from Guo et al. [1] and data from Paige and Ingersoll [6].

We incorporated this relationship into MarsWRF. For each time step, if the surface is covered by enough CO_2 ice, we calculated the instantaneous incident solar flux and then use Equation 1 to determine the surface albedo for the subsequent radiative calculations (of course the albedo value can not be larger than unity). Results of model runs are shown in the next session. Output from the second year of model simulations is shown.

Results: We first present the control or baseline scenario with time constant albedo. Time constant albedos and emissivities are assigned to the northern and southern CO_2 ice caps. The total CO_2 mass in the system was set to 2.83×10^{16} kg [3]. This setup generates a pressure cycle at the VL1 location agreeing with the VL1 records very well, but without a residual cap at either pole. The annual variation of the zonally averaged surface CO_2 frost is shown in the panel (a) of Figure 2.

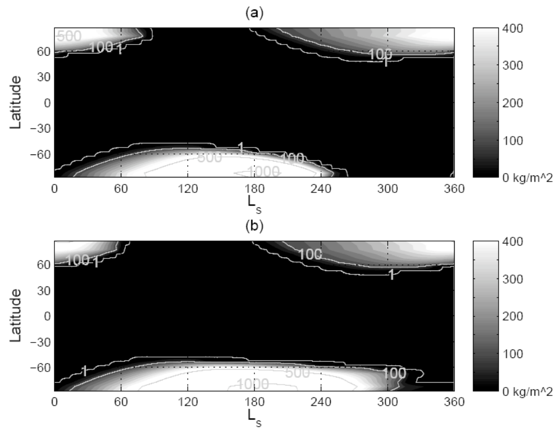

Figure 2: Annual variation of zonally averaged surface CO_2 ice deposition. The grey scale indicates the density of the deposition in kg/m^2. From the lower latitudes to the polar region, the grey contour lines indicate the deposition levels of 1 kg/m^2, 100 kg/m^2, 500 kg/m^2 and 1000 kg/m^2 respectively. Panel (a): This is the case with time-constant CO_2 frost albedos. Panel (b): The setting of this experiment is identical to that of panel (a), except the frost albedo is calculated using Equation 1 in each time step. From Guo et al. [1].

Next the surface CO_2 ice albedo is determined from the local incident solar flux according to Equation 1, while keeping the rest of the model unchanged (note that albedo of CO_2 ice present at any location on the surface is locally determined by this formula). We show the corresponding CO_2 ice surface deposition annual cycle in the panel (b) of Figure 2.

Following the seasonal cap evolution, starting with the onset of polar night in each hemisphere, CO_2 begins to deposit at the winter poles. At this time of the year, the season cap areal coverage in both hemispheres does not differ greatly in the time-varying albedo experiment compared to the control case, because during the polar nights the surface albedo is not relevant to the surface energy balance. When the surface frost is exposed to the sun, the abundance and the longevity of the surface CO_2 ice starts to differ from the control case. As the southern seasonal ice cap is exposed to sunlight as the spring wears on, the albedo is driven to higher values than in the north, and to higher values than those used in the south in the control simulation. This brightening of the southern cap leads to less solar energy absorption and thus reduces the cap sublimation rate. Indeed, thanks to the high albedos generated by Equation 1, the CO_2 ice at the southern pole is able to endure the summer and forms a perennial reservoir.

The reason for the existence of perennial CO_2 ice in the GCM is consistent with the Paige and Ingersoll [6] study of the heat balance of the residual cap. The perennial ice reservoir produced by the GCM is slightly displaced from the geographical south pole, and is longitudinally asymmetric, agreeing with observations [7] [8].

Conclusions: Viking data suggests an empirical linear relationship between the CO_2 ice cap albedo and the incident solar flux. When we include this relationship in the MarsWRF GCM we are able to reproduce a CO_2 cap that persists throughout the full year near the south pole. This perennial cap is not located exactly at the geographical south pole, nor is it zonally symmetric, which agrees with the observations. The predicted perennial cap is not at the same longitude as seen in the observations. The spatially invariant linear fit of albedo and insolation is a major oversimplification, albeit significantly better than time and space invariant treatment in models to date. The improvement in the simulation suggests insolation-dependence should be included in models, but misfits in cap location prediction and errors generated in the simulated pressure cycles also suggest that a more detailed, physically-based model of CO_2 surface ice radiative properties is needed to adequately prognose the Martian CO_2 cycle.

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