Modelling Radiatively Active Water Ice Clouds in the Martian Water Cycle

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MODELLING RADIATIVELY ACTIVE WATER ICE CLOUDS IN THE MARTIAN WATER CYCLE.

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Introduction:
The water cycle is one of the key seasonal cycles on Mars, alongside CO$_2$ and dust. However, our understanding of the interactions between the various reservoirs of water on the surface (polar ice caps, frost) and in the atmosphere (vapour, ice clouds) is currently incomplete.

As well as being a tracer of atmospheric motions, water can affect the composition of the Martian atmosphere by removing CO$_2$ and dust particles and locking them away in icy layers over the poles, which may remain for thousands of years.

A knowledge of the Martian water cycle can also help with the investigation of the existence of life, both past and present. If we can find areas on the surface or sub-surface where liquid water may have occurred in the past, or where it may still exist today, we can highlight these areas as potential landing sites for future space missions.

Water ice clouds have been observed at many locations in the Martian atmosphere, and they occur in many different guises, such as polar hood clouds, orographic clouds and ground fogs (see Figure 1 for an example). The largest spatial distribution of clouds belongs to the aphelion cloud belt, which appears each year during northern hemisphere spring and summer, in a zonal band between around 10$^\circ$ S and 30$^\circ$ N (Clancy et al., 1996; James et al., 1996). As can be seen in Figure 2, recent data from the Mars Climate Sounder (MCS) show that water ice clouds are present continuously in the Martian atmosphere, with seasonal variations in their opacity and spatial distribution.

Water ice clouds have also been studied from the surface of Mars. Using data from the LIDAR instrument on the Phoenix lander, Whiteway et al. (2009) detected fall streaks from clouds early in the Martian morning. The inferred speed of the falling ice crystals allowed their size to be calculated, and it was found they were columnar (42 $\mu$m wide and 127 $\mu$m long), and similar to ice crystals sampled in cirrus clouds on Earth.

The 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 (Liou, 1986; Jensen et al., 1994). Therefore, due to the presence of water ice clouds in the Martian atmosphere, it is necessary to take into account their

Figure 1: Mars Orbiter Camera (MOC) image of clouds over the residual north polar ice cap during northern-hemisphere mid-summer (Credit: NASA/JPL/MSSS).

Figure 2. Log$_{10}$ of the day-side retrievals of zonal average water ice density-scaled opacity ($m^2$ kg$^{-1}$), for MY29. The $L_s$ bins are labelled at the top of each panel, and the contours are shown every 0.1 log units (McCleese et al., 2010).

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radiative effects in Mars Global Circulation Models (MGCMs).

The current LMD MGCM (Forget et al., 1999) 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 (Böttger et al., 2005; Montmessin et al., 2004). As can be seen in Figure 3, the spatial and temporal distribution of clouds in the model agrees well with the TES observations, though the model opacities are consistently larger.

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. Wilson et al. (2008) have identified this absorption of radiation as being potentially significant in the equatorial middle atmosphere of Mars around aphelion, when the planet-circling cloud belt forms. Figure 4(a,b) shows the change in temperature between two simulations; a Reanalysis, which includes the assimilation of Thermal Emission Spectrometer (TES) temperature and dust opacity retrievals (Lewis et al., 2007); and a Control, which is an independent model experiment with an identical dust field, but without the temperature assimilation.

Figure 3. Seasonal and latitudinal distribution of water cloud opacity. Upper panel: as derived from TES observations (Smith, 2004). Lower panel: as given by model (Montmessin et al., 2004). Model data sampled to 2PM LT to remove potential bias induced by cloud diurnal variability, and to allow comparison with observations.

It can be seen that there is a cold bias in the Control simulation during the Martian summer season ($L_s = 45° – 135°$) in all three Martian years, which indicates that the model underestimates the temperature of the equatorial middle atmosphere. Comparing these results with the zonally averaged equatorial water ice cloud column opacity in Figure 4c reveals a strong correlation between temperature error and ice opacity. Thus, 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 4. (a) Seasonal evolution of zonally averaged equatorial temperature bias ($\Delta T = T_{\text{Reanalysis}} - T_{\text{Control}}$) over the course of the MGS mapping mission. The variable depth of the assumed dust distribution is indicated by the white contour. The black contour shows the 185° K isotherm and the red contour indicates the approximate height of the cloud condensation level. (b) The seasonal evolution of zonally-averaged temperature bias at 0.5 hPa. The contour interval is 5 K. (c) The seasonal evolution of zonally-averaged equatorial dust column opacity (red) and water ice cloud column opacity (blue). Dust opacity is scaled by 0.2 (Wilson et al., 2008).

A further discrepancy in water ice cloud model output is reported by Heavens et al. (2010), who find that the distribution and evolution of water ice over the tropics during northern summer differs between observations and model predictions. Using MCS limb observations, they found that water ice clouds are thinner and form higher in the atmosphere than in published model results. (This discrepancy may be partly due to the limited vertical range of MCS data, which is cut off below around 5 - 15 km due to possible surface emission.)
PhD project aims:
The aim of this project is to 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 (as used by Lewis et al., 2007) will be used to obtain a complete, dynamically self-consistent reconstruction of the entire global circulation for the complete period of the MCS mission to date (see also Montabone et al., abstract in this issue).

From the produced records, a series of diagnostic studies will then be made to characterise 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 validity of the new cloud schemes introduced to the model, which will improve our understanding of the Martian water cycle. Some initial results will be shown.

References: