OpenMARS MY24-27 reference manual

Dataset summary

This dataset contains our analysis of the global atmospheric state of Mars over the specified time period through a synthesis of the Mars Global Circulation Model (GCM) used at the Open University and observational data taken by the Thermal Emission Spectrometer (TES) instrument in orbit around Mars. This product is useful as a reference global Martian atmosphere that has been constrained by observations, and for several different studies related to the Martian atmospheric structure.

For any queries on the dataset, please contact: openmars@open.ac.uk

Accessing the dataset

Along with the data files that make up this dataset, there is also a sample Python script that shows an interested user how the data in the files can be easily accessed. The plot that will be created if the supplied Python script (sample_data_plot.py) is run without modification will be identical to the plot shown in Figure 1. The supplied sample Python script can be modified to produce various plots of the different variables stored in the dataset (for some examples of the different plots available, a good place to start is to have a browse at https://matplotlib.org/gallery/index.html).

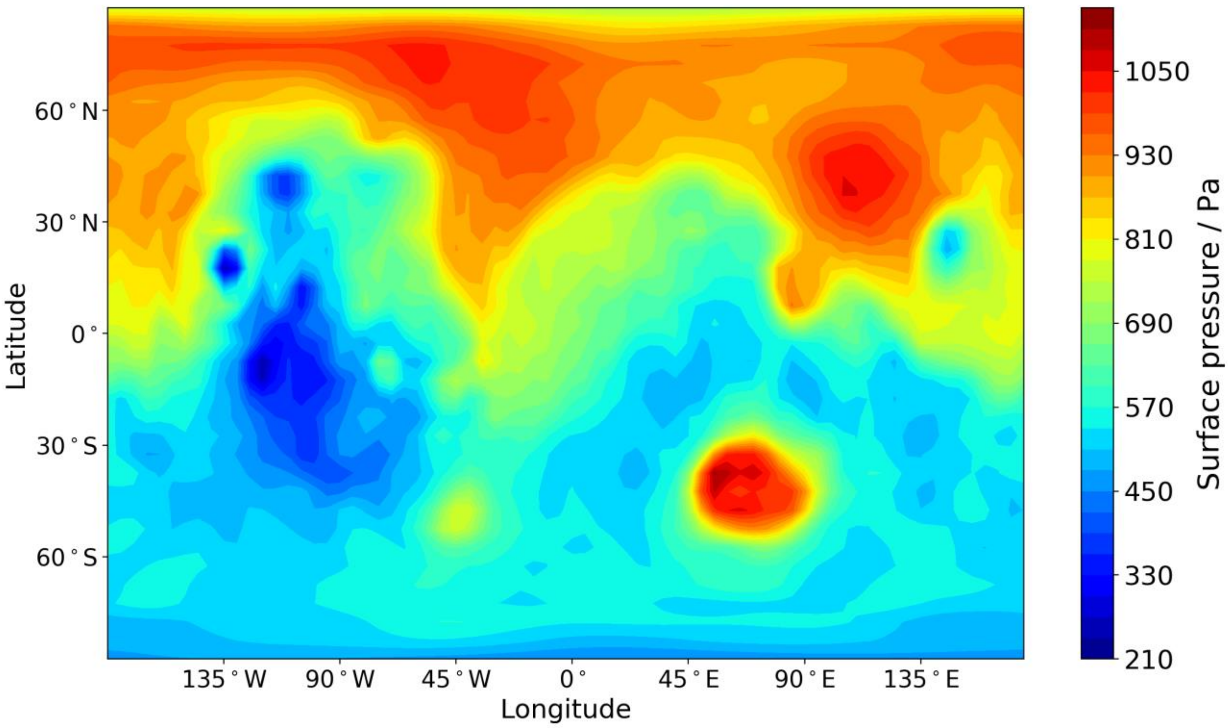

Figure 1 - Sample output of the surface pressure from the dataset created using the sample_data_plot.py script.

