

A CLOUD GREENHOUSE EFFECT ON MARS: SIGNIFICANT CLIMATE CHANGE IN THE RECENT PAST? R.M. Haberle¹, M.A. Kahre¹, J.L. Hollingsworth¹, J. Schaeffer², F. Montmessin³, and R.J. Phillips⁴, ¹Space Science and Astrobiology Division, NASA/Ames Research Center, Moffett Field, CA 94035, rob-ert.m.haberle@nasa.gov, melinda.a.kahre@nasa.gov, jeffery.l.hollingsworth@nasa.gov, ²Dell Services Federal Group, NASA/Ames Research Center, Moffett Field, CA 94035, james.r.schaeffer@nasa.gov, ³LATMOS-UVSQ/CNRS/IPSL, 11 bd d'Alembert, 78280 Guyancourt, France, franck.montmessin@latmos.ipsl.fr, ⁴Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, CO 80302, roger@boulder.swri.edu.

Introduction: The large variations in Mars' spin/orbit parameters are known to be significant drivers of climate change on the Red planet. However, these variations can force significant changes in atmospheric mass and global cloudiness. The discovery of ~ 5 mb global equivalent of CO₂ ice that may be buried underneath the South Polar Residual Cap (SPRC) [1] suggests that the minimum exchangeable inventory of CO₂ is ~ 12 mb, and that global mean surface pressures (hence mass) have varied by roughly this amount. Such variations will change the greenhouse effect and the seasonal cycles of dust, water, and CO₂. The ~ 10 m of water (global equivalent) that comprise the North Polar Residual Cap (NPRC) can also be mobilized and drive large amounts of water into the atmosphere at times of high obliquity raising global cloudiness as well [2]. Since the radiative effect of clouds can be significant they too must be considered when assessing climate change.

atmospheric mass, and global cloudiness. We show that within the past million years when the obliquity was higher than it is today, changes in global cloudiness can dominate the response of the climate system compared to changes in atmospheric mass. In particular, we show that clouds from a greatly intensified Martian hydrological cycle may have produced a greenhouse effect strong enough to raise global mean surface temperatures by as much as 40 K. This cloud greenhouse is made possible by the ability of the Martian atmosphere to transport water to high altitudes where optically thick cold clouds form, reduce the outgoing long wave radiation, and cause surface temperatures to rise to maintain global energy balance.

Context: The simulations we present follow those reported in [1] which gives SHARAD evidence for buried CO₂ ice at the South Pole. We speculated that all of that ice, ~ 5 mb global equivalent, would have sublimated into the atmosphere approximately 632,000 years ago when solar insolation at the South Pole during summer solstice was the highest its been in the past million years (~ 400 W m⁻² compared to ~ 210 W m⁻² for today's orbit). The orbital conditions then were obliquity=34.76°, eccentricity=0.085, and longitude of perihelion=259.4°. The simulations we presented in the that paper were based on a dry model and so focused on the changes in the greenhouse effect of a pure CO₂ atmosphere. Here we report results from our water cycle model, which includes the radiative effects of water vapor and clouds.

Model Description: The model hydrological cycle simulates the exchange of water between surface ice, atmospheric water vapor, and clouds. Water sublimates from surface deposits at a rate dependent on a complete surface energy budget. It is transported in the atmosphere by the large-scale circulation and convection, and it forms clouds using a microphysics package that includes nucleation, growth, and sedimentation. The clouds release latent heat and their radiative scattering properties depend on particle size and dust content, which are self-consistently predicted. We initialize the model with a large surface reservoir of water ice at the North Pole configured as it exists there today. For additional radiative heating (and a source of cloud nuclei) we assume dust particles are distributed nearly

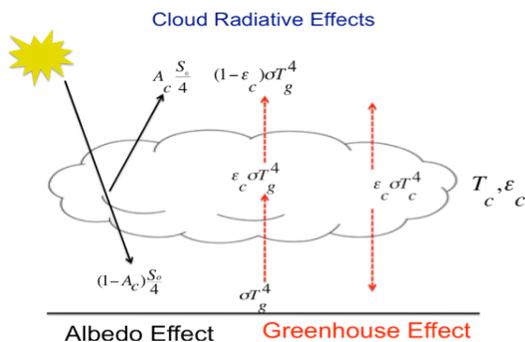


Fig. 1. Cloud Radiative Effects

As illustrated in Fig. 1, clouds over relatively dark surfaces reflect sunlight, raise the planetary albedo, and provide a negative forcing to climate system. On the other hand, they absorb infrared radiation and emit some to the surface thereby providing a greenhouse effect and a positive forcing to the climate system. The net forcing to the climate system depends on the magnitude of these effects, which in turn depends on the cloud optical depths, altitudes, and particle sizes.

In this paper we present results from the NASA/Ames Mars GCM that assess the sensitivity of the climate system to changes in orbit properties, at-

uniformly with altitude in the lower atmosphere and produce a column optical depth of ~ 0.3 . We run the model for 20 Mars years and compare cases with and without radiatively active clouds. We perform these simulations with two different inventories exchangeable CO_2 : One for 12.1 mb (to represent the hypothetical case where the 5 mb of buried CO_2 at the South Pole is released to the atmosphere), and one for 7.1 mb (which represents the present inventory).

Results: The simulated water cycle for the 12.1 mb inventory of CO_2 and radiatively active clouds (RAC) is shown in Fig. 2.

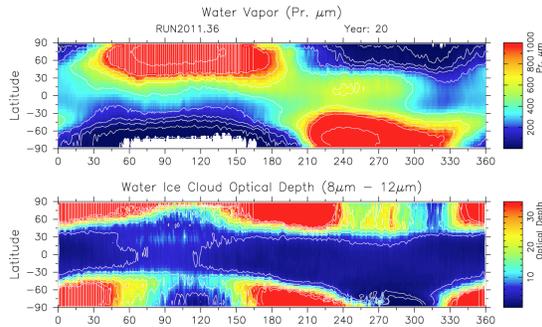


Fig 2. Column water vapor abundances (top) and cloud opacity (bottom) for the 12.1 mb / RAC simulation.

The water cycle is much wetter and cloudier than it is today. Peak water column abundances exceed several thousand microns and infrared cloud opacities are well over 10 in polar winter regions. This same run with passive clouds is much drier having peak water columns on the order of 500 pr- μm . Thus, the radiative effects of the clouds greatly increase atmospheric moisture.

The sensitivity of surface temperatures to the radiative effects of clouds is shown in Fig. 3.

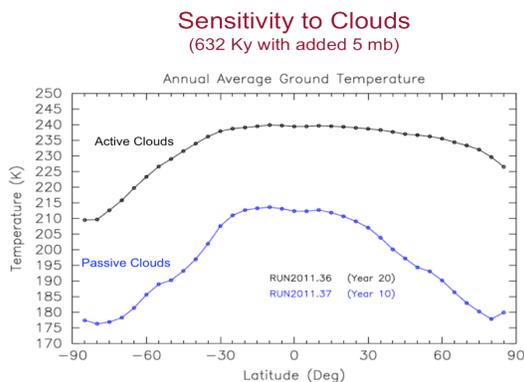


Fig. 3. Zonally averaged annual mean surface temperatures as a function of latitude for active (black) and passive (blue) clouds with a total CO_2 inventory of 12.1 mb and orbital conditions appropriate to 632Ky.

With passive clouds zonal and annual mean surface temperatures vary from ~ 175 K in polar regions to ~ 210 K in the tropical regions, a pattern not too dissimilar from today's climate. With radiatively active clouds, however, surface temperatures are much higher. Temperatures in the tropics and Northern Hemisphere range from 230-240 K, and decline to 210K at the South Pole. Thus, the clouds have a strong warming effect.

Sensitivity to Surface Pressure (632 Ky with Active Clouds)

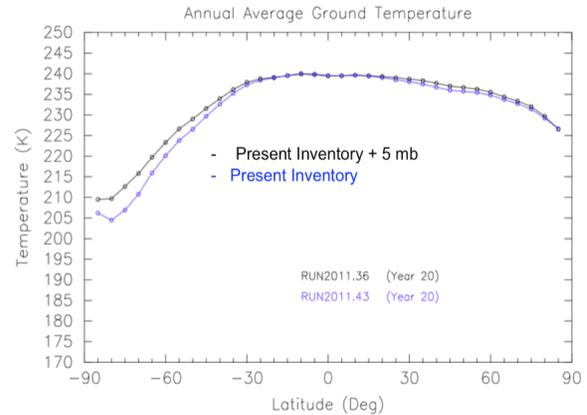


Fig. 4. Same as Fig. 2 but for 12.1 mb inventory (black) and 7.1 mb inventory (blue), orbital conditions appropriate to 632Ky and RAC.

The sensitivity of surface temperatures to the CO_2 inventory is shown in Fig. 4. Adding 5 mb has a very small effect on surface temperatures. “Doubling” the CO_2 boosts the greenhouse effect only slightly because there is very little pressure broadening of the lines in the already opaque $15 \mu\text{m}$ region. Thus, most of the warming is produced by the cloud greenhouse effect.

Table 1 summarizes our key results. The much wetter and cloudier atmosphere produces 39-41 K of greenhouse warming, which is about 7 times greater than today's climate system, in spite of the fact that the planetary albedo increases by almost 50%. Without clouds, the higher surface pressure and wetter atmosphere give 8 K of greenhouse warming, which is only several degrees greater than today's warming. Thus, clouds produce a strong greenhouse effect in these simulations.

Table 1. Planetary Albedo (A_p), effective temperature (T_e), effective surface temperature (T_{se}), and greenhouse warming ($T_{se}-T_e$), from indicated runs.

Run	A_p	T_e	T_{se}	$T_{se}-T_e$
Mars Today	0.24	207	213	6
632 Ky Pass 7.1 mb	0.24	208	214	6
632 Ky RAC 7.1 mb	0.35	200	239	39
632 Ky Pass 12.1 mb	0.24	207	215	8
632 Ky RAC 12.1 mb	0.35	199	240	41

The strong cloud greenhouse is due to: (a) the clouds form at high altitudes where temperatures are colder than the surface, (b) their particles sizes are large enough ($\sim 10\text{-}20\ \mu\text{m}$) to efficiently interact with infrared radiation, and (c) their concentrations are high enough to produce large infrared opacities (>1). The cooling they produce by reflecting sunlight is more than compensated by warming from increased thermal emission to the surface (Fig. 5).

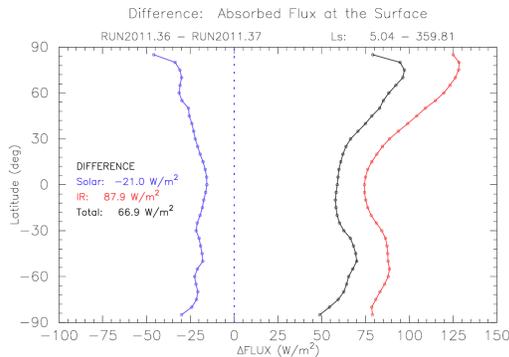


Fig. 5. Change in annual and zonal mean fluxes absorbed at the surface for radiative vs. passive clouds. Blue line is for solar radiation, red is for infrared, black is the net forcing.

The altitude of the clouds is critical. To produce a net warming the clouds must be high and cold. The circulation achieves this in our model through a cloud feedback effect that intensifies, expands, and deepens the Hadley circulation (Fig. 6). As a consequence the clouds form mainly (but not exclusively) in the upper branch of the Hadley circulation where temperatures are cold (Fig. 7).

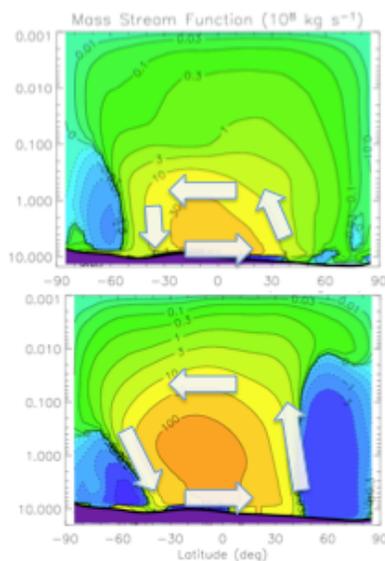


Fig. 6. Zonal mean mass stream function ($10^8\ \text{kg s}^{-1}$) at northern summer solstice for passive (top) and active (bottom) clouds.

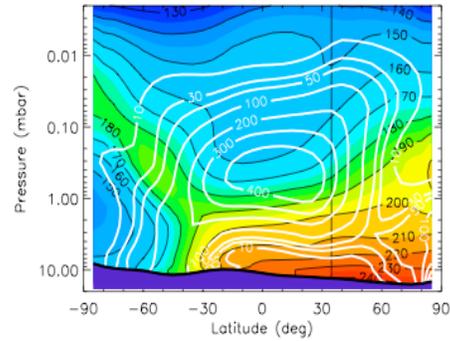


Fig. 7. Zonal mean cloud mass mixing ratio ppm (white) and temperature K (color) at $L_s=90^\circ$.

Discussion: How realistic is this? If we assume the clouds are perfect reflectors in the visible and there are no other opacity sources, a simple greenhouse model would predict a surface temperature of $T_g = T_c [2/(2-\epsilon)]^{2.5}$ where ϵ is the cloud emissivity. For an optically thick cloud ($\epsilon=1$) with $T_c \sim 200\ \text{K}$ (Table 1), this gives $T_g \sim 240\ \text{K}$ which provides about 40 K of greenhouse warming – about what the full model is producing. However, this only means that the clouds are optically thick, so it is natural to ask if the model is over predicting cloud opacities.

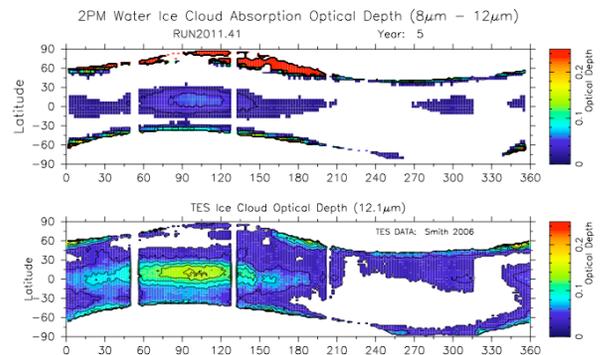


Fig. 8. Infrared cloud opacities for the present climate system as simulated by the model (top) and as observed by TES (bottom).

For the present climate simulation the model clouds are too thick in the polar regions and too thin in the tropics (Fig. 8). It is not clear what the implications of this are for the past climate simulation, but it does indicate that model is missing something. Thus, we cannot be sure the simulated past climate greenhouse warming is a real and robust result.

On the other hand, a significant cloud greenhouse effect does appear in other models. The post-impact climate change studies conducted by Colaprete et al. [3] and Segura et al. [4] each show a very sizeable warming due to clouds. More recent work by Madeleine et al. [5] for high obliquity conditions, and Urata

and Toon [6] for early Mars, also find warmings of comparable magnitudes. Thus, the potential for a strong cloud greenhouse clearly exists. To be effective, it requires an energy source to drive up atmospheric water content (e.g., high obliquity, impact energy), and a circulation that forms optically thick clouds at high altitudes where temperatures are cold. The Martian circulation is capable of producing such conditions.

It is worth noting that in these simulations the NPRC is stable, i.e., there is no net annual transfer of water to lower latitudes. Thus, these conditions could prevail for thousands of years. At higher obliquities, it is possible that the NPRC could be mobilized and its ice redeposited elsewhere on the planet leading to cooler conditions as in [2]. At lower obliquities, the cloud greenhouse would be muted as less energy would be available to mobilize the water. Thus, there may be an intermediate range of obliquities that maximizes the strength and duration of the cloud greenhouse effect. Given the geologically short time scale for obliquity oscillations ($\sim 10^5$ years) cloud greenhouse warming on Mars may have occurred on many occasions in the past. Connecting these possible episodes to the geological record would help validate or refute this idea.

Finally, we note that a cloud greenhouse may have been involved in deglaciating snowball Earth, or in its hothouse climates of the Phanerozoic [7]. Thus, a cloud greenhouse for Mars does not seem unreasonable.

Conclusions. We have investigated the potential for recent climate change on Mars by exploring the consequences of three forcing functions with a GCM: orbit variations, atmospheric mass, and cloudiness. For conditions appropriate to 632 Ky when the obliquity was $\sim 35^\circ$ and summertime insolation at the South Pole was the highest its been in the past 1 My, a 5 mb increase in atmospheric mass raises mean annual surface effective temperatures by several degrees. However, when the clouds are radiatively active temperatures increase by ~ 40 K. The strong cloud greenhouse effect is made possible by a feedback on the circulation, which forms optically thick clouds at high altitudes that increase the downward IR to the surface far more than they reduce solar radiation reaching the surface.

However, as intriguing as these results are they need to be interpreted with caution. There is much we don't know about cloud formation on Mars. Our model does not treat sub grid scale phenomena (e.g., cloud fraction) and there are many sensitivities of the cloud microphysics scheme that need to be assessed. Our assumption of a constant dust loading is certainly not correct. Simulations with interactive dust, water, and CO₂ cycles will ultimately be needed to fully understand the cloud greenhouse climate system.

References: [1] Phillips, R.J. (2011). *Science*, 332, p. 838. [2] Forget, F. et al. (2006). *Science*, 311, p. 368. [3] Colaprete, A., et al. (2003). 6th International Conference on Mars, No. 3281. [4] Segura et al., (2008). *JGR*, 113, doi:10.1029/2008JE003147. [5] Madeleine, J.-B., et al. (2011), Fall AGU, P23E-05. Urata, R., and Toon, O.B. 3th International Conf. on Early Mars, Carson City, NV. [7] Pierrehumbert, R. T. (2010). *Principles of Planetary Climate*, Cambridge Univ. Press.