INVESTIGATING THE ASYMMETRY OF MARS' SOUTH POLAR CAP USING THE NASA AMES MARS GENERAL CIRCULATION MODEL WITH A CO_2 CLOUD MICROPHYSICS SCHEME.

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Introduction

The largest Martian climate phenomenon is the exchange of CO_2 between the atmosphere and the surface. Composed of more than 95% of carbon dioxide, the thin atmosphere of Mars is the source of a daily and seasonal phenomenon consisting of the condensation-sublimation of CO_2 in and out of the poles. An intriguing feature of this cycle is the existence of a 500 km in diameter residual CO_2 ice cap that is offset to the north-west of the south pole of Mars (Figure 1). This residual ice sheet is characterized by a uniquely high albedo that increases from the end of the polar night into late spring and accounts for the residual cap's year-round survival. The rest of the ice cap is characterized by a lower albedo and experiences total sublimation. Although global climate models reproduce the CO_2 cycle well, ice albedos are a fixed parameter in time and space and the entire southern ice cap is predicted to completely sublimate by the end of southern spring.

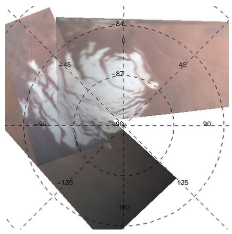

Figure 1: The residual CO_2 ice cap on Mars (ESA- Mars Express)

Colaprete et al. (2005)[1] hypothesized that the high albedo of the SPRC could result from the existence of a bimodial climate originating from a topographic forcing on the south polar regional atmospheric circulation. This asymmetry would result in higher atmospheric precipitation and snowfall rates over the region of the SPRC compared to the rest of the cap. Since the albedo value of ice strongly depends on the type of surface deposition (*snowfall* versus surface *frosts*), this high snowfall rate would contribute to the observed albedo asymmetry and contribute to maintaining the SPRC at a high enough albedo to allow for its year-round survival.

To test this hypothesis, we incorporate advanced CO_2 cloud microphysics in the Ames GCM and analyze the southern circulation and snowfall patterns obtained. We find that the model not only reproduces the available CO_2 cloud observations, but also that the model predicts an asymmetric cloud cover over the southern ice cap during southern fall and winter, favoring snowfall over a region encompassing the SPRC. Although further model development is needed to account for the observed albedo asymmetry of the southern ice cap, these results are a promising first step to modeling the SPRC and improving our understanding of the climate of current day Mars.

Model Presentation

The NASA Ames General Circulation model was run for 5 years assuming a 7 mbar atmosphere containing a constant mixing ratio of 95% of CO_2. We adapt a sophisticated water ice cloud microphysics package to represent CO_2 ice cloud nucleation, growth, and sedimentation[2] (Figure 2). The surface albedo when CO_2 ice is present is fixed to a constant value of 0.6 for the north cap and 0.3 for the south cap. The model uses MOLA topography and TES-derived maps of bare ground surface albedo and ground thermal inertia. The model is forced with a prescribed TES-observed dust map from MY 26. The free dust, clouds and cloud dust cores are modeled as radiatively passive.

General Model Results

The Viking Lander pressure curves and the Mars Odyssey GRS cap mass recordings are two of the data sets used to constrain the bulk of the CO_2 cycle. Figure 3 shows good reproduction of the Viking Lander surface pressure curves after tuning the ice cap albedo values (which govern the sublimation rates of the caps) and the subsurface water ice depths at the poles (which govern the amount of CO_2 condensing into the caps during fall and winter). The discrepancies between the simulated and observed cap recession rates during early and late spring occurs because the model assumes constant CO_2 ice cap albedos in time and space whereas observations suggest that the southern ice cap albedo is very asymmetric and greatly evolves during the subliming season.

