A CLOUD GREENHOUSE EFFECT ON MARS: SIGNIFICANT CLIMATE CHANGE IN THE RECENT PAST? R.M. Haberle[1], M.A. Kahre[1], J. Schaeffer[2], F. Montmessin[3], and R.J. Phillips[4], [1]Space Science and Astrobiology Division, NASA/Ames Research Center, Moffett Field, CA 94035, robert.m.haberle@nasa.gov, melinda.a.kahre@nasa.gov, [2]Dell Services Federal Group, NASA/Ames Research Center, Moffett Field, CA 94035, james.r.schaeffer@nasa.gov, [3]LATMOS- UVSQ/CNRS/IPSL, 11 bd d'Alembert, 78280 Guyancourt, France, [4]Southwest Research Institute, 1050 Walnut St, Suite 300, Boulder, CO 80302, roger@boulder.swri.edu.

Introduction: The large variations in Mars' orbit parameters are known to be significant drivers of climate change on the Red planet. The recent discovery of buried CO_2 ice at the South Pole adds another dimension to climate change studies [1]. In this paper we present results from the Ames GCM that show within the past million years it is possible that clouds from a greatly intensified Martian hydrological cycle may have produced a greenhouse effect strong enough to raise global mean surface temperatures by several tens of degrees Kelvin. It is made possible by the ability of the Martain atmosphere to transport water to high altitudes where cold clouds form, reduce the outgoing longwave radiation, and drive up surface temperatures to maintain global energy balance.

Context: The simulations we present follow those reported in [1] which gave SHARAD evidence for buried CO_2 ice at the South Pole. We speculated that all of that ice, ~ 5 mb global equivalent, would have sublimated into the atmosphere approximately 600,000 years ago when solar insolation at the South Pole during summer solstice was the highest its been in the past million years. 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 CO_2 atmosphere. Here we report results from our state-of-the-art 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, atmopheric water vapor, and clouds. Water sublimates from surface deposits at a rate dependent on a complete surface energy budet. 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 a constant background dust optical depth of ~0.3. We run the model long enough for the the top of the atmosphere radiative fluxes to balance, and the water cycle to equilibrate. The total inventory of exchangeable CO_2 is 12.1 mb to represent the hypothetical case where all the buried CO_2 at the South Pole is added to the present inventory of 7.1 mb.

Results: As found by previous investigators, the water cycle is much wetter at higher obliquities than it is today [2]. It is also much cloudier. Clouds can warm or cool the surface depending on their concentrations, particle size, and altitude. Our simulations suggest that clouds have a strong warming effect for the orbital conditions of 600,000 years ago. A net cloud surface warming was also found for different orbital conditions in [3]. Table 1 gives our key results. The much wetter, cloudier, and thicker atmosphere produces 33 K of greenhouse warming – equivalent to Earth's atmosphere - 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_e-T_{se})

Run	A_p	T_e	T_{se}	T_e-T_{se}
Rad Act Clds	0.34	199	232	33
Rad Inact Clds	0.23	207	215	8

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 (~10 μm) to efficiently interact with infrared radiation, and (c) their concentrations are high enough to produce large infrared opacities (>10). The cooling they produce by reflecting sunlight back to space is more than compensated by warming from increased thermal emission to the surface.

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 cloud feedback effect that an intensifies, expands, and deepens Hadley circulation. As a consequence the clouds form mainly in the upper branch of the Hadely circulation which is about a scale height higher than when the clouds are radiatively inactive (Fig. 1).

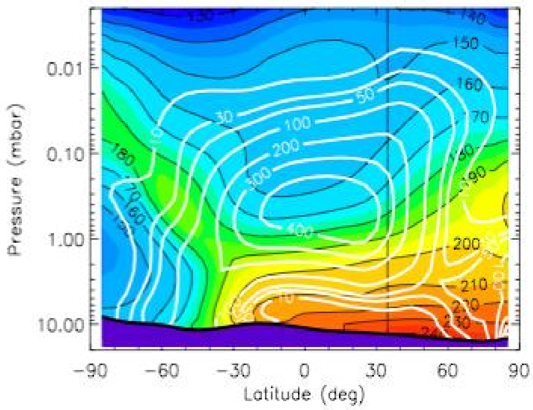

Fig.1. Zonal mean cloud mass mixing ratio ppm (white) and temperature K (color) at L_s=90°.

