Understanding the repeatable nature of the Viking surface pressure curves: Coupling Mars' CO_2 and dust cycles.

Melinda A. Kahre[1], Robert M. Haberle[1], Jeffery L. Hollingsworth[1] and James R. Murphy[2]. [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA, USA (Melinda.A.Kahre@nasa.gov), [2]Department of Astronomy, New Mexico State University, Las Cruces, NM, USA.

1. Introduction

Viking landers 1 and 2 measured the surface pressure on Mars for multiple annual cycles and found that Mars' CO_2 cycle is highly repeatable [1]. The dust cycle can affect the CO_2 cycle by altering the heat balance of the atmosphere and by modifying the emissivity and albedo of the polar caps [2, 3]. One would therefore expect that the highly variable nature of the dust cycle would lead to year-to-year variability in the CO_2 cycle. Interestingly, this is not the case.

In this study, we utilize a Mars General Circulation Model to investigate interactions between the dust and CO_2 cycles. During years of enhanced dust storm activity, one could expect two coupling mechanisms between the dust and CO_2 cycles to become important: the radiative and dynamical effects of increasing the atmospheric dust opacity and the albedo changes that will likely result from increased dust sedimentation in the polar regions. As shown below, numerical investigations of these coupling mechanisms suggest that they have opposite effects on the CO_2 cycle. Our working hypothesis is that feedbacks between the dust and CO_2 cycles could lead to a stable, repeatable annual CO_2 cycle.

2. Scientific approach: the NASA Ames Mars GCM

The numerical tool used for this study, the NASA Ames MGCM, is a global 3-D grid point model of the Martian atmosphere [4, 5]. The radiative effects of gaseous CO_2 and airborne dust are accounted for at both solar and infrared wavelengths. The atmospheric dust opacity can either be specified to be constant at a reference surface pressure level (e.g., 6.1) or it can be calculated based on temporally and spatially evolving dust concentrations. In the latter case, dust concentrations are determined in the model self-consistently through the implementation of a fully interactive dust cycle, which includes the lifting, transport and gravitational sedimentation of dust particles. The interactive dust cycle version of the model includes parameterizations for wind stress and dust devil surface dust lifting. Dust is transported in the atmosphere horizontally and vertically by model-resolved winds. Net vertical transport is dictated by the model's vertical winds, turbulent mechanical mixing, and size-dependent gravitational settling. The simulations presented here utilize both the constant dust opacity and interactive dust cycle setups to explore the interactions between the dust and CO_2 cycles on Mars.

3. Constant dust simulations

The dust cycle can affect the polar heat balance (and thereby interacts with the CO_2 cycle) through the radiative and dynamical effects of airborne dust and by altering the albedo of the polar caps due to dust falling to the surface in the polar regions. One would expect that increased dust storm activity (e.g., a global dust storm) would result in increased airborne dust concentrations and enhanced dust settling rates in the polar regions, reducing the polar cap albedo. We have therefore designed constant dust opacity simulations to investigate the effects of higher dust loadings and decreased polar cap albedos individually. We focus on the effects of a variable dust cycle during northern winter and spring, which corresponds to the seasons of maximum extent of the north seasonal CO_2 cap and its recession, respectively.

3.1 Airborne dust and the CO_2 cycle

Two simulations were designed to study the radiative and dynamical effects of increasing the quantity of airborne dust on the CO_2 cycle. When the dust opacity at a reference pressure of 6.1 mbar increases from 0.3 to 2.5, the CO_2 cycle is notably affected (Fig. 1). Throughout northern spring, the globally averaged surface pressure is less in the dust opacity of 2.5 case than the dust opacity of 0.3 case (Fig. 1; top panel). When the dust opacity increases, the mass of CO_2 contained in the cap increases and the time of the cap's maximum mass occurs later in the year (Fig. 1; bottom panel). Consistent with the results of Hourdin et al. [3], this difference results from differences in the sublimation phase of the north cap.

