MODELING THE MARTIAN DUST AND WATER CYCLES ~632,000 YEARS AGO.

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Introduction: Large variations in Mars' spin/orbit parameters are known to have likely affected Mars' climate significantly over the past few million years. Recently discovered buried CO_2 at the South Pole that could potentially exchange with the atmosphere adds additional complexity to recent climate change studies [1]. Haberle et al. [2; this workshop] show that thick water ice clouds 632,000 years ago may have produced a greenhouse effect strong enough to raise global mean surface temperatures by several tens of degrees Kelvin. The version of the MGCM used in that study utilized relatively simple assumptions for the dust distribution (constant in space and time) that was used to force the model and to provide seed nuclei for the water ice cloud microphysics. A realistic atmospheric dust distribution is important for accurately simulating the nucleation and growth of cloud particles. In turn, this will regulate the thickness of the cloud, the size and optical properties of the cloud particles, and ultimately the radiative effects of the clouds.

There are many reasons to expect that increasing the obliquity and approximately doubling the atmospheric mass will lead to a much different (likely intensified) dust cycle than Mars exhibits today. It is thought that dust is lifted from the Martian surface through the process of saltation, which occurs when the momentum imparted to the surface from the atmosphere (expressed as the wind stress, τ) exceeds the necessary threshold for the detachment of sand-sized particles. The wind stress depends on the near-surface air density, ρ, and the friction wind velocity, v_*, through the relation: $\tau = \rho v_*^2$.

Haberle et al. [3; 2003] and Newman et al. [4; 2005] show that the circulation and therefore the potential for dust lifting (through enhanced near-surface winds) increases as obliquity increases. Additionally, doubling the atmospheric mass will double the wind stress for a given friction wind speed. We therefore expect that dust lifting will increase when the atmospheric mass is increased. However, a competing effect may be that a more massive atmosphere may be sluggish which could result in lower friction velocities. Additionally, radiative-dynamic feedbacks between the amount of dust lifted, atmospheric heating, and the general circulation can either enhance or suppress dust lifting. A fully interactive dust model is therefore necessary to understand the effects of increasing atmospheric mass on dust lifting and atmospheric dust loading. A model in which the dust and water cycles are fully coupled is required to understand how a self-consistently predicted atmospheric dust distribution affects cloud formation and the radiative effects of clouds on Recent Mars.

We present preliminary results of a Mars general circulation modeling study that is a follow-up to the work of Haberle et al. Like in the initial study, we focus on a period of time (~632,000 years ago) when we speculate that the buried 5 mb of CO_2 at the South Pole would have sublimated into the atmosphere. This corresponds to an obliquity of 34.76°, an eccentricity of 0.085, and a longitude of perihelion 259.4° [5]. The processes of dust lifting, transport and sedimentation are modeled explicitly. The spatially and temporally evolving dust distribution forces the model and provides the seed nuclei for the water ice clouds. We will show aspects of the dust and water cycles that result from our simulations.

Methods: We use the NASA Ames Mars GCM (version 2.1d) for this investigation. A fully interactive dust cycle is included, which simulates the lifting, transport and removal of radiatively active dust [8]. Dust is lifted from the surface when the momentum imparted to the surface exceeds a critical value, $\tau^* = 22.5$ mN m^{-2}. Airborne dust interacts with solar and infrared radiation, provides seed nuclei for water ice clouds, and undergoes gravitational sedimentation as free dust and as cores of water ice cloud particles. A complete water cycle is included in some runs that contains sublimation from the north residual cap and the microphysical processes of nucleation, growth, and settling of water ice clouds [11,13]. When clouds form, they are radiatively active. Simulations were designed to investigate the effects of nearly doubling the atmopsheric mass on the dust cycle and the effects of fully coupling the dust and water cycles on the dust cycle, cloud formation and the potential for an efficient water ice greenhouse. To that end, four simulations were carried and are described in Table 1. All simulations are warm started from year 19 of simulations with these orbit parameters, the appropriate atmospheric mass, constant atmospheric dust loading and radiatively active clouds.

