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

L. Steele, S. R. Lewis, *Department of Physics & Astronomy, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK* (l.steele@open.ac.uk), **M. R. Patel**, *Planetary and Space Sciences Research Institute (PSSRI), The Open University, Walton Hall, Milton Keynes MK7 6AA, UK*, and **R. J. Wilson**, *Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA.*

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° S and 30° 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.

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).

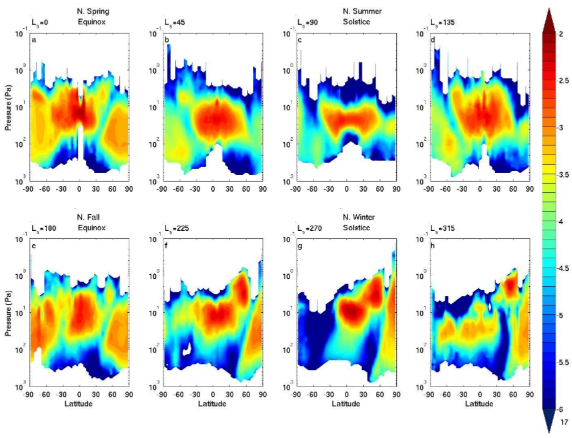

Figure 2. Plot of the day-side retrievals of zonal average water ice density-scaled opacity (m^2 kg^{-1}), for MY29. the L_S bins are labelled at the top of each panel, and the contours are shown every 0.1 log units (McCleese *et al*., 2010).

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 μm wide and 127 μm 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 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.

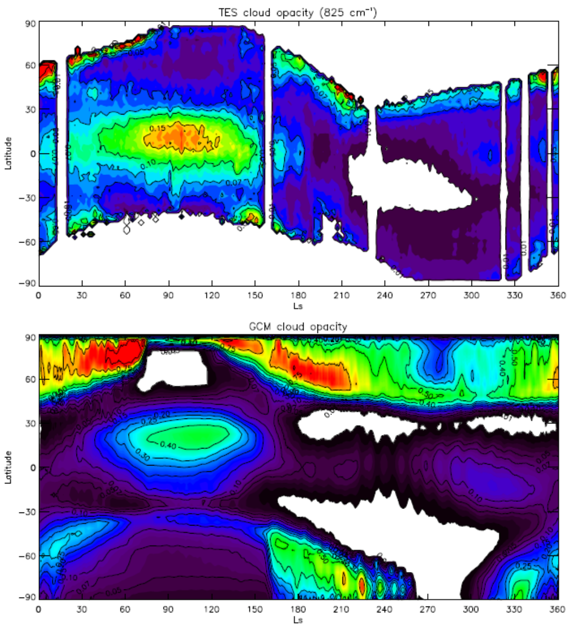

Figure 3. Seasonal and latitudinal distribution of water cloud opacity. Upper panel: as derived from TES observations (Smith, 2004). Lower panel: as given by model (Montmessin *et al*., 2004). Model data sampled to 2PM LT to remove potential bias induced by cloud diurnal variability, and to allow comparison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

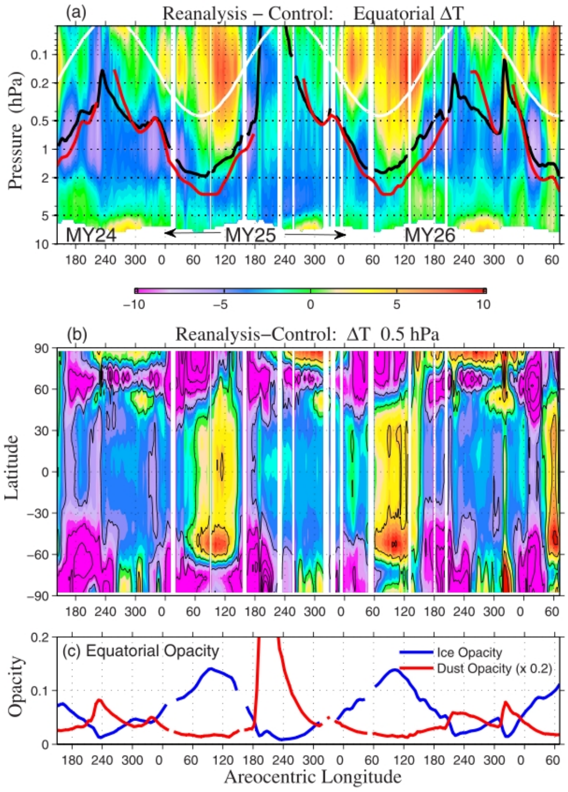

Figure 4. (a) Seasonal evolution of zonally averaged equatorial temperature bias ($\Delta T = T_{\mathrm{Reanalysis}} - T_{\mathrm{Control}}$) over the course of the MGS mapping mission. The variable depth of the assumed dust distribution is indicated by the white contour. The black contour shows the 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:

