RADIATIVE EFFECTS OF WATER ICE CLOUDS ON THE MARTIAN SEASONAL WATER CYCLE.

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Introduction:

Water ice clouds form and dissipate in the Martian atmosphere and though their abundance is small compared to the bulk atmosphere, they play a significant role in the regulation of the net annual meridional transport of water (Clancy et al., 1996; Montemssin et al., 2004; 2007). Here we show that the radiative effects of water ice clouds play an important role in the determining the thermal structure of the atmosphere, and the wetness of the seasonal global water cycle.

Approach:

We use version 2.1 of the NASA/Ames Mars General Circulation Model to demonstrate these effects. This version of the model of the model runs at 5° x 6° (lat/lon) with 24 vertical layers up to an altitude of ~ 80 km. It includes a tracer transport scheme based on the Van Leer formulation, a 2-stream radiation code that accounts for gaseous absorption in the presence of scattering aerosols, a complete water cycle package with microphysical processes that account for nucleation, growth, and settling, a PBL scheme based on the level-2 Mellor-Yamada formalism of turbulent mixing, and a subsurface module that allows for heterogeneous soil properties. We use MOLA surface topography, and LMD-derived albedo and thermal inertias for the lower boundary conditions, each smoothed to the model grid resolution.

Our model has the capability to transport aerosol tracers using bins or moments in order to account for particle size variations. For the present work, we use a moment scheme and assume a log-normal size distribution. We specify the effective standard deviation (σ_{eff}), which allows us to transport two quantities: mass and number density. From these we derive the effective radius (r_{eff}) of a given population of aerosols. Dust injected into the atmosphere follows a log-normal distribution with r_{eff} =2.5 μm, and σ_{eff}^2 =0.5. Once in the atmosphere dust concentrations and particle size distributions evolve by transport, turbulent mixing, settling, and cloud scavenging. For ice clouds we assume σ_{eff}^2 =0.1.

Model Simulations:

We run the model from dry initial conditions for 5 Mars years to allow the water cycle to equilibrate. In each simulation we assume that the NPRC, which exists in the model everywhere poleward of 80°N, is a permanent source for atmospheric water. We prescribe the atmospheric dust loading based on zonal mean TES Mars Year 26-27 observations (i.e., no global dust storm). Nominally, we specify an exponential variation of dust with altitude for the radiative heating calculations. Thus, dust radiative effects are not self-consistently determined. However, we do transport dust passively to allow it to serve as condensation nuclei, and in some simulations we have enabled fully interactive dust lifting and coupling to the water cycle (Kahre et al., 2011).

We begin our study by comparing the results of two simulations: a baseline run in which water ice clouds are not radiatively active; and a radiatively active cloud (RAC) run in which the clouds are radiatively active. For the latter, the cloud optical properties are calculated off line using a Mie theory and stored in a look up table where the scattering properties are a function of particle size and dust/ice ratio, both of which are predicted quantities in the model.

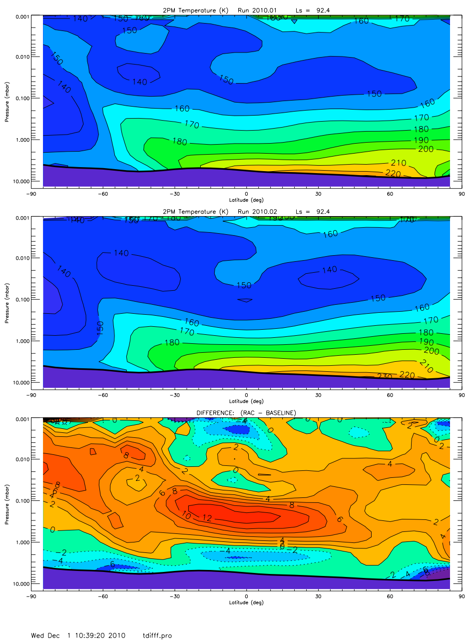

Fig. 1. Time and zonal mean 2PM temperatures at northern summer solstice for the RAC (top), baseline (middle), and difference (bottom).

Results:

Thermal effects. The main thermal effect of radiatively active clouds is to warm the tropical upper troposphere during northern summer (see Fig. 1), and cool the winter polar regions at low levels in both hemispheres (only the southern winter case is shown here). The cold aphelion clouds absorb upwelling radiation from the warmer surface below and this increases their temperatures by as much as 10°K and gives results that are more consistent with TES observations. Wilson et al (2008) reported a similar effect. In the winter lower troposphere, however, the polar hoods act as efficient radiators since these clouds form at temperatures comparable to surface temperatures. Hence, the polar hoods tend to cool the atmosphere (also by as much as 10°K). These changes in the tropical static stability and wintertime equator-to-pole temperature gradient can have a significant influence the dynamical response of the atmosphere (Hollingsworth et al., 2011).

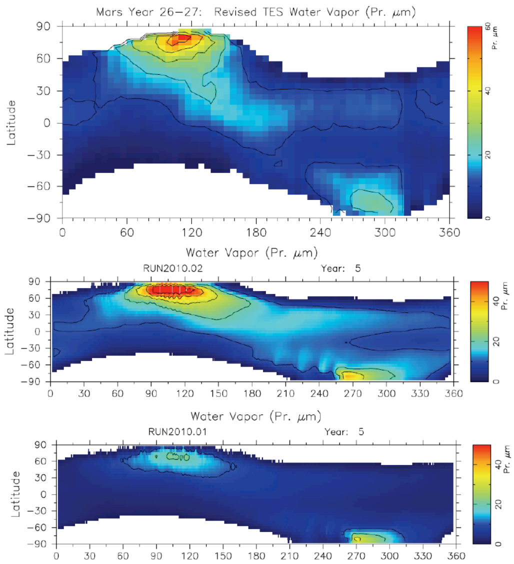

Fig. 2. Time and zonal mean TES (top), Baseline (middle), and RAC (bottom) column water vapor abundances.

Water cycle effects. Radiatively active clouds have a dramatic effect on the simulated water cycle. Overall, they tend to dry out the water cycle by more than a factor of two. This is illustrated in Fig. 2 where peak north polar simulated summertime column vapor maxima are reduced to ~ 20 pr-μm, compared to ~60 pr-μm in the baseline simulation.

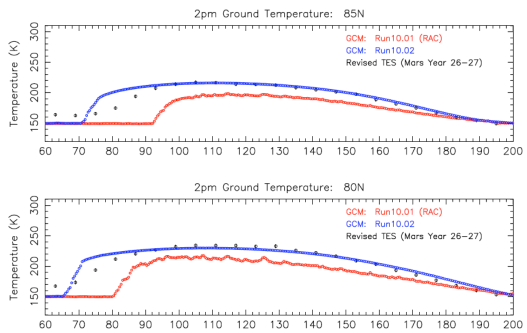

Fig. 3. Baseline and RAC zonal mean surface temperatures for the season of interest. Symbols are TES surface temperatures.

This drying of the water cycle is due to a number of factors, such as low level atmospheric cooling over the NPRC (Fig. 1), but is predominately the result of a reduction in sublimation rates caused by a pronounced decline in surface temperatures (Fig. 3). At the two latitudes where the NPRC exists in the model, zonal mean surface temperatures are lowered by 10-20°K when the clouds are radiatively active, and are well below the observed surface temperatures.

The reduction in surface temperatures is due to the formation of optically thick low-lying clouds that reduce the net radiative input at the surface. Clouds reflect sunlight thereby reducing the solar flux reaching the ground, but they also enhance thermal emission and thereby increase the downward infrared flux reaching the surface. In our simulations the reduction in solar radiation exceeds the increase in the downward infrared causing a net cooling effect (Fig. 4).

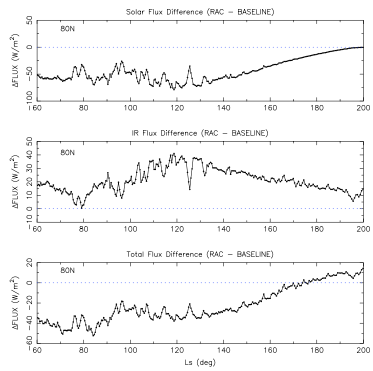

Fig. 4. Change (RAC-baseline) in zonal mean absorbed solar radiation at the surface (top), infrared radiation (middle), and net effect (bottom) at 80°N.

Do such clouds exist? Not at the levels predicted by the model. Model visible cloud opacities greatly exceed one throughout most of the NPRC region (Fig. 5).

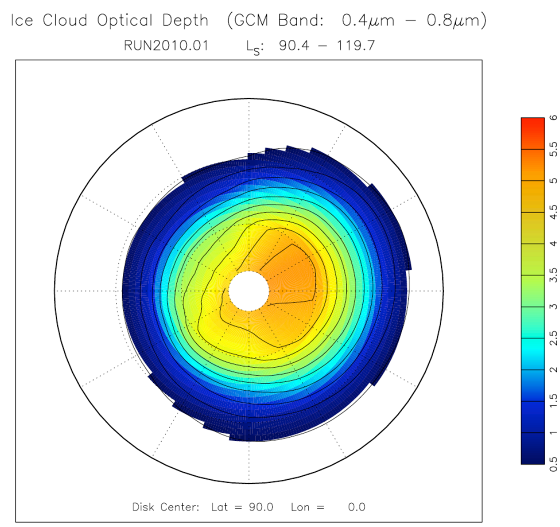

Fig. 5. Polar projected time mean column visible cloud opacities in the RAC run.

Widespread cloudiness at this level is not evident in imaging data. While it is difficult to detect clouds over bright surfaces, the clarity of the dark lanes and circumpolar sand seas in MARCI images is striking and suggests that optically thick low-level clouds are not present over the NPRC during summer.

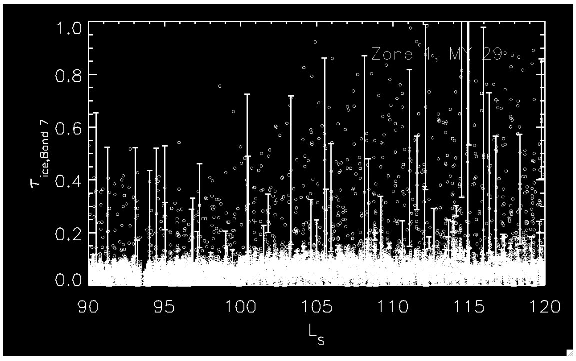

Fig. 6. Derived MARCI Band 7 UV cloud opacities for a narrow latitude band at 77°N centered on the prime meridian between 90°E and 90°W longitude.

To quantify this, we have computed cloud opacities at a number of points within the dark lanes of NPRC and in several latitude bands surrounding it. Fig. 6 shows our derived cloud opacities from MARCI band 7 (320 nm) images of a narrow latitude band just off the NPRC that covers the period of maximum expected sublimation. While clouds do exist, they are variable and have opacities generally less than one.

As noted earlier the radiative effect of these low-lying clouds is to cool the atmosphere. However, in this case, the change in thermal structure does not agree with observations (Fig. 7). Temperatures are too cold. Thus, we conclude that the model predicts excessive clouds in the NPRC region during early summer.

Discussion:

In addition to these two basic simulations we have conducted numerous additional experiments to determine plausible ways to reduce the summer clouds. We have examined the effect of water vapor latent heat release, water vapor radiative effects, differing dust contents of the north polar summer atmosphere, changes in NPRC surface properties, and the new Iraci et al. (2010) nucleation parameters. None of these changes improves the results: the simulated water cycle remains dry because of thick, reflective, low-lying clouds over the NPRC.

We have also tried throttling the sublimation rates to allow transport to remove water from the NPRC region faster than the surface supplies it. While this does reduce cloudiness, it leads to an overly dry water cycle. Unless our equatorward transport is greatly underestimated, this is not a promising solution to the problem.

There appears to be some physical process unique to the NPRC region that we are missing. There are several possibilities. It may be that small-scale circulations not resolvable by GCMs are playing some role. This is a topic that the mesoscale modeling community can and should address. Another possibility, and one we are pursuing, is that we are not capturing the NPRC region cloud formation process correctly. For example, we may be overestimating the number of cloud condensation nuclei, or we may be overestimating their sizes. Nucleation depends critically on available nuclei and their sizes, and it is possible that the atmosphere in the NPRC region during summer is cleaner and/or contains smaller nucleation particles than we simulate.

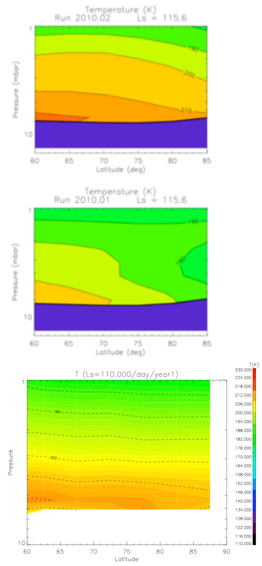

Fig. 7. Time and zonal mean temperatures in the NPRC region during early northern summer from the baseline run (top), RAC run (middle), and MCS data (bottom).

Conclusions:

While incorporating the radiative effects of clouds in the GCM improves the model thermal structure in the northern summer tropics and both winter polar regions, they have a definite negative impact on the simulated seasonal water cycle. Optically thick, low-lying clouds form over the exposed NPRC during summer that cool the surface and reduce sublimation. These clouds are robust and form regardless of a variety of plausible assumptions to reduce their mass and opacity. This suggests that in spite of the high level of sophistication we have achieved with the model, we are still missing an important physical process that is unique to the NPRC region during summer.

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