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Modelling radiatively active water ice clouds in the Martian water cycle

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Introduction
Aerosols, both water ice and dust, play a key role in the Martian climate. However, our understanding of the interactions between the atmosphere and surface (solar ice caps, frost) in the atmosphere (vapour, ice clouds), and the distribution and properties of dust is currently incomplete.

Water ice clouds have been observed at many locations in the Martian atmosphere, and they occur in many different forms, such as polar hood clouds, cirrus clouds and ground fog. The largest spatial distribution of clouds belongs to the aphelion cloud belt, which appears during northern hemisphere spring and summer each year in a zonal band between around 10° S and 30° N [1, 2].

In this paper, we demonstrate the potential impact of water ice clouds on a Mars Global Circulation Model (MGCIM), and test the sensitivity of the model to varying dust opacity. We use independent model experiments and assimilations of the Mars Climate Sounder (MCS) to develop the model and validate the model against Mars Climate Sounder (MCS) observations.

Effects of water ice clouds in MGCIM simulations
It is known that cirrus clouds in the Earth’s atmosphere can scatter and absorb incoming solar radiation, and absorb and emit thermal infrared radiation, causing a warming of the atmosphere [3,4]. Therefore, due to the presence of water ice clouds in the Martian atmosphere, it is necessary to take into account their radiative effects in MGCIMs.

The current LMD MGCIM [5] run in the UK uses a spectral dynamical core, and includes a simplified water cycle in which there is atmospheric transport of water vapour and ice, a bulk cloud scheme, and interaction with the Martian regolith [6,7]. However, in the model run in the UK, the water ice opacity is not yet coupled with the MGCIM radiation scheme, so absorption of visible/infrared radiation by the water ice clouds is not taken into account. This absorption of radiation has been identified as being potentially significant in the equatorial middle atmosphere of Mars around aphelion, when the planet-circling cloud belt forms [8]. As can be seen in Figure 1, it appears as though the cold-down in-ira radiation emitted by the aphelion cloud belt is introducing a warming of the atmosphere not accounted for in the model.

Figure 1. (a) Seasonal evolution of zonally averaged equatorial temperature bias over the course of the MCS mapping mission; White, red and black contours indicate variable depth of assumed dust distribution, 185° K isotherm and approximate height of cloud condensation, (b) Seasonal evolution of zonally averaged temperature bias at 0.5 HPA [8].

Sensitivity of the model to dust disturbance
Due to the radiative effects of dust, its temporal and spatial distribution will have a large effect on other atmospheric properties. To test the sensitivity of the MGCIM to the distribution of dust, both zonally-averaged and spatially-resolved dust distributions have been run using the UK version of the LMD MGCIM.

The two dust schemes used in the independent experiments are derived from assimilations of TES dust and 2003 and 2005 dust schemes. As can be compared with the standard schemes, both simulations used identical initial conditions.

Figure 2 shows the difference in visible dust opacity averaged over Mars month 5 for both dust schemes. As can be seen, the 2005 dust scheme shows increased opacity globally, particularly in the southern hemisphere poleward of around 40° S.

Figure 2. Difference in dust column visible opacity between simulations run with different TES dust schemes (2005 – 2003), averaged over L= 120° 150°.

Figure 3 shows the effect of this increased dust opacity on the atmospheric temperature: the newer dust scheme results in increased middle atmosphere warming, particularly over the poles, and especially over the north pole. This increase in temperature can be attributed to the adiabatic warming of the air that is sinking over the poles. The increased dust in the atmosphere from the 2005 scheme leads to stronger meridional circulation, and hence increased polar warming.

Figure 3. Difference in temperature between simulations run with different TES dust schemes (2005 – 2003), averaged over MY= 2003.

Plots of the meridional mass streamfunction (MMS) averaged over an entire Martian year are shown in Figure 4. The MMS from both the simulations and the modelled data from the Mars Climate Database (MCD) shows the dominant role of the northern hemisphere circulation, though the flux from the MCD is not as strong as that from the assimilation. None of the plots accurately portray the southerly circulation that is present in the assimilation. The two simulations using the 2003 and 2005 dust schemes show stronger, southerly circulation than that from the MCD, but it is still weaker than in the assimilation.

Figure 4. Plots of the meridional mass streamfunction (10° kg/s), zonally and time-averaged over a Martian year for (a) modelled data from the MCD; (b) MY24 simulation with 2003 dust scheme; (c) MY24 simulation with 2005 dust scheme; and (d) MY24 assimilation using TES thermal and dust retrievals.

As well as comparing the two simulations with each other, we have also carried out comparisons with observations from the MCS and modelled data from the MCD, which is used as a convenient summary of model experiments from the LMD MGCIM. Figure 5 shows mean vertical profiles of temperature at varying latitudes in Mars' southern hemisphere. The implementation of the 2005 dust scheme has produced temperature profiles that are more in agreement with the MCS observations compared to the 2003 dust scheme. The 2005 profiles are also in better agreement compared to the profiles obtained from the MCD. The profiles from the assimilation using TES dust and thermal retrievals are in much better agreement, particularly below around 40 km.

Figure 5. Mean vertical profiles of temperature at varying latitudes from: (a) MY24 simulation using 2003 dust scheme; (b) MY24 simulation using 2005 dust scheme; (c) MY24 assimilation using TES thermal and dust retrievals; and (d) modelled data from the MCD v3. (Panels (d) and (e) are from [6].

Above around 40 km, there is no data from the TES, and so the profiles are less accurate. Even so, it can be seen that the assimilation of volatiles improves the output of the MGCIM. This is to be expected as the assimilation includes the radiative effects of clouds, unlike the current UK version of the model. Strong temperature inversions can be seen close to the ground in the model simulations, but these are not apparent in the MCD or MCM profiles, as they are too close to the surface to be resolved by the instruments.

Figure 6 compares the temperature profile near the south pole in more detail. As can be seen immediately, the profiles from the simulation with the new dust scheme and the assimilation are in much closer agreement with the MCS observations than the profile from the MCD. The lower temperature close to the pole in the simulation are apparent, but the middle atmosphere warming agrees well with the MCD plot.

As has been seen, the distribution of dust in the MGCIM has a large impact on atmospheric temperature. It would also therefore be expected to influence the temporal and spatial distribution of clouds, though such simulations have not yet been carried out.

Figure 6. Daytime and night time temperature profiles for southern hemisphere mid-winter from: (a) modelled data from the MCD; (b) MY24 simulation using 2005 dust scheme; (c) MY24 assimilation using TES thermal and dust retrievals; and (d) MCS limb retrievals with mean times 0916 LST and 1516 LST. (Panel (d) from [6].

Project aims
The project will model the Martian water cycle, including radiatively active water ice clouds, to interpret new observations from MCS. We will be using the latest version of the LMD MGCIM, which includes the new LMD physics routines. A unique data assimilation system [10] will be used to obtain a complete, dynamically self-consistent reconstruction of the extratropical circulation for the complete period of the MGS mission data. A series of diagnostic studies will be made to characterize the climatology and synoptic meteorology of Mars over seasonal and interannual timescales, including detailed case studies of events such as the formation of cyclonic weather systems. The assimilation results can be used to test the viability of the new cloud schemes introduced to the model, improving our understanding of the Martian water cycle.

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References: