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## MACDA II: A New Reanalysis for the Martian Atmosphere Using Vertically-Resolved Dust Opacity Observations.

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# MACDA II: A NEW REANALYSIS FOR THE MARTIAN ATMOSPHERE USING VERTICALLY-RESOLVED DUST OPACITY OBSERVATIONS

**P. L. Read, A. Valeanu, Ruan Tao**, *Atmospheric, Oceanic & Planetary Physics, University of Oxford, UK* ([peter.read@physics.ox.ac.uk](mailto:peter.read@physics.ox.ac.uk)), **L. Montabone**, *Space Science Institute, Boulder, CO, USA, & Laboratoire de Météorologie Dynamique, IPSL, Sorbonne Université, Paris, France*, **S. R. Lewis**, *The Open University, UK*, **R. M. B. Young**, *Department of Physics & National Space Science and Technology Center, UAE University, Al Ain, United Arab Emirates*.

**Introduction:** The dust cycle is a key component of the Martian climate, and is extremely important for understanding the interannual, seasonal and synoptic evolution of the Martian environment. (e.g., Kahre et al., 2017; Newman et al., 2002a, and references therein). Intensive measurements of atmospheric temperature and dust extending over more than eleven Mars years (MY) now exist with unprecedented spatial coverage, thanks to various orbital spacecraft. Such observations have already helped to improve our understanding of Mars' weather and climate. However, the incomplete coverage of these measurements across the planet constrains our ability to study the general circulation in full detail, particularly those aspects related to dust opacity.

On the other hand, numerical models provide four-dimensional simulated data with moderate to high temporal and spatial resolution and complete coverage in space and time, but often fail to reproduce the dust cycle's full range of variability. Even the most sophisticated free-running GCMs still struggle to capture realistic interannual variability associated with dust lifting and transport.

To aid in this task, data assimilation has become an optimal approach to provide a solution that is consistent with both observations and modeled physical constraints. Data assimilation corrects model-predicted variables toward observations such that the resulting solution can represent the full observed variability of the climate. Such an assimilated record is often termed a “reanalysis” by analogy with the practice in Earth weather and climate forecasting.

Several publicly available reanalyses of observations of the Martian atmosphere have been produced in recent years, based mainly on remote sounding measurements of atmospheric temperature, dust and ice opacity and chemical constituents from various orbital platforms (e.g. Montabone et al. 2014; Greybush et al. 2019; Holmes et al. 2020). However, almost all of these have so far mainly used measurements of column dust opacity without information on the vertical distribution of dust. Such products provide much useful information on how dust evolves during the Martian year, but may misrepresent some important features, such as elevated layers of dust (Heavens et al. 2011), and give no information on the vertical extent of dust loading in the atmosphere.

In the present work, we have extended the Analytic Correction assimilation scheme (Lorenc et al.

1991), as used for the MACDA and OPENMARS reanalyses, to make use of both column-integrated (CIDO) and layer-integrated dust opacity (LIDO), such as obtained from Mars Climate Sounder limb observations. Here we outline the new assimilation scheme and present some results (a) that validate the reanalysis with independent observations and (b) that demonstrate significant improvements in the representation of the 3D distribution of dust opacity in the Martian atmosphere, even when this distribution differs markedly from the long term climatology.

**Outline of the Assimilation Scheme:** In this work the model used is based on the UK version of a three-dimensional Martian Global Climate Model (UK-LMD MGCM, v5.1.3) (Forget et al., 1999; Mulholland et al., 2013). The model combines a spectral dynamical solver at triangular truncation T31, corresponding to a 96 x 48 longitude-latitude grid in real space, a tracer transport scheme and dust lifting and deposition routines, along with a full range of physical parameterizations.

The observations used in the present reanalysis mainly comprise the retrievals of atmospheric temperature and dust opacity from the Mars Climate Sounder (MCS) instrument on board the Mars Reconnaissance Orbiter spacecraft (Kleinböhl et al. 2009). These consist of vertical profiles with a vertical resolution of around 5 km and a horizontal foot

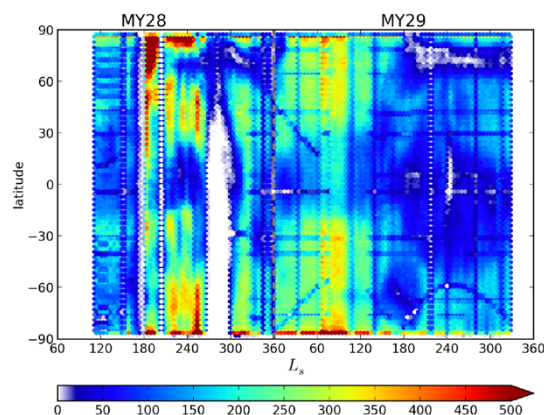


Figure 1: Spatial and temporal distribution of available dust opacity data from Mars Climate Sounder during MY28 and 29. The color scales show the number of measurements in 5°  $L_s$  and 3° latitude bins.

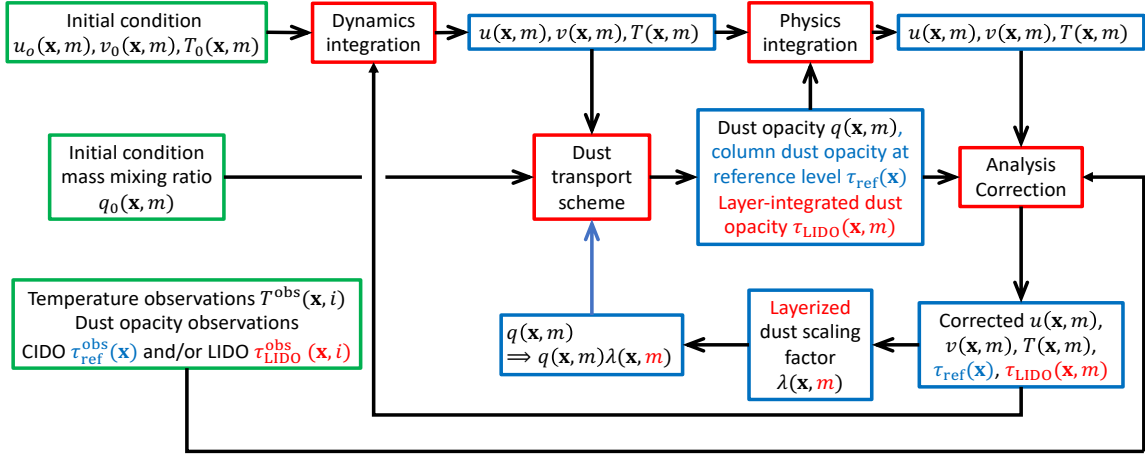


Figure 2: Sequence of operations in the new data assimilation scheme with active dust transport. Green boxes show initial conditions and input observations, blue boxes show data generated by Mars General Circulation Model (MGCM) integration, and red boxes show individual MGCM modules. Text in black applies to both column integrated dust opacity (CIDO) and layer-integrated dust opacity (LIDO) assimilation, text in blue applies to CIDO assimilation only, and text in red applies to LIDO assimilation only. Only variables related to the data assimilation scheme are included.

print of around 250 km, covering an altitude range from near the surface up to around 80 km. An additional vertically integrated dust opacity is also derived from the dust opacity profiles to provide an estimate of the total column opacity using the methodology described by Montabone et al. (2015,2020). A typical horizontal distribution of available data is illustrated in Figure 1 for MY28 and 29, which we use below to validate the reanalysis and demonstrate its capabilities.

The data assimilation scheme is based on the analysis correction sequential estimation (AC) scheme (Lorenz et al., 1991) but with modifications specific to Mars (Lewis et al., 2007; Ruan et al. 2021a). The assimilation step is computationally expensive compared with the rest of the model, and so is usually performed at each dynamical timestep (typically of 3 min). Lewis et al. (2007) describe the scheme in full detail. Temperature assimilations are the same as in that work, except for the observational data set used. In this work we extend the dust assimilation to incorporate advective transport of radiatively active dust in the simulation model as well as to assimilate both CIDO and LIDO observations. An identical free-running simulation without any assimilation, but with a fully active dust lifting and transport cycle tuned to reproduce plausible seasonal variations of dust loading (cf. Mulholland et al., 2013; Newman et al., 2002), was run in parallel.

For dust assimilation, the sequence of operations is described in detail by Ruan et al. (2021a) and illustrated in Figure 2. First the dynamics timestep is integrated, and then the dust is advected to obtain the three dimensional distribution of dust mass mixing ratio  $q(x, m)$ . The CIDO at position  $x$ , predicted from this distribution ( $\tau_c$ ) is obtained by summing

model layer ( $\tau_{LIDO}$ ). The reference column dust opacity  $\tau_{ref}$  at a reference pressure  $p_{ref}$  is then determined from the model by rescaling by the ratio of local surface pressure to  $p_{ref}$ . To compare the results with observations, modeled CIDO values are rescaled to 610 Pa. The dust transport scheme transports a 3D dust mass mixing ratio field, but the assimilated CIDO dust observations constrain  $\tau_{ref}$  only, so the dust mass mixing ratio at each model layer must be adjusted after the assimilation. This adjustment simply consists of a multiplicative scale factor  $\lambda(x)$ , which ensures that the shape of the vertical dust profile at each horizontal grid point remains the same before and after the assimilation of  $\tau_{ref}$ .

LIDO observations are assimilated separately and the approach used here resembles the assimilation of thermal profiles into the UK-LMD MGCM (Lewis et al., 2007). First, we use the modeled dust opacities  $\tau_{LIDO}(m)$  to predict the dust opacity within each observation layer  $i$ . Model layers that overlap more than one observed layer are split linearly in  $\ln p$  among the observed layers. The horizontal assimilation then uses these increments, summed over contributions from each observation level  $i$ , to update the modeled dust field. Dust is transported in terms of dust mass mixing ratio, so the assimilation needs to correct this quantity. As dust mass mixing ratio is proportional to LIDO, it is multiplied by a factor of  $\eta = \tau'_{LIDO}(x, m) / \tau_{LIDO}(x, m)$ , where the primed and unprimed quantities are the corrected and uncorrected LIDO values.

The advected dust opacity and mass mixing ratio fields are then used to integrate the physical parametrizations. Finally,  $\tau_{ref}$  and  $T$  are updated using data assimilated by the AC scheme, followed by increments to  $u$  and  $v$  in thermal wind balance.

**Reanalysis verification:** The new reanalysis has been verified by comparison of the reanalysed fields with both in-sample and out-of-sample observations, e.g. using data from other spacecraft. Figure 3 shows one example where the reanalysis, interpolated to the location of the Spirit and Opportunity rovers (shown in magenta), has been compared with predictions from a free-running model (without assimilation – shown in green) and the measured opacity from each rover (at 880 nm) in blue symbols.

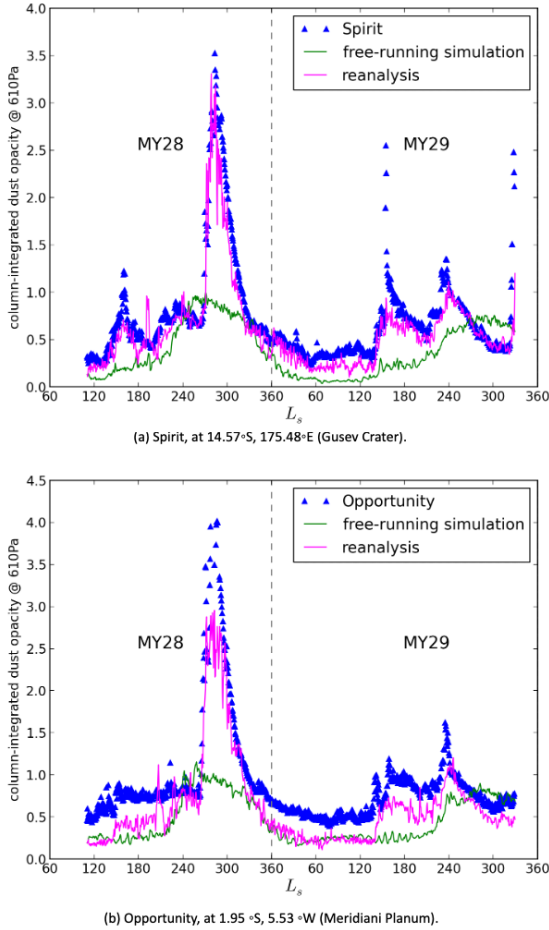


Figure 3:  $\tau_{ref}$  from the reanalysis (magenta) and free-running model (green) compared with (a) Spirit and (b) Opportunity Pancam observations. Each point is averaged over one sol.

