Icarus 302 (2018) 308–318

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

A reanalysis of ozone on Mars from assimilation of SPICAM observations

James A. Holmes[a,*], Stephen R. Lewis[a], Manish R. Patel[a,b], Franck Lefèvre[c]

[a] School of Physical Sciences, The Open University, Walton Hall, Milton Keynes MK7 6AA, UK
[b] Space Science and Technology Department, Science and Technology Facilities Council, Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire OX11 0QX, UK
[c] LATMOS, CNRS/Université Pierre et Marie Curie/UVSQ, Paris France

ARTICLE INFO

Article history:
Received 13 April 2017
Revised 4 October 2017
Accepted 21 November 2017
Available online 22 November 2017

Keywords:
Mars atmosphere
Mars data assimilation
Atmospheres
chemistry

ABSTRACT

We have assimilated for the first time SPICAM retrievals of total ozone into a Martian global circulation model to provide a global reanalysis of the ozone cycle. Disagreement in total ozone between model prediction and assimilation is observed between 45°S–10°S from L_S =135–180° and at northern polar (60°N–90°N) latitudes during northern fall (L_S =150–195°). Large percentage differences in total ozone at northern fall polar latitudes identified through the assimilation process are linked with excessive northward transport of water vapour west of Tharsis and over Arabia Terra. Modelling biases in water vapour can also explain the underestimation of total ozone between 45°S–10°S from L_S =135–180°. Heterogeneous uptake of odd hydrogen radicals are unable to explain the outstanding underestimation of northern polar total ozone in late northern fall.

Assimilation of total ozone retrievals results in alterations of the modelled spatial distribution of ozone in the southern polar winter high altitude ozone layer. This illustrates the potential use of assimilation methods in constraining total ozone where SPICAM cannot observe, in a region where total ozone is especially important for potential investigations of the polar dynamics.

1. Introduction

Observations and modelling of ozone have the potential to greatly improve our understanding of the Martian atmosphere. It can be observed by the strong and wide absorption band centred at 255 nm detectable by UV spectrometers (Perrier et al., 2006) and imagers (Clancy et al., 2016), 9.7 µm at which IR spectrometers can ascertain measurements (Fast et al., 2006) and also indirectly in the 1.27 µm $O_2(a^1\Delta_g)$ emission band (Fedorova et al., 2006; Altieri et al., 2009).

There are a multitude of atmospheric processes which can be investigated by studying the ozone cycle. Firstly, it can be used as a tracer for OH (produced from the photolysis of water vapour), an odd hydrogen radical which readily destroys ozone. The infrared emission of OH has recently been detected by Clancy et al. (2013) and is known to play a key role in the stability of the atmosphere. Ozone has also been found to be quasi-passive in the polar night (Lefèvre et al., 2004) due primarily to the suppression of photochemical ozone destruction and a negligible presence of HO_x (H, OH and HO_2) radicals at this time of the year. The dynamics associated with the northern polar vortex can therefore be traced by monitoring ozone abundance (Holmes et al., 2017), an application raised when investigating recent observations of total ozone (Clancy et al., 2016). 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 have been known from the first observations of ozone by Mariner 9 (Barth et al., 1973), and more recently been shown to be governed primarily by the hygropause level at different times of the year (Clancy and Nair, 1996). A one-dimensional photochemical model developed by Krasnopolsky (2006, 2009) investigated latitudinal and diurnal variations of photochemical species including ozone. The model does however use a fixed temperature profile and due to its nature is unable to represent horizontal transport. Moreau et al. (1991) used a two-dimensional model to describe vertical profiles of ozone, but this was in a dust-free atmosphere

* Corresponding author.
E-mail address: james.holmes@open.ac.uk (J.A. Holmes).

https://doi.org/10.1016/j.icarus.2017.11.026

and also neglected cloud effects. To investigate the combined dynamical, physical and chemical processes affecting ozone distribution requires ideally a three-dimensional model.

Lefèvre et al. (2004) was 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 on HO_x species (Lefèvre et al., 2008) which had previously been theorised (Krasnopolsky and Parshev, 1979), although this has recently been put into question by Clancy et al. (2016) with little evidence of a correlation between total ozone and water ice optical depth retrievals from the Mars Color Imager (MARCI) on the Mars Reconnaissance Orbiter (MRO) spacecraft. Comparisons to spatially averaged observations provide good constraints on the seasonal distribution. For an in-depth approach, identifying differences between models and observations on a range of temporal and spatial scales can identify specific regions where the largest differences exist, and thus a deficiency in our understanding of the physical processes at work. The added spatial dimension hence informs models about the cause and evolution of the differences on a local, rather than global, scale. Higher resolution models with less restricted physical parameterisations can subsequently be used to study the identified area in more depth (Spiga and Forget, 2009), which would otherwise be computationally expensive.