3.2 Cap albedo and the CO_2 cycle

Two additional constant dust opacity simulations were designed to study the effects of decreasing the albedo on the CO_2 cycle. The north and south cap albedos in the

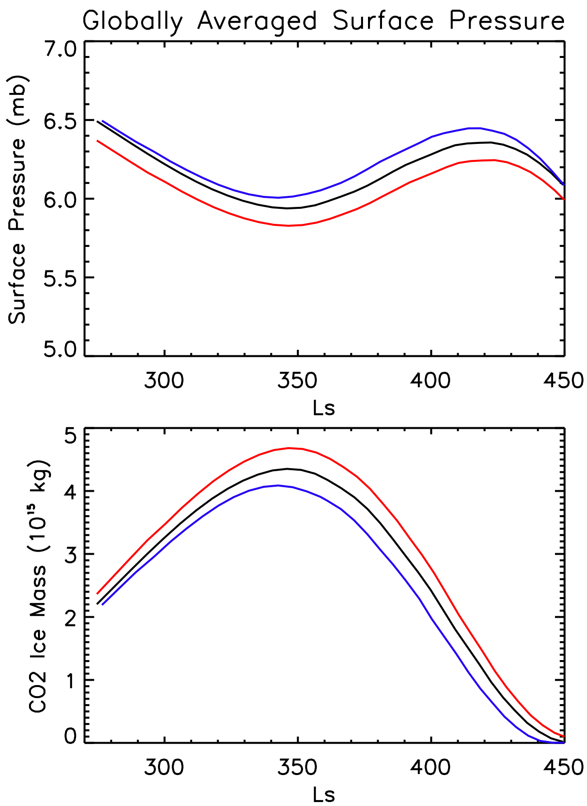

Figure 1: Globally averaged surface pressure (top) and total CO_2 ice mass in the north polar cap (bottom) from three constant dust opacity simulations: 1.) dust opacity of 0.3; nominal cap albedos (black), 2.) dust opacity of 2.5; nominal cap albedos (red), and 3.) dust opacity of 0.3; cap albedos reduced by 10% (blue).

first simulation are those used in standard GCM simulations, and they were chosen because they yield the best-fit to the surface pressures at the Viking landers. The north and south cap albedos in the second simulation were the nominal values reduced by 10%. Each simulation included dust opacities of 0.3, which makes the first simulation identical to one of the simulations in Section 3.1. As shown in Fig. 1, reducing the polar cap albedos also notably affects the CO_2 cycle, but in the opposite manner than increasing the dust opacity. Throughout northern spring, the globally averaged surface pressure is approximately a tenth of a millibar more in the reduced albedo case than the nominal albedo case (Fig. 1; top panel). Because albedo only affects the polar heat balance when the sun is above the horizon, the differences in the CO_2 cycle between these simulations occur during the sublimation phase of the cap. Reduced cap albedos lead to increased sublimation rates and faster cap recession.

These constant dust opacity simulations show that the interactions between the dust and CO_2 cycles are complex and that the radiative/dynamical and cap albedo effects caused by enhancing dust storm activity may compete with each other. The possibility exists that these competing effects may stabilize the CO_2 cycle, leading to the highly repeatable annual pressure curves measured by the Viking landers.

4. Interactive dust cycle simulations

The constant dust opacity simulations suggest that feedbacks between the radiative/dynamical effects of airborne dust and the cap albedo effects may lead to a repeatable annual CO_2 cycle. However, before such a feedback can be tested, we must quantify the role of dust in determining the albedo of the CO_2 caps and the possible year-to-year variability in these albedos. To do this, we utilize the interactive dust cycle version of the Ames Mars GCM. The dust lifting parameterizations are tuned in the baseline simulation to produce atmospheric dust opacities consistent with a non-global dust storm year (similar to the second Viking year). The model predicts temporal and spatial patterns in dust sedimentation rates; we utilize these dust sedimentation rates in the polar regions in combination with model-predicted surface CO_2 ice to calculate polar cap albedo.

4.1 Albedo calculations

A simple scheme is used to calculate the albedo of the polar caps. This scheme is based on the assumption that the dust falls onto the CO_2 ice such that the dust particles remain separate entities from the ice particles. While this is unlikely to be strictly correct, we believe that it is a reasonable starting place. Following Toon et al. [6], we utilize the two-stream approximation for isotropic scattering and make a correction to account for the anisotropic scattering nature of dust particles. This approximation allows us to relate the albedo of a semi-infinite medium to the single scattering albedo of the CO_2 ice/dust medium.

