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Modelling radiatively active water ice clouds in the Martian water cycle

L. Steele1, S. R. Lewis1, M. R. Patel2 and R. J. Wilson3

1Department of Physics & Astrophysics, The Open University, MK7 6AA, UK
2Planetary and Space Sciences Research Institute (PSSRI), The Open University, MK7 6AA, UK
3Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA

Email: L.Steele@open.ac.uk

Introduction

Aerosols, both water ice and dust, play a key role in the Martian climate. However, our understanding of the interactions between the surface and the atmosphere (e.g., dust clouds, 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, orographic clouds and ground fogs. 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 (MGCM), and test the sensitivity of the model to varying dust opacity. We use independent model experiments and assimilations of Mars Climate Sounder (MCS) retrievals to validate the model against Mars Climate Sounder (MCS) observations.

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 regolith [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.

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 dominance of the northerly circulation, though the influence from the MCD is not as strong as that from the assimilation. None of the plots accurately portrays the southerly circulation that is present in the atmosphere in the absence of the ETV and the atmosphere is currently incomplete.

As has been seen, the distribution of dust in the MGCM has a large impact on atmospheric temperature. It would also be seen that the assimilation of volatiles improves the output of the MGCM. This can 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 MCS or MCD profiles, as they are too close to the surface to be resolved by the instruments.

Figure 8 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 MCS plot.

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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 dust, the 2005 TES dust scheme and the 2005 MSC dust scheme have been run against the MCS simulations.

The two dust schemes used in the independent simulations are derived from assimilations of TES dust total dust opacity. They are based on earlier and revised retrievals, henceforth denoted as 2003 and 2005 dust schemes. As can be seen in the simulations, both simulations used identical initial conditions.

Figure 3 shows the effect of this increased dust opacity on the atmospheric temperature profile. The 2005 dust scheme results in increased middle atmosphere warming, particularly over the poles, and especially over the north pole. The 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.

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 can 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 MCS or MCD profiles, as they are too close to the surface to be resolved by the instruments.

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 extraterrestrial circulation for the complete period of the MMS mission data. A series of diagnostic studies will be made to characterise the climatological and synoptic meteorology of Mars over seasonal and interannual timescales, including detailed case studies of events such as the formation of volcanic plumes.

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References:


Figure 1. (a) Seasonal evolution of zonally averaged equatorial temperature bias over the course of the MGS 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 kmPa [8].

Figure 2. Difference in dust column visible opacity between simulations run with different TES dust schemes (2005 – 2003), averaged over L = 120°, 155°.

Figure 3. Difference in temperature between simulations run with different TES dust schemes (2005 – 2003), averaged over MY24.

Figure 4. Plots of the meridional mass streamfunction (10¹⁷ kg/s), zonally and time-averaged over a Martian year for (a) modelled data from the MCD; (b) MY24 simulation with 2005 dust scheme; (c) MY24 simulation with 2003 dust scheme; and (d) MY25 assimilation using TES thermal and dust retrievals.

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) MY25 assimilation using TES thermal and dust retrievals; and (d) MCD dust retrievals and (e) modelled data from the MCD v3. (Panels (d) and (e) are from [6]).

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 TES dust scheme; (c) MY25 assimilation using TES dust and thermal retrievals; and (d) MCS dust retrievals with mean local times 03 16 LST and 15 36 LST (Panel (d) from [6]).

Figure 7. Difference in dust column visible opacity between simulations run with different TES dust schemes (2005 – 2003), averaged over MY25 assimilation.

Figure 8. Comparison of 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 MCS plot.

Figure 9. Table comparing 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 MCS plot.