The cloud greenhouse raises annual mean surface temperatures to 226 K compared to today's 201 K. The 25 K increase is not uniform in latitude (Fig. 2). Much greater warming occurs in the Northern Hemisphere where annual mean temperatures increase by as much as 40 K.

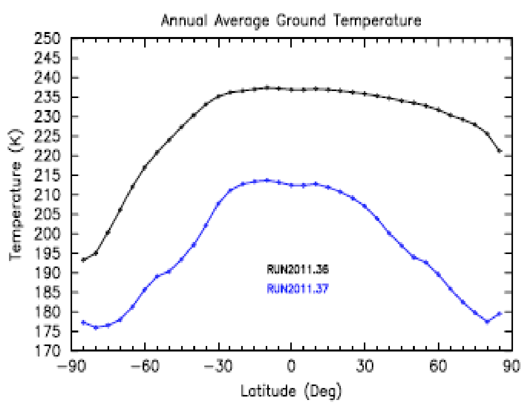

Fig. 2. Annual averaged ground temperatures for rad act clds (black) and rad inact clds (blue).

Furthermore, the warming in the Northern Hemisphere is so strong during winter that surface temperatures do not get cold enough to form a seasonal CO_2 ice cap (Fig. 3).

Discussion: An important result of these simulations is that the north polar ice sheet is stable. Ice does not accumulate at latitudes outside this region. This means that our experimental setup is plausible. A simulation with today's inventory of CO_2 (not shown) indicates that a cloud greenhouse still exists, though less pronounced. Thus, the extra 5 mb delivers a stronger cloud greenhouse. We also note that a cloud greenhouse may have been involved in deglaciating snowball Earth, or in its hothouse climates of the Phanerozic [4]. Thus, a cloud greenhouse for Mars does not seem unreasonable.

However, as intriguing as these results are they need to be interpreted with caution. The shear magnitude of the warming we simulate is stunning. There is much we don't know about cloud formation on Mars. Our model tends to predict clouds that are too thick in the present atmosphere so it is possible we are overpredicting cloudiness. And our assumption of a constant dust loading is certainly not correct. Simulations with interactive dust, water, and CO_2 cycles will ultimately be needed to fully understand the climate system. Yet our results do show the potential for a significant cloud greenhouse effect on Mars that may have warmed the planet on many occasions in the past to levels not previously anticipated. Connecting these episodes to the geological record would help validate or refute this mechanism.

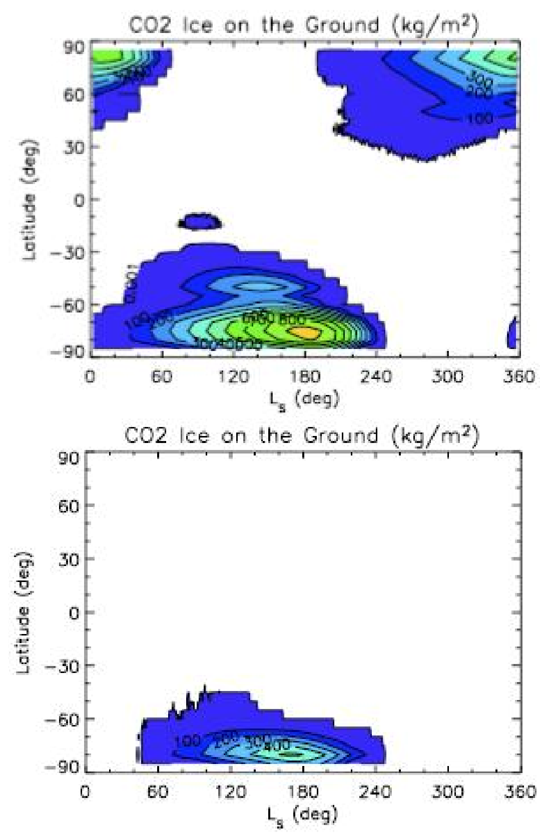

Fig. 3. Zonal mean CO_2 ice on the ground for rad act clds (bottom) and inact clds (top).

References: [1] Phillips, R.J. (2011). *Science*, 332, p. 838. [2] Forget, F. et al. (2006). *Science*, 311, p. 368. [3] Madeleine, J.-B., et al. (2011), Fall AGU, P23E-05. [4] Pierrehumbert, R. T. (2010). Principles of Planetary Climate, *Cambridge Univ. Press.*