We can relate the relative contribution of the ice and the dust to the total single scattering albedo ($\tilde{\omega}_0$) if we assume that the single scattering albedo of pure CO_2 ice is unity using the following relationship for the volume mixing ratio of dust to ice (V):

$$V = \left(\frac{N_i}{N_d}\right)^{1/2} \left[\frac{(1-\tilde{\omega}_0)}{\tilde{\omega}_0 - \tilde{\omega}_{0d}}\right]^{3/2}, \quad (1)$$

where N_i/N_d is the ratio of the number of ice particles to the number of dust particles, and $\tilde{\omega}_{0d}$ is the single scattering albedo of dust. If we assume an ice grain size, (e.g., 1 mm), a single scattering albedo of dust (0.92; Clancy et al., 2003), and a dust grain size (1.5 μm in the model), we can utilize model results for the number ratio of dust to ice in the cap region to calculate a polar cap albedo. These calculated albedos are compared to TES-observed albedos. Because the CO_2 ice grain size is a free parameter in these calculations, we can use it to calibrate the albedo calculation scheme.

4.2 Year-to-year variability in predicted cap albedos

In order to quantify the effects of the variable nature of the dust cycle on potential variability in the albedo of the polar caps, we designed an additional interactive dust cycle simulation to compare with the baseline simulation. In this simulation, the dust lifting parameterizations were tuned to produce atmospheric dust opacities consistent with those observed during the first Viking year. We again focus on the north cap.

As shown in Fig. 2, the differences in the dust deposition and surface CO_2 ice inventories between the two interactive dust cycle simulations give rise to differences in the calculated cap albedos. The most substantial differences (up to about 7%) occur near the edge of polar cap where the increase in atmospheric dust loading in one simulation leads to a higher dust-to-CO_2 ice ratio.

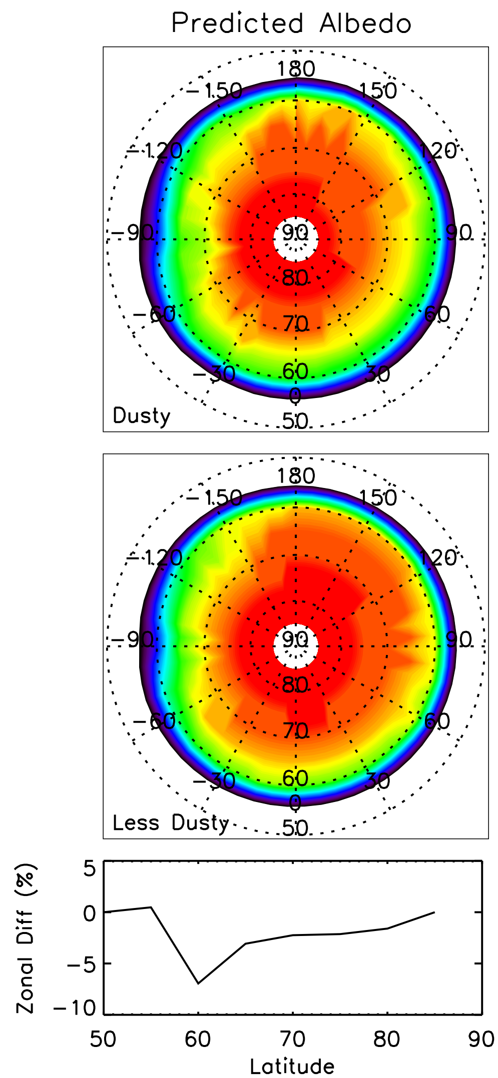

Figure 2: North polar cap albedos calculated from model output for the baseline (top) and enhanced dust storm activity (middle) simulations. Zonally averaged difference between these two sets of model-predicted albedos (bottom).

5. Summary and Future Work

Thus far, this investigation has suggested to us that feedbacks between the dust and CO_2 cycle could lead to a stable, repeatable CO_2 cycle. Constant dust opacity simulations have indicated that the effects of enhanced dust storm activity will likely compete with (and potentially negate) each other. Interactive dust cycle simulations have indicated that year-to-year variations in polar cap albedos can result from enhanced dust storm activity. The only way to fully understand if these couplings between the dust and CO_2 cycles can lead to a highly repeatable annual CO_2 cycle in the presence of a variable annual dust cycle is to implement albedo feedbacks into the interactive dust cycle model. This will be our next step.

5. References

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