To make optimal use of information, observations and GCMs are combined by the process of data assimilation. 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 becoming an increasingly reliable technique for the input of observations into a GCM to study a variety of topics (Lewis and Barker, 2005; Lewis et al., 2007; Montabone et al., 2006; Hoffman et al., 2012; Greybush et al., 2012; Navarro et al., 2014a; Steele et al., 2014a,b). The majority of these publications use retrievals from the Thermal Emission Spectrometer (TES) aboard the Mars Global Surveyor due primarily to the wealth, and good spatial coverage, of these observations (Conrath et al., 2000). Mars Express carries the Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (SPICAM) instrument from which total ozone can be retrieved (Perrier et al., 2006). Ozone has never before been assimilated for Mars, but is a widespread technique for Earth (Levelt et al., 1996; Eskes et al., 2003; Grassi et al., 2004; Kiesewetter et al., 2010). The SPICAM instrument was the first to provide a spatial and temporal coverage of the global climatology of ozone suitable for data assimilation techniques.

Data assimilation has multiple benefits over direct comparison between GCM simulated and observed quantities; providing estimates for parameters which are not directly observed, additional information on observations from the physical constraints imposed by GCMs, and combining observational datasets to optimise the value of the resulting data set. Assimilating observations of multiple trace gases on Mars in the future will also be achievable, allowing for investigations into interactions between chemical species which will improve our understanding of the martian chemical environment. Chemical rate coefficients defined through reconciling observed and modelled quantities would add to existing determinations of these rate coefficients, which in some cases are poorly constrained by laboratory measurements. The assimilation of total ozone can also be used to inform future investigations on the best observing strategy for upcoming missions such as the ExoMars Trace Gas Orbiter (TGO) and provide a comprehensive analysis, constrained by satellite observations, of the ozone cycle on Mars.

In this paper we investigate the effect of total ozone assimilation using SPICAM data on improving our understanding of the ozone cycle. Section 2 details the GCM and assimilation scheme used in this investigation and Section 3 outlines the SPICAM retrievals and quality control performed on the data. Section 4 provides the results of total ozone assimilation, and Section 5 states the conclusions of this investigation.

2. Global circulation model and assimilation method

To perform the model simulations, we use the UK version of the Laboratoire de Météorologie Dynamique (LMD) Mars GCM (hereafter MGCM). This 4D-model uses the physical parameterisations (Forget et al., 1999) and LMD photochemical module (Lefèvre et al., 2004) shared with a recent version of the LMD Mars GCM coupled to a UK-only spectral dynamical core and semi-Lagrangian advection scheme (Newman et al., 2002). It has been developed in a collaboration between the Laboratoire de Météorologie Dynamique, the Open University, the University of Oxford and the Instituto de Astrofisica de Andalucia. The dust distribution has been prescribed horizontally based on an interpolation of numerous sets of observations from orbiters and landers using a kriging method (Montabone et al., 2015), with a'semi-interactive' two-moment scheme used to freely transport dust vertically in the model (Madeleine et al., 2011). The model was run at T31 resolution in the horizontal, corresponding to a resolution of 5° latitude by 5° longitude, with 32 vertical levels in the range 0–105 km. Vertical levels are much closer to one another near the surface and further spread higher in the atmosphere.

The MGCM includes the latest sub-models to provide the most realistic modelling of the planetary boundary layer and water and dust cycles. A thermal plume model is used to better represent turbulent structures in the planetary boundary layer (Colaïtis et al., 2013). Regarding the martian water cycle, the most recent cloud microphysics package is included (Navarro et al., 2014b) which also accounts for the effects of radiatively active water ice clouds and supersaturation. 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. It also includes heterogeneous processes removing odd hydrogen radicals, a process which has been shown to improve the agreement between models and observations (Lefèvre et al., 2008). Time-varying dust amounts are also taken into account in the photolytic reactions. Tracers are advected using the semi-Lagrangian advection scheme.

Full details on the production and loss of ozone calculated at each timestep are in Lefèvre et al. (2004). The photolysis rate coefficient is calculated by the Tropospheric Ultraviolet and Visible model adapted to Martian conditions and stored in a lookup table offline to save computational expense. During the day, ozone is considered to be in photochemical equilibrium and implicitly solved as part of the O_x (O and O_3) family. At night, ozone is integrated separately from O with production and loss calculated via the associated chemical reaction rates. The simulations in this investigation are run over the time period of available SPICAM retrievals, which covers the time period from $L_S = 341°$ MY 26 to $L_S = 69°$ MY 28.

The assimilation is performed using a form of the Analysis Correction (AC) scheme (Lorenc 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. Other assimilation schemes are also now available for use, including a Local Ensemble Transform Kalman Filter (Navarro et al., 2014a). This particular assimilation