Structure of the reanalysis data files

This section details the structure of the files from the reanalysis which are made publicly available to interested users.

Dataset description

The reanalysis produced for this dataset covers almost three complete Mars years, with any particular data file covering 30 sols. The data files are provided in netCDF4 format which are easily accessible by Python (see sample_data_plot.py for an example of how to access the data). The filename convention is as follows:

openmars_myMM_lsL_myMM_lsL.nc

where MM (24 to 27) indicate the Mars Year (MY) and L (0 to 359) the start/end value of solar longitude (to the nearest integer) for the period covered by the data file.

Dimensions

The dimensions of the reanalysis data files are listed in Table 1. The surface and atmospheric reanalysis output in the data files depend on three (longitude, latitude, time) and four dimensions (longitude, latitude, level, time) respectively, with one exception being the visible column dust optical depth which depends on only three (longitude, latitude, time) dimensions. The horizontal grid spacing is 5˚ in both longitude and latitude, with four-dimensional atmospheric variables defined on model sigma levels σ (where $\sigma = p/p_s$, p is atmospheric pressure and p_s is surface pressure) that are non-dimensional terrain-following levels. There are 35 vertical levels in this reanalysis data product extending to an altitude of around 105 km.

Table 1 - Dimensions used for variables in the reanalysis data files.

Dimension	Number of values	Description
lon	72	Longitude
lat	36	Latitude
lev	35	Vertical level
time	360	Time

The primary time variable used for each data file is the Martian sol (see Table 2 for all time variables). For ease of conversion and since the majority of the Mars science community use solar longitude and Mars year, these values are also included. The surface and atmospheric variables are output every 2 Martian hours starting at 2 a.m. on sol 241 of MY 24, with sol 0 corresponding to L_S = 0˚ MY 24.

Table 2 - One-dimensional variables in each reanalysis data file.

Variable	Dimension	Description	Units
lon	lon	Longitude	Degrees east
lat	lat	Latitude	Degrees north
lev	lev	Model sigma level	NU
time	time	Martian Sol	Sols since 0.0
Ls	time	Solar longitude	Degrees
MY	time	Mars Year	NU

Surface variables

The surface variables included in each reanalysis data file are listed in Table 3. Although only the surface pressure is included in the reanalysis data files, the atmospheric pressure can be calculated for each vertical level of the atmosphere by multiplying the surface pressure variable ps by the corresponding sigma value of each vertical level in lev.

Although none of the surface variables are directly assimilated in the reanalysis product, each one is altered indirectly as a result of the assimilation of temperature profiles and column dust optical depth.

Table 3 - Surface variables in each reanalysis data file.

Variable	Dimension	Description	Units
ps	lon, lat, time	Surface pressure	Pa
tsurf	lon, lat ,time	Surface temperature	K
co2ice	lon, lat, time	Surface CO_2 ice	kg m^{-2}

Atmospheric variables

The atmospheric variables included in each reanalysis data file are listed in Table 4. As previously mentioned, as the variable dustcol is a column value it only has three dimensions whereas the other atmospheric variables are all four-dimensional. The zonal wind u and meridional wind v are positive in the eastward and northward direction respectively. Although not directly assimilated, u and v are both indirectly altered as a result of the assimilation procedure.

Table 4 - Atmospheric variables in each reanalysis data file.

Variable	Dimension	Description	Units
dustcol	lon, lat, time	Visible column dust optical depth	NU
temp	lon, lat, lev, time	Atmospheric temperature	K
u	lon, lat, lev, time	Zonal wind (Eastward)	ms^{-1}
v	lon, lat, lev, time	Meridional wind (Northward)	ms^{-1}

Overview of the components used to create the dataset

This section gives an overview of the three different components used to create the OpenMARS dataset, namely the Mars GCM, TES observational data and the Data assimilation scheme that combines the two sources of information.

