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INVESTIGATING THE OZONE CYCLE ON MARS USING GCM MODELLING AND DATA ASSIMILATION

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Introduction:

In this work we use atmospheric modelling and data assimilation to study the annual ozone cycle. There are a multitude of current issues which can be investigated including the chemical stability of the atmosphere, the polar vortices and habitability. OH (part of the odd hydrogen family HO_x and produced from the photolysis of water vapour) is known to play a key role in the stability of the atmosphere and is also a major catalytic destructor of ozone. This chemical species has only recently been detected by Clancy et al. (2013) and for further studies a possible option is to use ozone as a tracer for OH.

Ozone has also been found to be quasi-passive in the polar night (Lefèvre et al. 2004) due primarily to the lack of daylight hours and a negligible amount of HO_x radicals present at this time of the year. The dynamics associated with the northern polar vortex can therefore be traced using the ozone abundance. The UV flux reaching the ground, an important parameter for the habitability of Mars, is controlled by the atmospheric ozone. A more realistic ozone cycle reduces the uncertainties of the amount of UV radiation reaching the surface of Mars. Further analysis of the ozone cycle can also provide a broader understanding of the Martian atmospheric chemistry.

Providing a consistent temporal and spatial agreement between models and observations of ozone is also of great benefit in furthering the understanding of important photochemical processes in the Martian atmosphere. Seasonal variations, that are governed primarily by the hygropause level at different times of the year (Clancy and Nair, 1996), have been known from the first observations of ozone by Mariner 9. Ozone on Mars is primarily observed by the strong and wide absorption band centred at 255 nm detectable by UV spectrometers (Perrier et al., 2006). It can also be retrieved at 9.7 μm where IR spectrometers can ascertain measurements (Fast et al., 2006) and indirectly in the 1.27 μm O_2 ($a^1\Delta_g$) emission band (Altieri et al., 2009).

To investigate the combined dynamical, physical and chemical processes affecting ozone distribution requires ideally a three-dimensional model. Lefèvre et al. (2004) were the first to use a three-dimensional Martian global circulation model (GCM) coupled to a photochemical module to increase knowledge of the properties of ozone in the Martian atmosphere. The agreement between the model and observations was later improved by inclusion of heterogeneous reactions (Lefèvre et al., 2008). Comparisons to spatially averaged observations provide good constraints on the seasonal distribution. For an in-depth approach, identifying differences between models and observa-

tions on a temporal and spatial scale can identify specific regions where the largest discrepancies exist. Higher resolution models with less parameterisations can consequently be used to study the identified area in more depth (Spiga and Forget, 2009), that would otherwise be computationally expensive.

To make optimal use of information, observations and the model are combined by the process of data assimilation. The outcome of this process is a dynamical global reconstruction of the observations. The satellites currently orbiting Mars, combined with the future planned satellite missions, create a great opportunity for the development of a data assimilation technique for ozone and more generally trace gases on Mars. Although data assimilation is now commonplace on Earth, it is a fairly new concept for other planetary systems.

Data assimilation is fast becoming a common technique for input of observations into a GCM to study a variety of topics (Lewis and Barker, 2005; Montabone et al., 2006; Greybush et al., 2012). Mars Express carries the Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) instrument from which total-column ozone can be retrieved. Ozone data has never before been assimilated for Mars, but the use of this technique is widespread for Earth (Kieseewetter et al., 2010 for example).

The assimilation of total-column ozone can also be used to inform instrument planning on upcoming missions such as the Trace Gas Orbiter (TGO) and provide a comprehensive analysis, constrained by satellite observations, of the ozone cycle on Mars.

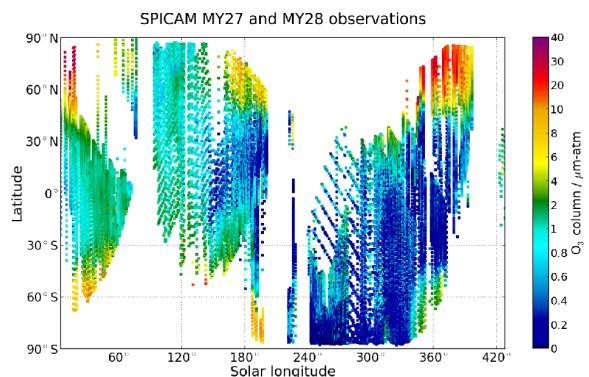


Figure 1: Retrievals of total-column ozone from the SPICAM instrument aboard Mars Express.