Run ID	Atmospheric Mass	Interactive RA Dust?	RA Clouds?
NoCld_7mb	7 mb	Yes	No
NoCld_12mb	12 mb	Yes	No
RACld_7mb	7 mb	Yes	Yes
RACld_12mb	12 mb	Yes	Yes

Table 1: Simulation parameters.

Results: Simulations were executed for two Martian years; results presented here are from the second simulated year. We note that these simulations need to be run out further in the future to ensure equilibration. This will be particularly important for simulations that include radiatively active clouds because we know from experience that equilibration with radiatively active clouds takes many Martian years.

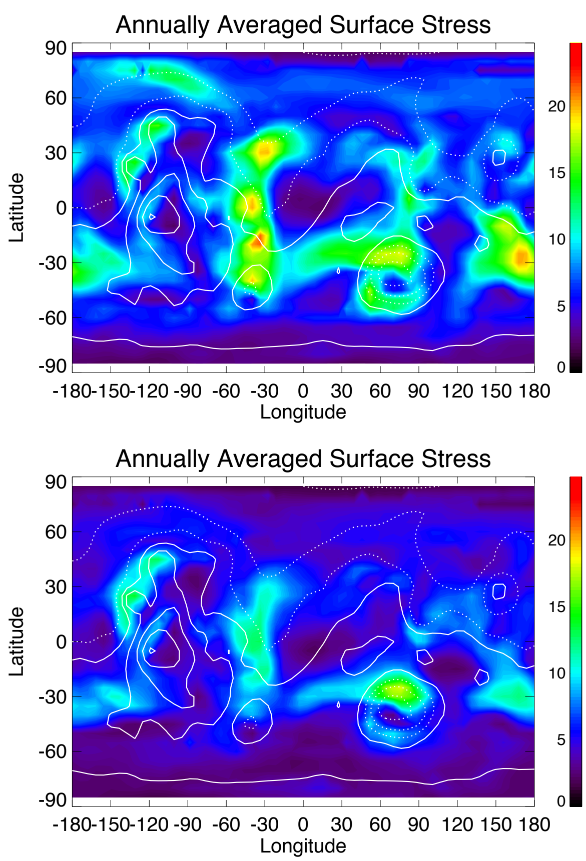

Figure 1: Annually averaged surface stress for a simulation with 12 mbars of CO_2 (top) and a simulation with 7 mbars of CO_2 (bottom).

Effect of extra 5 mbars on atmospheric dust load: To investigate the effect of approximately doubling the mass of the Martian atmosphere on dust lifting and the overall atmospheric dust loading, two simulations were conducted with the orbit parameters discussed above: one with a total CO_2 inventory of 7 mbars and one with a total CO_2 inventory of 12 mbars. These simulations did not include cloud formation.

Increasing the atmospheric mass by nearly a factor of two has a large effect on the simulated dust cycle. Not unexpectedly, the surface stresses are substantially higher in the higher atmospheric mass simulation (Figure 1). The spatial pattern of annual averaged surface wind stress shows that increasing the atmospheric mass alters the magnitude of the surface stress (in many cases by approximately a factor of two) but does not change the locations of maximum stresses. In both simulations, regions of maximum stresses occur on the north and northwest side of Hellas, on the northwest flanks of Tharsis, and through the low-elevation corridor to the east of the Tharsis Highlands (Figure 1).

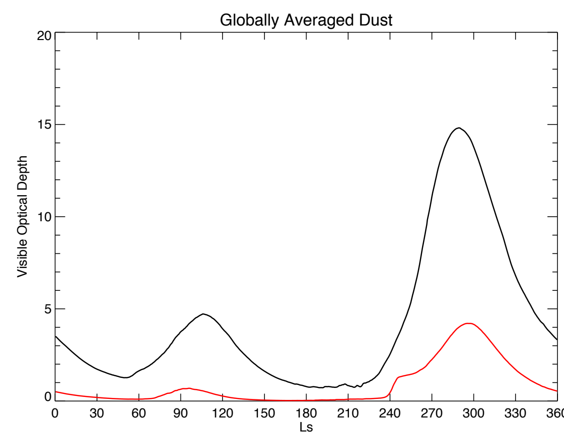

Figure 2: Globally averaged dust optical depth for two simulation without cloud formation. Black curve is from NoCld_12mb; red curve is from NoCld_7mb.

