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The radiative impact of water ice clouds on Mars from a reanalysis of Mars Climate Sounder data

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Abstract

We investigate the radiative impact of water ice clouds on the atmosphere of Mars via a reanalysis of Mars Climate Sounder (MCS) temperature and ice opacity profiles. Polar hood clouds only have a small radiative impact, while tropical clouds increase diurnally-averaged temperatures at the 10 Pa level by ∼10–15 K. Cloud radiative heating also impacts on the global circulation, strengthening the meridional overturning cells and changing the positions and wind speeds of the tropical and high-latitude jets. An effective ice particle radius of $r_{\text{eff}} = 1.4\,\mu$m produces tropical temperatures during aphelion season in close agreement to MCS temperature retrievals, but for high-altitude tropical clouds during northern autumn a better agreement is found using $r_{\text{eff}} = 0.8\,\mu$m.

1. Introduction

Recent observations and modelling studies have begun to reveal the importance of water ice clouds in terms of modifying the atmospheric temperature structure and circulation on Mars [1, 2, 3]. As the radiative impact of clouds is dependent upon the location and time of day in which they form, the results of modelling studies will be affected by any incorrect cloud predictions. To overcome this problem, we use a data assimilation scheme [4] with MCS data to construct a four-dimensional time-space map of water ice opacities. This is used by the MGCM [5, 6] to produce the radiative forcing associated with clouds.

2. Simulations performed

Three simulations were performed to investigate cloud radiative effects. The first is the control run (CR) in which dust and CO_2 are the only atmospheric constituents that are transported and influence the radiative transfer. Next, assimilations of MCS ice opacities (IA) and temperatures (TA) were performed using the same model and initial conditions as the CR. Comparison between the CR and IA allows the radiative impact of clouds to be investigated, while comparison between the IA and TA allows the performance of the IA and any remaining temperature biases to be assessed.

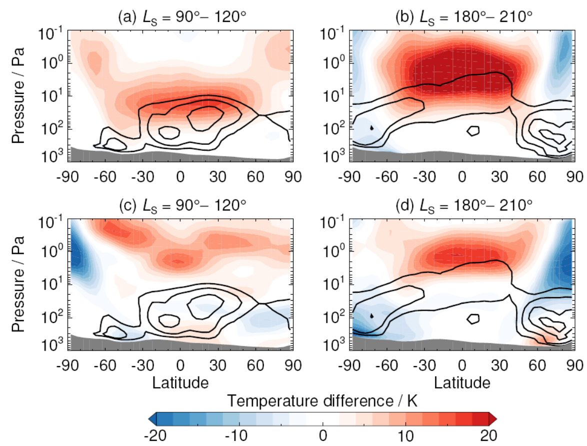

Figure 1: Time- and zonal-mean temperature differences $T_{\text{IA}} - T_{\text{CR}}$ (a,b) and $T_{\text{IA}} - T_{\text{TA}}$ (c,d) for northern summer and autumn of MY 30. Black contours show the visible ice opacity, with values of 0.005, 0.01, 0.02 and 0.03. Grey shading represents topography.

3. Results

3.1. Radiative impact of clouds

The impact of water ice clouds on atmospheric temperatures can be seen in Figure 1(a,b). In the tropics and mid-latitudes there is an increase in temperature at and above the cloud level of ∼10–15 K during northern summer and winter, and >30 K during northern autumn. The increased heating in autumn is because the clouds in the tropics are located around 20 km higher compared to summer, resulting in larger density-scaled opacities. Tropical clouds produce local heating of ∼10–30 K sol^{-1} during the day, and cooling of ∼5–10 K sol^{-1} at night, dependent on season. The polar hoods are generally the most optically thick clouds, but they have little impact on the local atmospheric temperature structure. This is because of their low density-scaled opacities and less significant absorption of upwelling radiation.

Cloud radiative effects also alter the atmospheric circulation. There is generally a strengthening of the overturning cells, with a 50% increase in transport away from the centres of the cells, and peak increases approaching 200% in the upwelling and downwelling branches. This causes dust in the tropics to be transported higher into the atmosphere, and the increased dust mass is responsible for around 2 K of the tropical temperature increases shown in Figure 1(a,b).

The increasing strength of the meridional circulation also increases temperatures in the polar warmings by ∼6–8 K (see Figure 1). This is due to increased adiabatic heating in the descending branches of the overturning cells. Jet speeds and positions are also altered because of temperature changes. In the autumn and winter hemispheres the cores of the westerly jets are strengthened by $\sim$10–20 $\mathrm{m\,s^{-1}}$, while over the equator during northern autumn the core easterly jet speed is reduced from $>100\,\mathrm{m\,s^{-1}}$ to $\sim$40 $\mathrm{m\,s^{-1}}$.

3.2. Comparison with an assimilation of MCS temperature profiles

Figure 1(c,d) shows the temperature difference between the IA and TA. The inclusion of cloud radiative effects produces tropical temperatures at cloud-forming height in the IA that are in good agreement with the TA. Above cloud-forming height, atmospheric temperatures in the IA are generally too warm compared to the TA. This is particularly noticeable in Figure 1d, where temperatures in the IA are ∼10–20 K higher than in the TA. This excess heating is related to the particle size of $r_{\text{eff}} = 1.4\,\mu$m used in the radiative transfer scheme. Tests with $r_{\text{eff}} = 0.8\,\mu$m showed much better agreement with the TA.

Figure 2 shows the zonal-mean daytime and night-time equatorial temperatures at the 10 Pa level in all three simulations over one Mars year (no MCS data are available until $L_\mathrm{S} \approx 20°$). At most times of year the IA improves the fit with the TA. However, at night the IA is too warm compared to the TA, suggesting larger ice particles are present (which will result in greater cooling through increased infrared emission). The times of year when the CR provides a better fit to the TA (around $L_\mathrm{S} = 240°$ and $330°$) correspond to the occurrence of local dust storms.

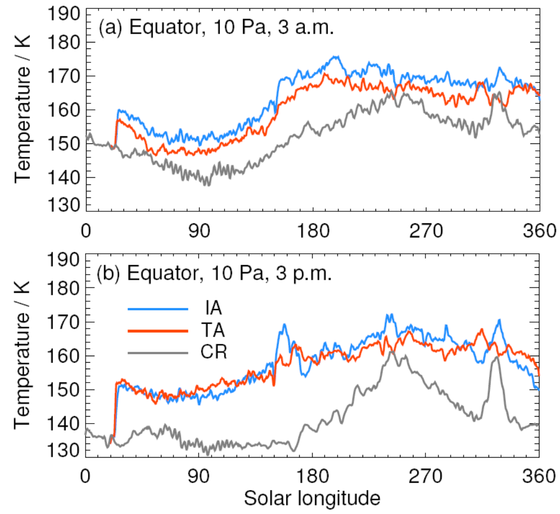

Figure 2: Zonal-mean temperature variation at 10 Pa over the equator for (a) 3 a.m. and (b) 3 p.m. local times. Data are smoothed over 2° of L_S.

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