SPICAM Observations:

The first total-column ozone observations we have assimilated into our model are from the SPICAM instrument on Mars Express (Figure 1). The gaps in data from $L_S = 70-90^\circ$ and $L_S = 200-240^\circ$

are due to a night side pericentre preventing observations and other instruments aboard the spacecraft taking priority respectively. Maximum values are seen around northern hemisphere spring equinox, after ozone has had time to build up due to the constant darkness over the north pole in winter. There is less observed total-column ozone in the tropical regions at the start of Mars year (MY) 28 than towards the beginning of MY 27, hinting at annual variations of atmospheric ozone. The majority of retrievals at the start of MY 28 occur earlier in the morning than the previous year's retrievals however, so these differences have to be analysed with caution.

The retrieval of total-column ozone from the Hartley band of intense absorption (220-280 nm) is detailed in Perrier et al. (2006), with the outcome being almost 28,000 high signal-to-noise ratio observations for almost one and a half Martian years.. The ground resolution at pericentre is around 4 km² with an average uncertainty in total-ozone of 10-15%. Observational datasets for other chemical species such as water vapour from TES have around 8,000 observations a day, putting into perspective the relative sparseness of the SPICAM dataset. Nevertheless, valuable information can be extracted from the data available.

GCM Modelling:

For modelling of the ozone cycle we use the UK version of the LMD GCM which is currently in use at the Open University and the University of Oxford. This GCM uses the physical parameterisations and photochemical module shared with the LMD GCM coupled to a UK-only spectral dynamical core and semi-lagrangian advection scheme. It has been developed in a collaboration of the Laboratoire de Météorologie Dynamique, the Open University, the University of Oxford and the Instituto de Astrofísica de Andalucía.

The dust distribution is prescribed horizontally using an interpolation of numerous sets of observations from orbiters and landers using a kriging method (Montabone et al. 2013, in preparation) and vertically using the Conrath dust profile. The model was run at T31 resolution in the horizontal, corresponding to a resolution of 5° latitude by 5° longitude, with 32 vertical sigma levels in the range 0-105 km. Vertical levels are much closer to one another near the surface and further apart in the upper atmosphere.

The photochemical module provides multiple photolytic and chemical reactions with up-to-date reaction rates between 16 advected species including carbon dioxide, water vapour and ozone. Time-varying dust amounts are also taken into account in the photolytic reactions. Tracers are advected using the semi-lagrangian advection scheme (Newman et al., 2002).

Assimilation method:

The assimilation is performed using the Analysis Correction scheme (Lorenz et al., 1991) converted to Martian conditions, and has been shown in the past to

be a computationally inexpensive and robust method (Lewis et al., 2007). Using this methodology, observations of short-lived (and long-lived) species can be supplemented by knowledge of the transport and atmospheric chemistry from a GCM.

Where observations exist, the model value is incremented towards the assimilated value, weighted by a horizontal correlation scale and time factor depending on how close in space and time the model grid point and observation are. Since we are incrementing an integrated 2-D column value which is transported in 3 dimensions each timestep, the approach is to assume the vertical distribution predicted by the model and normalise this with the total-column ozone observations. The ozone mass mixing ratio at each level is scaled equally using the ratio of the assimilated value to the model value. Currently, the model-observation error ratio has been defined to be unity, therefore an assumption has been made that the error in the model is also around 10-15% for the total-column ozone.

Results:

To investigate the effect of total-column ozone assimilation on the seasonal cycle, we ran a 'control' model run with no assimilation and a second 'assimilation' run where the observations from SPICAM have been assimilated. Both runs start at $L_s = 330^\circ$ in MY 26 with the same initial distribution and include a well-established water cycle. The evolution of ozone for the assimilation run is displayed in Figure 2. The figure displays the total-column ozone values at 12LT everywhere to provide a fairly direct comparison to the SPICAM daytime observations in Figure 1. The general temporal and spatial distribution of ozone is familiar, with winter polar maximums and the least abundance in the southern hemisphere around perihelion. Our model also agrees quantitatively with the 3:1 ratio of total-ozone from just before aphelion to perihelion in the equatorial region.

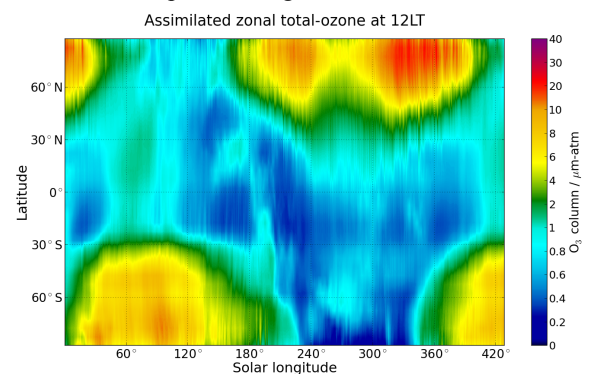


Figure 2: Assimilated zonally averaged ozone column for MY 27 and the start of MY 28.