Mars GCM

The GCM used to produce this reanalysis product is the UK version of the LMD GCM (hereafter MGCM), which has been developed in a collaboration of the Laboratoire de Météorologie Dynamique, the Open University, the University of Oxford and the Instituto de Astrofisica de Andalucia. This model uses physical parameterisations shared with the LMD GCM, which are coupled to a UK-only spectral dynamical core alongside an energy and angular momentum conserving vertical finite-difference scheme. Tracers such as CO_2 and dust are transported by a UK-only semi-Lagrangian advection scheme (Newman et al., 2002) with mass conservation (Priestley, 1993).

The MGCM is similar to the model used in Montabone et al. (2014) for a previous reanalysis dataset but now includes additional sub-models. CO_2 is now transported as an additional tracer providing a better representation of the CO_2 cycle. A thermal plume model is used to better represent turbulent structures in the planetary boundary layer (Colaïtis et al., 2013), of importance for the evolution of tracers. A `semi-interactive' two-moment scheme is used to freely transport dust in the model (Madeleine et al., 2011), although the dust column optical depth at each grid point is scaled to match the observed dust distribution which is assimilated into the MGCM from spacecraft observations.

The model is truncated at wavenumber 31 resulting in a 5˚ physical longitude-latitude grid (and 3.75˚ longitude-latitude grid for the dynamical core) with 35 vertical levels extending to an altitude of ~105 km. The time-stepping regime for the physical and dynamical parts of the MGCM is 15 and 1.5 minutes respectively.

TES observational data

This section describes the observational data available from the TES instrument aboard the Mars Global Surveyor (MGS) spacecraft. The TES instrument operates in the thermal infrared between 6–50 µm (200-1600 cm^{-1}). The spectrometer began its mapping operations on 1 March 1999 (L_S = 104°, MY 24) and ended on 31 August 2004 (L_S = 81°, MY 27). MGS completed 12 orbits each sol, creating two sets of 12 narrow strips of data, running roughly north-south and separated by ~30° in longitude. The two sets of data contain observations at local times around 2 a.m. and 2 p.m. respectively, with the variation larger near the poles (for example, in the polar regions the daytime observations range between 12:30–14:30).

TES temperature profiles

The temperature retrievals used in the assimilation, along with the retrieval methods, are described in detail by Conrath et al. (2000) and Smith (2004). Briefly, temperature profiles are retrieved from nadir radiances in the 15 µm CO_2 band, and extend up to an altitude of around 40 km. The vertical resolution is around one pressure scale height (~10 km), though the temperature retrievals provided for assimilation have a vertical sampling on a one-quarter pressure scale height (~2.5 km). Uncertainties for each profile are around 2 K, but are larger in the lowest scale height above the ground because of possible errors in estimating the surface pressure (Conrath et al., 2000; Smith, 2004). Systematic errors greater than 5 K may also be present in retrievals over the winter polar regions because of errors in the absolute radiometric calibration. Conrath et al. (2000) noted that evidence for systematic errors was found in retrievals with temperatures lower than the CO_2 condensation temperature: it would be expected that the latent heat released during condensation would keep the temperature close to the CO_2 condensation temperature of ~145 K.

Figure 2 displays the number of TES temperature profiles that are assimilated into the MGCM to form part of the final reanalysis product. Fewer temperature profiles are available during the majority of MY 25 as the TES instrument during this period was observing at a higher spectral resolution that took twice as long to acquire compared to running at the lower resolution for the rest of the time period covered by the observations.

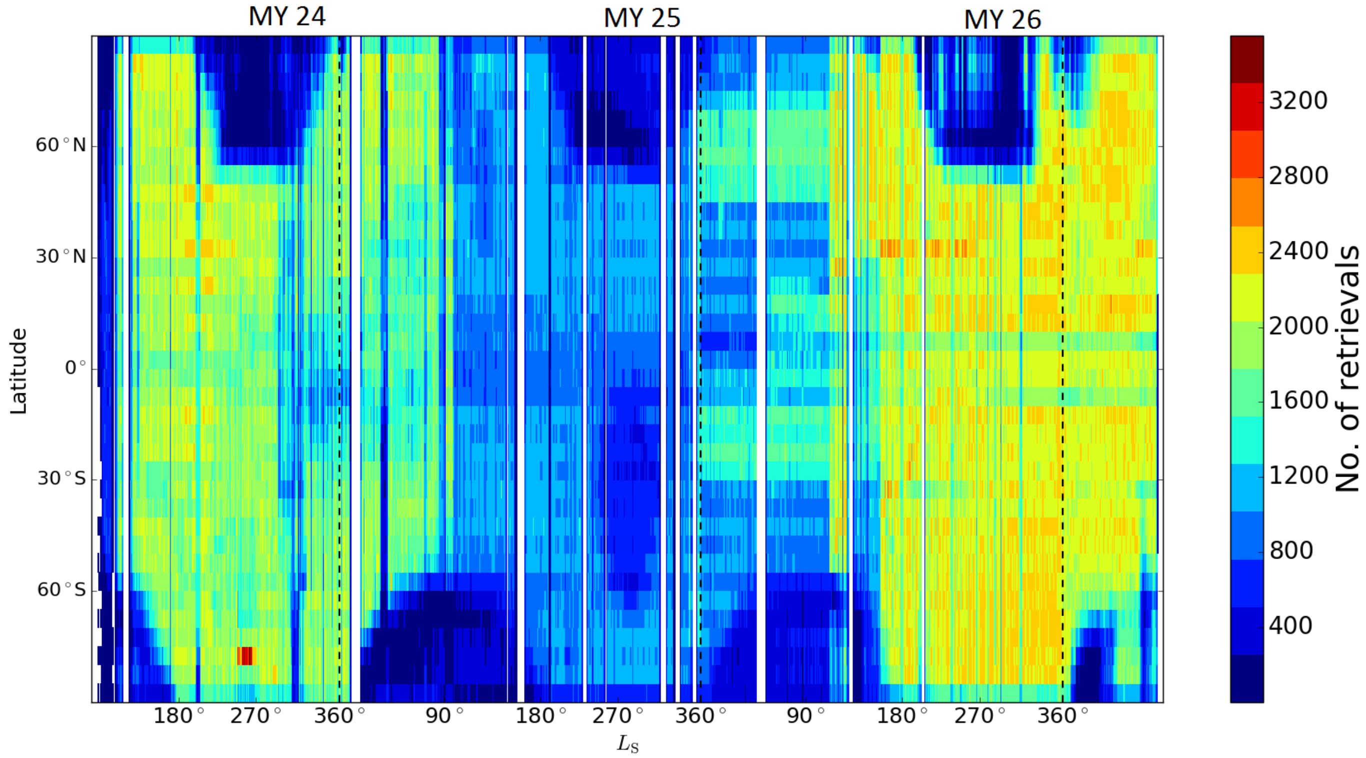

Figure 2 - Number of TES temperature profiles in 2 sol by 5˚ latitude bins. Dashed vertical lines indicate the end of a Mars year. White indicates no data available in this particular bin.

TES dust opacity retrievals

The TES instrument in nadir-viewing geometry measured dust opacity at 1075 cm^{-1} in the infrared, with the retrievals method detailed in Smith et al. (2000). Briefly, using the TES spectra an equivalent column-integrated opacity of pure absorbers as a function of wavenumber is first computed. Then, the contribution of dust to the total opacity is estimated by fitting predetermined spectral shapes (opacity as a function of wavenumber) for dust, water ice, and the effect of a non-unit emissivity surface to the observed opacity spectrum.

Figure 3 displays the number of TES column dust optical depth retrievals that are assimilated into the MGCM to form part of the final reanalysis product. There is a notable lack of coverage of column dust optical depth retrievals at high latitudes during polar winter of each Mars years, a result of the minimal thermal contrast between the surface and atmosphere preventing a reliable retrieval being derived. Fewer retrievals of column dust optical depth are also available during the majority of MY 25 for the exact same reason detailed in the description of the TES temperature profiles, namely that the TES instrument during this time was observing at a higher spectral resolution.

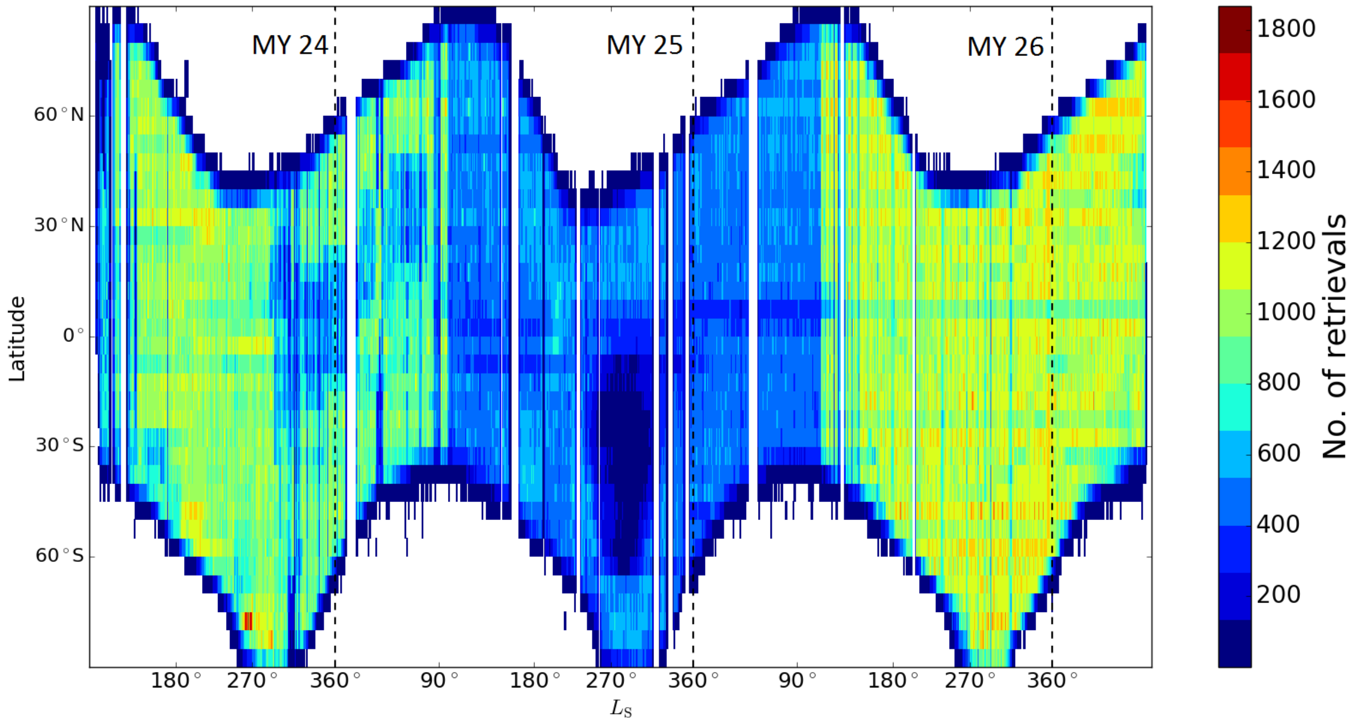

Figure 3 - Number of retrievals of TES column dust optical depth in 2 sol by 5˚ latitude bins. Dashed vertical lines indicate the end of a Mars year. White indicates no data available in this particular bin.

Quality control

The quality control applied to the TES temperature profiles follows the procedure described in Lewis et al. (2007). Profiles marked as bad by the retrieval algorithm are automatically rejected, with remaining retrievals filtered to remove any profiles that contain a temperature below 130 K (lower than the CO_2 condensation temperature), or temperatures above 300 K in the lower atmosphere (falling linearly to 220 K at 40 km altitude). This additional filtering is applied in order to remove excessively high or low temperatures which may cause problems with the model's physical schemes, and also removes some of the retrievals affected by possible systematic errors in the radiometric calibration. The filtering removes around 0.5% of the available observations. Throughout its lifetime, the TES instrument retrieved approximately 46 million temperature profiles.

For dust opacity, the quality control procedure is also detailed fully in Lewis et al. (2007). Following Smith et al. (2000), only opacities where the surface temperature was greater than 220 K were retained. This requirement, for a good surface–atmosphere temperature contrast, unfortunately further restricts the dust information to day-time, and mostly to the summer hemisphere, regions of the planet. Most dust information is in the equatorial region and the southern hemisphere. Finally, checks were run to see that the dust opacity was indeed positive, that the retrieved water ice opacity was also positive (actually $\tau > -0.05$, to allow for noise but to disallow fits which balanced large dust opacities with negative water ice opacities) and similarly to check that the carbon dioxide hot bands opacity fit was reasonable ($-0.01 > \tau < 0.05$) and that the total fit residual was not too large ($\tau < 0.05$). Over the time period used for the present reanalysis, around 16 million TES dust opacity retrievals are available for assimilation into the MGCM.

Data assimilation scheme

To assimilate the observations, the MGCM uses the Analysis Correction (AC) scheme (Lorenc et al., 1991) adapted to Martian conditions. The AC scheme has previously been used to assimilate thermal and dust opacity retrievals from TES (Lewis & Barker, 2005) which are used to indirectly study the thermal tides. The dust opacity retrievals have also been used to perform a multi-annual study of interannual dust variability (Montabone et al., 2005, 2015), indicating localised regions which triggered the onset of the global dust storm in MY 25 and also found dust lifting by dust devils to contribute little. Observations during the TES aerobraking phase have been assimilated indicating an atmospheric warming at the onset of northern hemisphere winter due to the dust storm in MY 23 (Lewis et al., 2007). The AC scheme has also been validated against radio occultation (RO) measurements (Montabone et al., 2006), with the assimilation of TES thermal and dust opacity retrievals improving the agreement between the MGCM and the RO profiles. Recent work with the AC scheme has moved on to the assimilation of chemically passive water vapour and water ice (Steele et al., 2014a,b) to investigate the Martian water cycle and radiative effect of water ice clouds respectively and chemically active species such as ozone (Holmes et al., 2018).

The AC scheme is a form of successive corrections in which analysis steps are interleaved with each model dynamical time step. The modified successive corrections equation used by the scheme is

$$\mathbf{x}_a = \mathbf{x}_b + \mathbf{WQ}[\mathbf{y}_o - H(\mathbf{x}_b)]$$

where $\mathbf{x}_a$ is the analysis vector, $\mathbf{x}_b$ is the model background, $\mathbf{y}_o$ is the observation vector, H is the observation operator and **W** and **Q** are matrices of weights and normalization factors respectively. In each analysis step, the above equation is split into separate vertical and horizontal stages in order to spread the analysis increments from the observation locations to the surrounding model grid points. This is followed by the derivation of multi-variate increment fields for dynamical balance where applicable (e.g. after assimilating temperatures, geostrophic wind adjustments are applied).

Observations are inserted over an asymmetrical specified time window of 6 hours (five hours before an observations valid time until one hour after), optimally selected so that the assimilation will not unrealistically smooth out any inherent model variation. The asymmetrical time window is also used as it is beneficial because it biases the assimilation gains to regions ahead of the satellite ground track, which have not recently been observed. Spreading in time was also found to be beneficial in the case of relatively sparse data, where it is often better to use an observation from a slightly different time, with a reduced weight, rather than release the model which would then quickly relax back toward a temperature determined principally by its dust distribution, since the radiative timescale of the Martian atmosphere is only 1–2 sols.

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