The reanalysis is clearly shown to capture most of the variations in dust optical depth during MY28 and 29, including the large planet-encircling dust storm around  $L_s = 270^\circ$ - $300^\circ$  in MY28 and smaller regional dust storms at other times in MY29.

The advantage of assimilating LIDO profiles from MCS as well as total column dust opacities is clearly evident in Figure 4. This shows zonally averaged maps of dust opacity produced by a free-running model and assimilations that use either CIDO only data or combined CIDO and LIDO observations from MCS, compared with raw binned MCS observations alone.

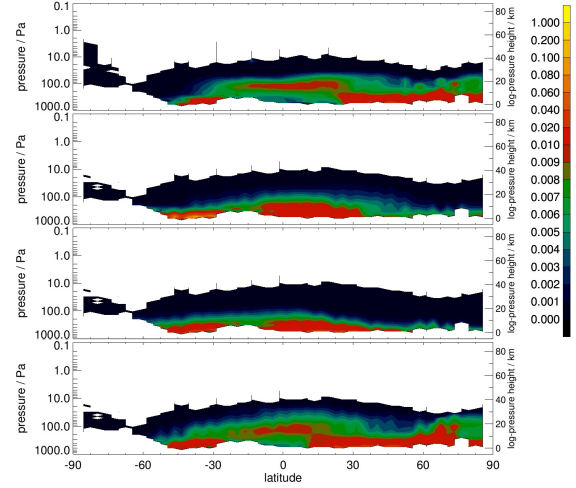


Figure 4: Night-time (18:00-06:00 local time) zonal-time mean dust opacity (km) during MY28  $L_s = 122.5^\circ$ , with detached dust layers. From top: MCS observations, free-running model, CIDO-only reanalysis, joint CIDO/LIDO reanalysis. Time averages are over  $5^\circ L_s$ .

The binned raw data in the top frame exhibits a case with a pronounced elevated dust layer at low latitudes (Heavens et al. 2011) which is not captured either by the free-running GCM or by assimilating CIDO observations alone. But the elevated layer is well captured in the bottom frame, which was obtained by assimilating both CIDO and LIDO observations together. This clearly shows the importance of assimilating the vertical structure of the dust distribution, which would otherwise lead to the reanalysis misrepresenting the dust and corresponding heating and cooling rates. Further details can be found in Ruan et al. (2021a).

**MACDA II:** The assimilation scheme and model described above have been used to assimilate temperature and dust observations from MCS and the earlier dataset from the Mars Global Surveyor/Thermal Emission Spectrometer instrument used for the original MACDA reanalysis (Montabone et al. 2014), covering the whole period from  $L_s = 141^\circ$  in MY24 until the end of MY35.

The new dataset retains the same T31 (72 x 36 gridpoints in longitude x latitude) horizontal resolution as MACDA v1.0 and on 25 vertical levels on terrain-following  $\sigma$ -levels. Fields and variables provided in the new reanalysis include everything that was provided in the MACDA v1.0 dataset (Montabone et al. 2014), plus additional fields representing the 3D time-varying dust distribution, atmospheric density and vertical velocity, together with surface wind stress and dust lifting rates, all provided 12 times per sol.

The new MACDA II reanalysis dataset will be archived as CF-compliant netCDF files and made publicly available to registered users via the Centre for

Environmental Data Analysis (CEDA) group (<https://archive.ceda.ac.uk/>). An earlier version of this re-analysis using MCS data and total column dust opacity measurements from the THEMIS instrument on Mars Odyssey for MY28-29 only is available on Zenodo (Ruan et al. 2021b).

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