FORMATION TIMESCALES OF WATER-ICE CLOUDS ON MARS IN THE NASA AMES MARS GCM

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Introduction:

Modeling the water cycle on Mars accurately is a complex problem that is difficult to solve. The water cycle is highly coupled to atmospheric temperature, dust, surface ice temperature, atmospheric mixing, and radiation, just to name a few. In particular, producing an accurate annual water cycle that models both water vapor and water-ice clouds is very problematic.

Common problems include a water vapor cycle that is too dry, or clouds that are too optically thick. Most often, either the water vapor or the clouds can be satisfied, but not simultaneously. Here, we present results from recent developments in the NASA Ames Mars GCM that improve water cycle simulations.

The solution requires cloud nucleation and growth calculations to be performed on very short timescales. This allows few cloud condensation nuclei (CCN) to be nucleated, which then in turn grow to be large particles. Because the cloud particles are few and large, the clouds have smaller opacities, and also tend to fall out quicker.

Model Description:

We use the NASA Ames Mars General Circulation Model (Haberle et al., 1999). The model is run at a typical resolution of 5°x6° (lat/lon) with 24 vertical layers. It uses a two-stream k-coefficient radiation transfer scheme with gaseous absorption and scattering aerosols, including dust and ice. Tracer microphysics includes nucleation, growth, settling of cloud particles, as well as tracer mixing and sedimentation. The boundary layer scheme is based on the level-2 Mellor-Yamada formulation of turbulent mixing. Surface topography is based off of MOLA measurements, and uses Oregon State-derived surface albedo and thermal inertias. Tracer transport is done using a moment scheme assuming a log-normal size distribution. We specify an effective standard deviation (σ_{eff}), and transport tracer mass and number density. We can use these values to derive the effective radius (r_{eff}). The model contains a temporally and spatially varying background dust based off of TES observations. If the dust opacity is lower than the observations, dust is injected into the bottom atmospheric layer at a rate of opacity 0.1/sol.

Method:

A plot of the water cycle for a few Mars years of the base simulation is shown in Figure 1. In this simulation, microphysics is calculated every 12 minutes. What stands out is that although the polar clouds are relatively thin during the summer time, the water vapor column mass is very low. The expected values for the water vapor column mass and polar cloud opacities are approximately 60 pr-μm and <0.1 respectively. Here, the peak water vapor column mass reaches only just above 20 pr-μm, which is about a third of what is expected. Additionally, even with the reduced amount of water, the clouds are more optically thick than expected. Both are signs of a problem with the model.

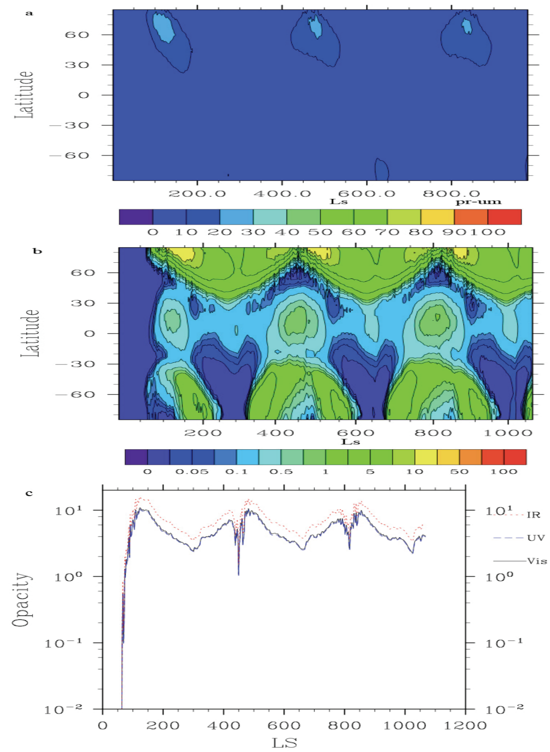

Figure 1. (a) Zonal mean water vapor column mass vs. L_s, (b) zonal mean IR cloud opacity vs. L_s, and (c) a 1D version of (1b) at 85°.

Recent results suggest that the issue of optically thick clouds over the north pole during the summer can be solved by using short time steps (Navarro et al., *submitted*). In order to investigate this conclusion, the model was run with shorter time steps than the typical two minute dynamical time step, and 12 minute physical time step. Running the full model at sub-minute time steps however, is extremely computationally expensive, and not practical for sensitivity tests.

1-Dimensional simulations.

Instead of running the full model at short time steps, we have adapted the 3-dimensional model to a 1D version. This version is much more practical for running sensitivity tests to the time step. The results of running the model at various time steps are shown in Figures 2-3. The time steps shown here are for 10 minutes, 30 seconds.

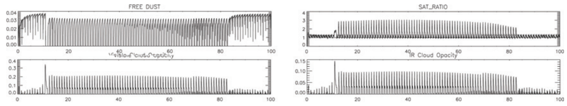

Figure 2. 100 sols of modeling with 10-minute time steps showing the mixing ratio of free dust (top left), water vapor saturation ratio (top right), visible cloud opacity (bottom left), and IR cloud opacity (bottom right).

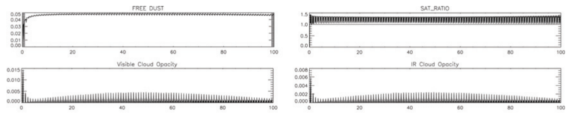

Figure 3. Same as Figure 2, except for 30 seconds.