Deviations in total-column ozone from the control run are apparent primarily around the northern polar maximum build up and decrease (high latitudes from $L_s = 150-180^\circ$ and $L_s = 0-360^\circ$ of MY 28). These locations have been previously linked to possible heterogeneous uptake of OH, which would decrease the abundance of OH in these regions and hence increase

the observed total-column ozone. Both the control and assimilation runs have included the heterogeneous parameterisation from Lefèvre et al. (2008). An increase in the uptake of OH is seen to decrease the positive bias in the identified regions with the greatest difference in total-column ozone, however a subsequent negative bias in the second half of MY 27 is apparent. This suggests that a global increase of heterogeneous uptake does not provide a better match to the observations but results in a greater abundance of total-column ozone residing to the end of the year.

Water ice availability:

Figure 3 displays the water ice cloud opacity at 14LT which can be directly compared to TES retrievals. The aphelion cloud belt and northern polar hood are clearly visible. The coefficient of heterogeneous uptake of OH is increased when the water ice surface is fresh (Cooper and Abbatt, 1996), which would be the case for the aphelion cloud belt where the residence time of water ice clouds is fairly short. The analysis in this region from the assimilation shows a good agreement between the model and observations. The northern polar hood conversely has a long residence time and so the low uptake coefficient seems more appropriate, but this is where we find the largest discrepancies between the control and assimilation run.

This suggests that heterogeneous uptake of odd hydrogen radicals on water ice clouds is not at least the primary cause of the mismatch between the model and observations.

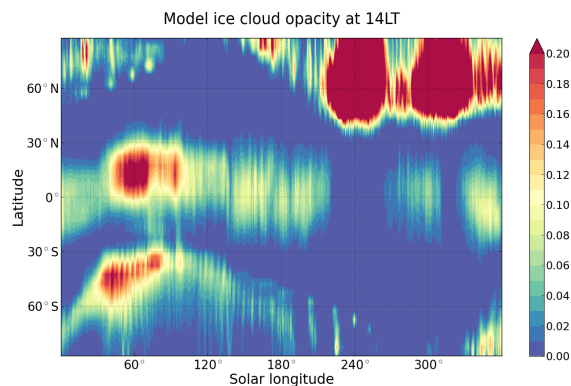


Figure 3: Model ice opacity at 14LT everywhere to compare with the TES observations.

The extent of the northern polar hood and the abundance of southern water ice clouds in late southern winter ($L_s = 180-220^\circ$) are much less when compared to the distribution in Lefèvre et al. (2008). These regions are precisely where our model is finding it difficult to reconcile the SPICAM observations with the modelled ozone, suggesting the water ice cloud distribution to be of extreme importance in a realistic ozone cycle.

Trace gas assimilation:

Assimilating observations of other trace gases in future will also be achievable, allowing for investigations into interactions between chemical species and

subsequently improving our understanding of the Martian chemical environment. Chemical rate coefficients imposed by reconciling observational datasets and theoretical models would add to our current estimates which come primarily from laboratory experiments only. The Nadir and Occultation for Mars Discovery (NOMAD) instrument on the TGO is set to measure water vapour and ozone abundance using the same instrument which would allow for a direct look at their apparent anti-correlation and deviations from this.

The Mars Color Imager (MARCI, Clancy et al., 2011) on the Mars Reconnaissance Orbiter provides near-daily global mapping of ozone column concentration extending the currently available ozone dataset. Alongside Mars Climate Sounder temperature and dust opacity observations, a fully comprehensive analysis of the ozone cycle should be possible.

Summary:

We have assimilated for the first time retrievals of ozone from SPICAM into a GCM to investigate the evolution of ozone on Mars. The water ice distribution, especially during the onset of polar night at high latitudes, is an important factor in the initial build up of the polar maximum. Refined parameterisation of water ice cloud formation should also lead to an improved modelled ozone cycle.

In the near future, assimilation of the MARCI and MCS observations will result in further constraints on the possible missing mechanisms contributing to the sources and sinks of ozone in our GCM. This technique could also be used for a number of trace gases which are likely to be observed by NOMAD on the TGO.

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