Global dust loading is increased by a factor of three or more throughout the year when the atmospheric mass is nearly doubled (Figure 2). In both simulations, there are two peaks in the globally averaged dust optical depth, one at Ls~110°, and a higher magnitude peak at Ls~290°. The factor of three results from the the classic dust/dynamic feedback, whereby the circulation is strengthened when dust loading increases, which in turn increases surface wind stress and dust lifting. In this case, the catalyst for a strong feedback is the increased atmospheric mass and its affect on surface wind stress.

Effect of cloud formation on atmospheric dust load: To investigate the effect of the fully coupled dust and water cycles on the dust cycle, two more simulations were conducted that included radiatively active cloud formation: one with a total CO_2 inventory of 7 mbars and one with a total CO_2 inventory of 12 mbars.

The fully coupled simulations produce significantly different dust cycles than the simulations that did not include cloud formation. The total dust loading in both of the simulations that include radiatively active cloud formation is greatly reduced compared to the two simulations without cloud formation (Figures 2 and 3). The peak in the globally averaged dust optical depth during southern summer is reduced in the 12 mbar / coupled simulation by a factor of three compared to the 12 mbar / no-cloud simulation. Similarly, the peak in the globally averaged dust optical depth during southern summer is reduced in the 7 mbar / coupled simulation by a factor of three compared to the 7 mbar / no-cloud simulation. This result implies that cloud formation and/or the radiative effects of clouds has a stabilizing effect on dust lifting. The reason for this is not yet understood, but it will be the focus of investigation in the near future. It is interesting to note that, even in the simulations that include cloud formation, increasing the atmospheric mass results in an increase in atmospheric dust loading of approximately the same magnitude as in the no-cloud cases.

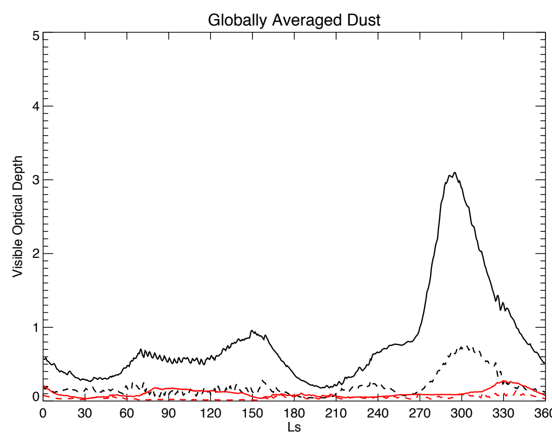

Figure 3: Globally averaged dust optical depth for two simulation with radiatively active clouds. Black solid curve is from RACld_12mb; red solid curve is from RACld_7mb. Dashed curves are the globally averaged optical depth of the dust that is incorporated into the cores of the water ice cloud particles.

Effect of coupling dust and water cycles on the water ice cloud greenhouse: The final goal of this work is to understand how fully coupling the dust and water cycles affects cloud formation and the effectiveness of the cloud greenhouse. We compare results from the 12 mbar simulation that includes radiatively active cloud formation (RACld_12mb from Table 1) to the 12 mbar radiatively active cloud simulation from Haberle et al. (this workshop), which did not include an interactive dust cycle.

Figure 4 shows the annual and zonal average cloud mixing ratio for the RACld_12mb and the Haberle et al. simulation. Compared to the simulation without an interactive dust cycle, the fully coupled simulation produces clouds that are comparable but slightly thinner. The cloud particle sizes are also similar between the two cases (not shown). The similar cloud thickness and particles sizes lead to greenhouse warming that is also comparable to that seen in the constant dust simulation.

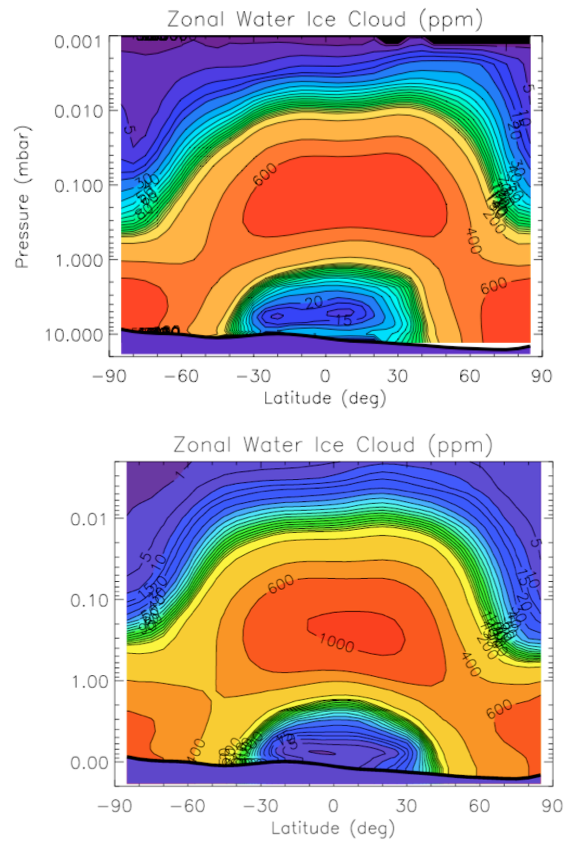

Figure 4: Annual and zonal mean water cloud mass mixing ratio from the fully coupled simulation (RACld_12mb; top panel) and the constant dust simulation from Haberle et al. (this workshop; bottom panel).

Table 2 summarizes the results of the fully interactive and coupled simulation (RACld_12mb) and compares it to a current Mars simulation and the constant dust simulation of Haberle et al. The greenhouse power from RACld_12mb is 38 K, which is slightly lower than in the constant dust simulation, but is still considerably higher than the current Mars case. We note again that the coupled simulation discussed here is warm started from a Haberle et al.'s constant dust run and has not yet equilibrated.

Because the cloud greenhouse power is trending slightly downward compared to the constant dust simulation, we do not yet know the magnitude of the cloud greenhouse in the interactive/coupled case.

	Ap	Te	Tse	Te-Tse
Today	0.24	207	212	5
632 Kya + 5 mb; Constant Dust	0.35	199	240	41
632 Kya + 5 mb; Interactive Dust (RACld_12mb)	0.33	201	239	38

Table 2: Planetary Albedo (Ap), effective temperature (Te), effective surface temperature (Tse), and greenhouse warming (Tse-Te).

Preliminary Conclusions and Future Work: There are several preliminary conclusions from this investigation:

1. The effect of increasing atmospheric mass on the simulated dust cycle is not linear. The classic dust/dynamics feedback tends to amplify dust lifting whether clouds are present or not.
2. Radiatively active clouds reduce dust lifting, which suggests that there is a stabilizing effect in the system.
3. The cloud greenhouse is reduced in the fully interactive simulations. We are uncertain about the magnitude of the reduction because our preliminary simulations have not yet equilibrated.

We plan to extend these runs until they equilibrate and then we will conduct a comprehensive analysis of the results to better understand the nature of the cloud feedback mentioned above and the magnitude of the resulting cloud greenhouse effect.

References: [1] Phillips, R.J. et al. (2011). *Science*, 332, p. 838. [2] Haberle, R.M. et al., MRCC Workshop, this C.P. [3] Haberle, R.M. et al. (2003). Icarus, 161, p. 66. [4] Newman, C.E. et al. (2005). Icarus, 174, p. 135. [5] Laskar, J. et al. (2004). Icarus, 170, p. 343.