With the 10-minute time steps, the free dust was completely nucleated on a regular basis. With no sites to nucleate on to, no further cloud particles were formed, and the saturation ratio reached very high values. This in turn led to all of the dust particles being consumed again when they were replenished. Additionally, because the number of cloud particles was so high during these periods, the particle sizes were small, and the cloud opacities became large (~0.1). In contrast, with the 30-second time steps, the free dust was never completely consumed, the saturation ratio never reached above 1.5, and the cloud opacities were typically on the order of 10^{-3}.

The 1-D results suggest that the model should be run at 1-minute time steps or smaller. This however does not necessarily account for all cases. For example at high altitude the atmospheric temperature is lower than near the surface, meaning that the saturation vapor pressure is also lower, and it is easier to become highly supersaturated. In such cases, the free dust can all be nucleated, and situations similar to the 10-minute time step simulation can occur. Time steps shorter than 30 seconds would be required then.

Substepping.

Running the 3-D GCM, or even just the microphysics, at sub-second time steps is highly computation intensive, and quite impractical. Some preliminary tests for running the model with short time steps resulted in the model simulating less than a quarter of a Mars year in 5 days for 5-second time steps, and less than 50 sols for the 1-second time steps. This led to the necessity for a different approach to achieving the shorter time steps.

The core concept behind why the shorter time steps work is that the intervals are small enough such that the change in saturation ratio is low, and only a small fraction of the free dust is nucleated. Then the nucleated particles will tend to grow, and there will only be a few large particles, instead of many small particles. Therefore it follows that the short time scales are only necessary during cloud nucleation and growth, and not during all other times such as mixing and sedimentation. The substepping method we implemented uses this assumption, and calculates the cloud formation microphysics on short time scales only during cloud formation and growth. At all other times the normal time step is used. This method allows for sub-second time steps where clouds are forming, and normal time steps elsewhere, so that the model computation time is only moderately impacted.

Substepping is activated in the microphysics both when more than 50% of the particles will be nucleated, or if a cloud is present and the grid point is supersaturated. If substepping is activated, the number of substeps to perform is found as follows. For a given saturation ratio (S), the excess above saturation (S-1.0) is divided so that 1% of the saturation ratio is added within each substep. In other words, the number of substeps $N=(S-1.0)/0.01$. Currently the maximum number of substeps is limited to 500 in order to prevent the model from hanging, but this may be required to change. The result of using the substepping method is shown in Figure 4.

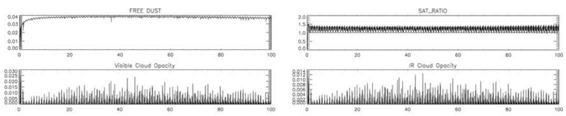

Figure 4. Same as Figure 2, except with substepping.

With substepping, the free dust is not all nucleated, and the saturation ratio does not exceed 1.5 even with a 10-minute time step. The cloud opacities are on the order of 10^{-2}, which is not quite as low as the 30-second time step case, but still an order of magnitude lower than the 10-minute time step case with no substepping.

Results:

The first two years of simulation from the full 3-D model are shown in Figure 5.

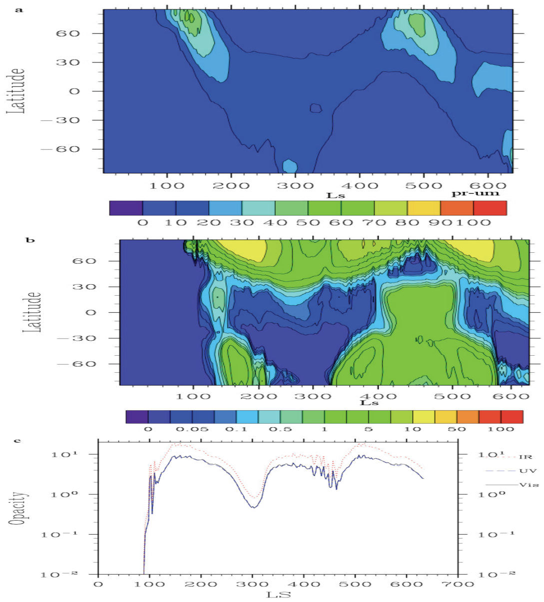

Figure 5. (a) Zonal mean water vapor column mass vs. L_s, (b) zonal mean IR cloud opacity vs. L_s, and (c) a 1D version of (1b) at 85°.

The first thing to notice is that the water vapor annual cycle is much wetter. The peak column depth is 40-50 pr-μm, which is significantly closer to the observations. At the same time, the polar clouds have not dissipated; though they have marginally smaller opacities compared to Figure 1 during the summer. One issue is that the aphelion cloud belt is too optically thick, which is likely related to the available water vapor being significantly higher than previous simulations. This, coupled to the fact that these clouds tend to form high in the atmosphere where the temperatures are cooler, could mean that the model is falling into the "nucleate all free dust" mode, and that 500 substeps is not large enough.

Conclusions:

1-dimensional simulations suggest that the time-scale for cloud formation is short, as concluded by Navarro et al. (*submitted*). However the time steps required to properly resolve the formation are impractically short for the full 3-dimensional model. Instead of using a short time step for the whole model, we use a substepping method where a short time step is only used during cloud formation. This results in a great improvement for the water vapor, and a slight improvement for the clouds. Further investigation into the substepping method is required to see if the remaining water cycle issues can be resolved.

Acknowledgements:

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