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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, surface and subsurface 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, icy 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 (MGCMM), and test the sensitivity of the model to varying dust opacity.

We use independent model experiments and assimilations of Mars Climate Sounder (MCS) limb retrievals to test the sensitivity of the model to varying dust opacity. We use the LMD MGCM to simulate the Martian atmosphere, and they occur in many different forms, such as polar hood clouds, icy 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].

Effects of water ice clouds in MGCM 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 MGCMs.

The current LMD MGCM [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 greenhouse [6,7]. However, in the model run in the UK, the water ice opacity is not yet coupled with the MGCM 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 downward infra-red 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 MGS mapping mission; white, red and black curves show (a) inferred dust distribution, 185° K isotherm and approximate height of cloud condensation/dew point surfaces. (b) Seasonal evolution of zonally averaged temperature bias at 0.5 hPa [8].

Sensitivity of the model to dust distribution

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 MGCM to the distribution of clouds, tests were made for both 2003 and 2005 dust schemes, with both simulations run with different TES dust schemes (2005 – 2003), averaged over MY24. As can be seen in Figure 2, the 2005 dust scheme shows increased optical depth, particularly in the southern hemisphere poleward of around 40° S.

Figure 2. Difference in dust opacity between simulations run with different TES dust schemes (2005 – 2003), averaged over MY24.

As has been seen, the distribution of dust in the MGCM 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.

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 MGCM. 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 lower boundary in the model simulations, but these are not apparent in the MCS or MCD profiles, as they are too close to the surface to be resolved by the instruments.

Figure 5. Mean vertical profiles of temperature at varying latitudes from: (a) MY24 simulation using 2005 dust scheme; (b) MY24 simulation using 2005 dust scheme with TES dust and thermal retrievals; (c) MY25 assimilation using TES dust and thermal retrievals; and (d) modelled data from the MCD v3. (Panels (a) and (d)) are from [6].

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 polar regions to be dominated by a mid-latitude belt of cold air 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 data assimilation. The two simulations using the 2003 and 2005 dust schemes do 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 (10º latitude bands) 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) MY25 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 MCD and modelled data from the MCD, which is used as a reference. Figure 5 shows mean vertical profiles of temperature at varying latitudes from the MCD. Figure 5 shows mean vertical profiles of temperature at varying latitudes from the MCD. The MMS from both the simulations and the modelled data from the Mars Climate Database (MCD) shows the polar regions to be dominated by a mid-latitude belt of cold air from the MCD is not as strong as that from the assimilation. The two simulations using the 2003 and 2005 dust schemes do show stronger, southerly circulation than that from the MCD, but it is still weaker than in the assimilation.

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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 MGCM, 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 state of the global circulation for the entire period of the MCS mission. A series of diagnostic studies will be made to characterise the Martian atmospheric state and test the sensitivity of the model. Strong temperature inversions can be seen close to the lower boundary in the model simulations, but these are not apparent in the MCS or MCD profiles, as they are too close to the surface to be resolved by the instruments.

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) MY25 assimilation using TES dust and thermal retrievals; and (d) MCS limb retrievals with mean local times 03:16 LST and 15:16 LST. (Panel (d)) from [6].

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References