Böttger, H. M., Lewis, S. R., Read, P. L. and Forget, F. (2005) The effects of the Martian regolith on GCM water cycle simulations, *Icarus*, 177, 1, 174–189, doi: 10.1016/ j.icarus.2005.02. 024

Clancy, R. T., Grossman, A. W., Wolff, M. J., James, P. B., Rudy, D. J., Billawala, Y. N., Sandor, B. J., Lee, S. W. and Muhleman, D. O. (1996) Water vapor saturation at low latitudes around aphelion: A key to Mars climate?, *Icarus*, 122, 36-62

Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M., Lewis, S. R., Read, P. L. and Huot, J.-P. (1999), Improved general circulation models of the Martian atmosphere from the surface to above 80 km, *J. Geophys. Res*., 104, 24,155–24,175

Heavens, N. G., Benson, J. L., Kass, D. M., Kleinböhl, A., Abdou, W. A., McCleese, D. J., Richardson, M. I., Schofield, J. T., Shirley, J. H. and Wolkenberg, P. M. (2010) Water ice clouds over the Martian tropics during northern summer, *Geophys. Res. Lett*., 37, L18202, doi:10.1029/ 2010GL044610

James, P. B., Bell, J. F., Clancy, R. T., Lee, S. W., Martin, L. J. and Wolff, M. J. (1996) Global imaging of Mars by Hubble space telescope during the 1995 opposition, *J. Geophys. Res*., 101, E8, 18,883-18,890, doi:10.1029/96JE01605

Jensen, E., Kinne, S. and Toon, O. B. (1994) Tropical cirrus cloud radiative forcing: Sensitivity studies, *Geophys. Res. Lett.*, 21, 18, 2023–2026, doi:10.1029/94GL01358

Lewis, S. R., Read, P. L., Conrath, B. J., Pearl, J. C. and Smith, M. D. (2007) Assimilation of Thermal Emission Spectrometer atmospheric data during the Mars Global Surveyor aerobraking period, *Icarus*, 192, 2, 327–347, doi: 10.1016/j.icarus.2007.08.009

Liou, K. N. (1986) Influence of cirrus clouds on weather and climate processes: A global perspective, *Mon. Weather Rev*., 114, 1167–1199, doi:10.1175/1520-0493

McCleese, D. J., Heavens, N. G., Schofield, J. T., Abdou, W. A., Bandfield, J. L., Calcutt, S. B., Irwin, P. G. J., Kass, D. M., Kleinböhl, A., Lewis, S. R., Paige, D. A., Read, P. L., Richardson, M. I., Shirley, J. H., Taylor, F. W., Teanby, N. and Zure, R.W. (2010) The Structure and Dynamics of the Martian Lower and Middle Atmosphere as Observed by the Mars Climate Sounder: 1. Seasonal variations in zonal mean temperature, dust and water ice aerosols, *J. Geophys. Res*., 115, 10.1029/2010JE003677

Montabone, L., Read, P. L., Lewis, S. R., Smith, M. D., Kleinboehl, A., Kass, D., Schofield, T. and McCleese D. J. A five Mars year climatology from data assimilation using MGS/TES and MRO/MCS observations, abstract in this issue

Montmessin, F., Forget, F., Rannou, P., Cabane, M. and Haberle, R. M. (2004) Origin and role of water ice clouds in the Martian water cycle as inferred from a general circulation model, *J. Geophys. Res*., 109, E10004, doi:10.1029/ 2004JE002284.

Smith, M. D. (2004) Interannual variability in TES atmospheric observations of Mars during 1999-2003, *Icarus*, 167, 148-165

Whiteway, J. A., Komguem, L., Dickinson, C., Cook, C., Illnicki, M., Seabrook, J., Popovici, V., Duck, T. J., Davy, R., Taylor, P. A., Pathak, J., Fisher, D., Carswell, A. I., Daly, M., Hipkin, V., Zent, A. P., Hecht, M. H., Wood, S. E., Tamppari, L. K., Renno, N., Moores, J. E., Lemmon, M. T., Daerden, F. and Smith, P. H. (2009) Mars Water-Ice Clouds and Precipitation, *Science*, 325, 68

Wilson, R. J., Lewis, S. R., Montabone, L. and Smith, M. D. (2008) Influence of water ice clouds on Martian tropical atmospheric temperatures, *Geophys. Res.* Lett., 35, L07202, doi:10.1029/2007GL032405