[1] Albedo of the south pole on Mars determined by topographic forcing of atmosphere dynamics, A.Colaprete, J.R. Barnes, R.M. Haberle, J.L. Hollingsworth, H.H. Kieffer and T.N. Titus. Nature, May 2005

[2] "Nucleation studies in the Martian atmosphere", A.Määttänen et al., JR, 2005 and "Origin and role of water ice clouds in the Martian water cycle as inferred from a general circulation model", F. Montmessin et al. JGR, 2004

Accounting for the variability of the CO_2 ice albedo would likely improve the predicted cap recession rate.

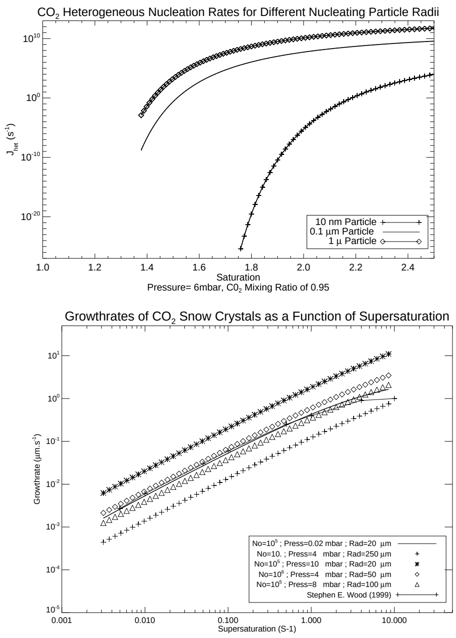

Figure 2: Top to bottom: CO_2 cloud nucleation rates (in s^{-1}) as a function of saturation (for a 1 μm, 0.1 μm and 1 nm dust particle), and CO_2 growthrates as a function of supersaturation with a dt=360 s (GCM and as calculated by Stephen E.Wood (1999))

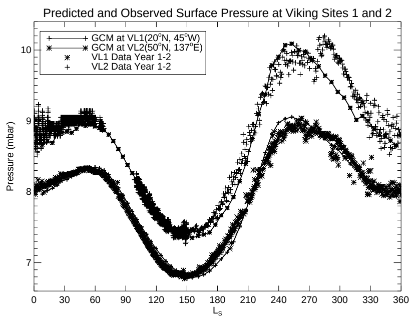

Figure 3: Surface pressures at Viking 1 and 2 landing sites and surface pressures taken from the corresponding Mars GCM grid points

The predicted seasonal evolution of the north and south CO_2 ice caps agrees well with the 2-year data set from the Gamma Ray Spectrometer (GRS) onboard Mars Odyssey (Figure 4). Cap masses are reasonable compared to observations with a slighly lower prediction for the southern cap. Again, discrepancies in cap recession rates are consistent with the discrepancies seen in the surface pressure comparison but does not significantly impact the good reproduction of the seasonal cycle of CO_2 by the model.

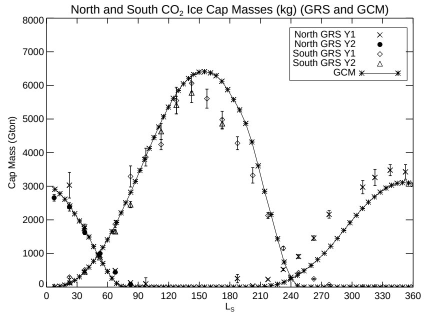

Figure 4: Polar cap masses as observed by GRS (based on the hydrogen line and including error bars for data years 1 and 2) and as simulated by our baseline Mars GCM run binned over 10 sols

Predicted CO_2 Cloud Pattern

The model predicts three distinct types of CO_2 clouds over a Martian year (Figure 5): mesospheric equatorial and mid-latitude clouds, polar night clouds, and clouds that form over the subliming caps (cap edge clouds).

Predicted mesospheric clouds form above 60 km of altitude in the cold phases of the diurnal tides at specific seasons and reach radii of about 20-30 microns. Equatorial clouds form within 20 degrees of the equator from late northern winter (L_s=340°) to mid northern summer (L_s=180°) while mid-latitude clouds form around 50 degrees of latitude in the winter hemispheres at the seasons of maximum CO_2 seasonal ice cap extent. The longitudinal pattern is influenced by the martian topography.

Cap edge clouds form within 0.5 km of the surface in a 5 degree latitudinal band on the outskirts of the polar night during fall and winter, and over most of the subliming caps during the respective spring seasons. They contribute to 0.1-1% less cloud mass than polar night clouds and contribute 1-10% of the total snowfall accumulated on the ice caps. The clouds form in the cold phases of both stationary planetary waves originating from the topography and transient traveling waves due to the unstable baroclinic state of the atmosphere over the ice caps. Their radii averaged 10-20 microns and only the fall and winter cap edge clouds have yet been observed on Mars.

Polar night clouds form from the surface up to about 40 km altitude during the respective polar nights of both hemispheres. Compared to mesospheric and cap edge clouds, polar night clouds correspond to the thickest cloud cover over a Martian year and contribute up to 90% of the total snowfall over the ice caps. In the dark of the polar nights, similarly to cap edge clouds, clouds form in the cold phases of both stationary and transient atmospheric waves. For both cap edge and polar night clouds, the topography and geometry of the martian orbit result in hemispheric asymmetries in longitudinal pattern as well as in relative influence of either type of wave on cloud formation. In both hemispheres, polar night cloud radii range from 40 to 150 microns.

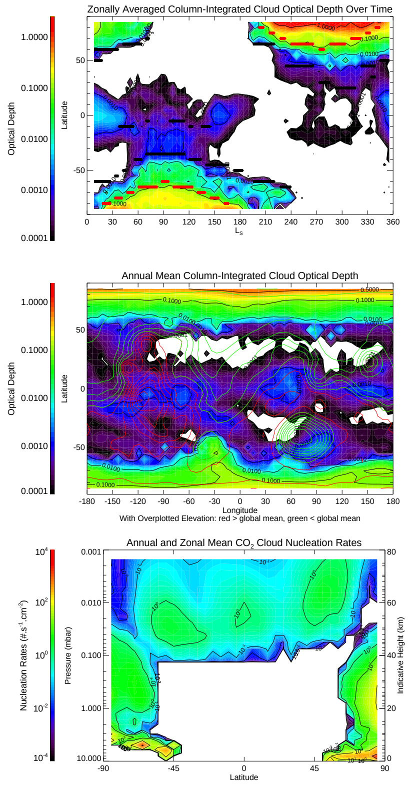

Figure 5: Top to bottom: zonally averaged and column integrated CO_2 cloud optical depth in the visible, annually averaged column-integrated cloud optical depths in the visible as a function of latitude and longitude with overplotted topography (red contours > global mean)- 10 sol averages, and annually/zonally averaged cloud nucleation rates as a function of altitude and latitude

Predicted Southern Hemisphere Asymmetry

The model predicts a strong asymmetry in the atmospheric circulation over the cap during southern fall and winter. Around winter solstice (L_s=91-96°), a wave number 2 atmospheric pattern favors cloud formation in the longitudinal corridor of 45°W-135°E (Figure 6) which agrees well with observations by Giuranna et al. (2008) [3]. The dashed (resp. full) contours of figure 6 represent the negative (resp. positive) temperature deviations from the zonal mean in a pressure level close to the surface. A simulation using a topography map where Arygre and Hellas basins have been removed shows similar patterns (central panel of fig 6), whereas a simulation using a zonally averaged topography map suggests that the East-West asymmetry is lost and that the wave's amplitude is greatly reduced. The asymmetry and topographic origin are coherent with [1]. The latter however produced a strong wave number 1 system established by the basins of Argyre and Hellas and observed little influence of Tharsis except for weakening the amplitude of the temperature wave.

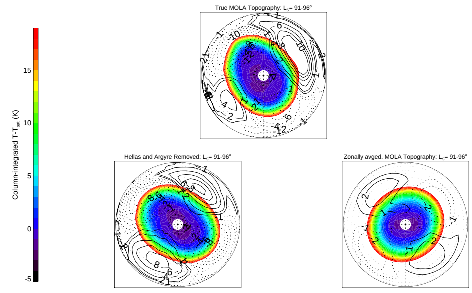

Figure 6: Column-integrated δT_{sat} (coloured contours) and temperature deviations from the zonal mean at pressure level 3.5 mbar from L_s=91-96°. From top to bottom right: true MOLA topography; Hellas and Argyre removed; zonally averaged MOLA topography

During the late fall season (L_s=22-26°), the predicted circulation is dominated by a strong wave number 1 pattern governed by Hellas and Argyre which results in enhanced saturated temperatures at the vertical of the location of the SPRC (Figure 7). This season corresponds to the southern ice cap seasonal maximum in cloud mass and radius over this same region. This result is again in very good agreement with [3].

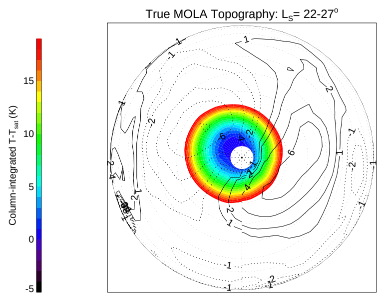

Figure 7: Column-integrated δT_{sat} (coloured contours) and temperature deviations from the zonal mean at pressure level 3.5 mbar around L_s=22-27°

The ratio of snowfall to total ice deposition (snowfall + frost) reflects the predicted asymmetric circulation and is influenced by the dust loading considered (Figure 8). Increased dust loading in the polar night increases the emissivity of the atmosphere and enhances the amplitude of the temperature wave during southern winter. This effect is once again maximized during late fall and over

[3] "PFS/MEX observations of the condensing CO_2 south polar cap of Mars" , M. Giuanna et al., Icarus, 2008

the region of the residual cap.

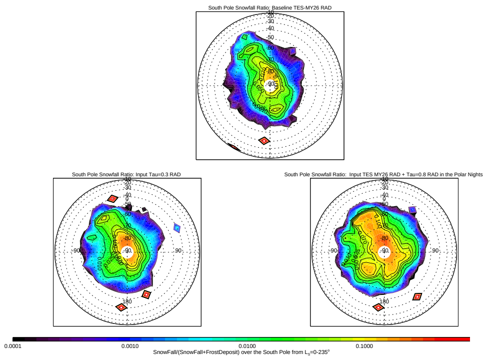

Figure 8: Ratio of snowfall to total ice depositon (snowfall + surface frosts) summed up over the entire southern ice cap season (L_s=0-235°) for the baseline radiating TES map (top), for an input dust loading of constant tau=0.3 (bottom left) and for an input TES dust map of MY-26 with additional tau=0.8 in the polar nights. All dust loadings are radiatively active (RAD)

Discussion and Future Research

With incorporated CO_2 cloud micophysics, the Ames GCM reproduces the observed cloud patterns on Mars without precedent as well as reinforces the thesis suggested by [1]. The topography modulates the southern winter circulation in such a way that the atmosphere is more regularly saturated over a western region encompassing the SPRC, thus providing enhanced snowfall to this region. We particularly notice that this asymmetry is most pronounced during late southern fall (L_s=20-50°). As already observed by [3], this period corresponding to the initial build up of the ice cap could play a major role in building up the asymmetry of the cap.

These positive results could lead further interesting studies. On the one hand, the current horizontal grid resolution is too coarse to refine the study to the region of the SPRC. This could be improved by a mesoscale modeling investigation around the region of the residual cap to refine the local circulation. On the other hand, the GCM assumes constant ice albedo values in space and time. Implementing more sophisticated ice albedo scheme dependant on the amount and size of aerosols falling onto the cap during fall and winter (snow, frost, dust) as well as surface metamorphism processes (due to sintering and incoming solar radiation for example) could further help understand the formation and current evolution of the southern residual ice cap.