OpenMARS MY28-32 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 Mars Climate Sounder (MCS) 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).

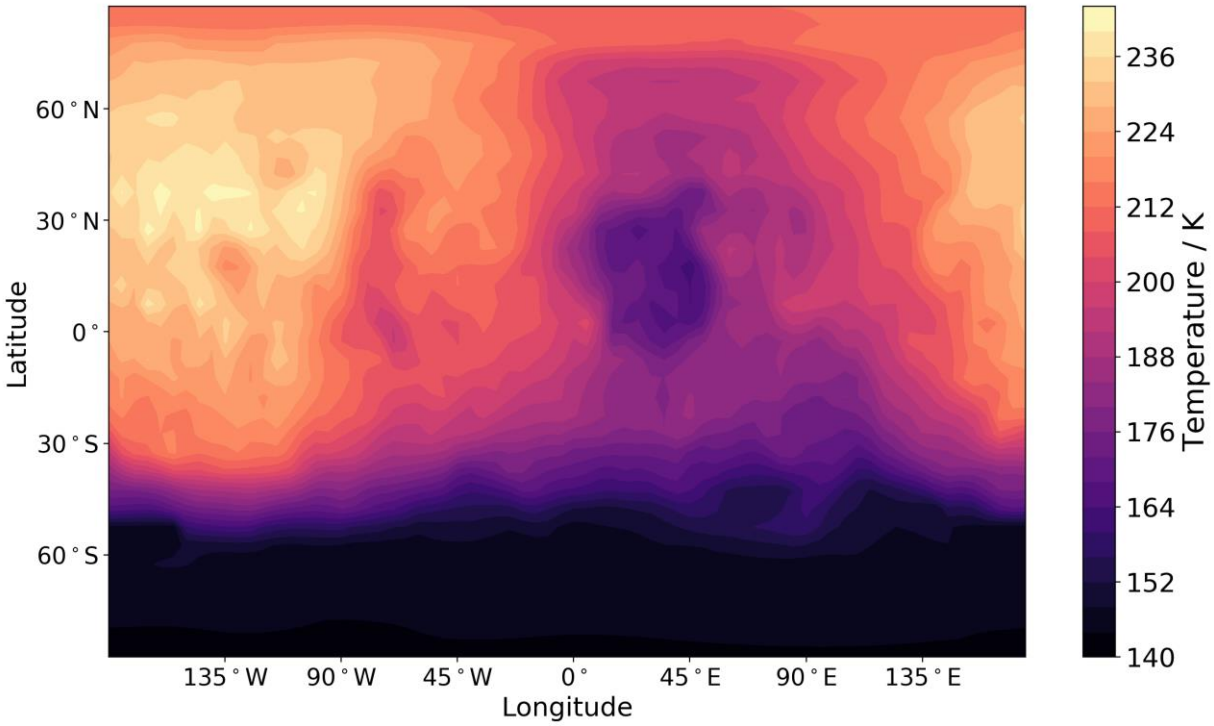

Figure 1 - Sample output of the temperature in the first layer of the atmosphere from the dataset created using the sample_data_plot.py script.

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 five complete Mars years, with any particular data file covering 30 sols. As a result of extended gaps in the MCS time period when the instrument was switched off the data files are not continuous. 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 (28 to 32) 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 2911 (sol 235 of MY 28), with sol 0 corresponding to $L_S = 0^\circ$ 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, MCS 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.

MCS observational data

This section describes the observations available from the MCS instrument aboard the Mars Reconnaissance Orbiter (MRO) spacecraft. The MCS instrument employs a nearly continuous limb viewing strategy in order to achieve greatly increased sensitivity to minor and trace constituents (McCleese et al., 2007). The instrument is a passive radiometer which retrieves in 9 spectral bands covering the visible and mid- to far-infrared channels. It is capable of retrieving vertical profiles of water ice and dust opacity alongside temperature profiles with a greater vertical resolution than TES (5 km for MCS as opposed to ~10 km). The vertical coverage of the profiles is from the surface up to altitudes of ~85 km (as opposed to ~40 km for TES). The MCS observations comprise two sets of twelve narrow strips of data, separated by ~30° in longitude, a similar pattern to that observed by the TES instrument. Due to the Sun-synchronous orbit of MRO, the MCS observations away from the pole occur at local times around 3 a.m. and 3 p.m., though the actual local time of an observation varies with both latitude and season. The instrument began its coverage of Mars on 24th September 2006 (or L_S = 111° MY 28), in the primary science phase of the mission.

MCS temperature profiles

The retrieval of vertical temperature profiles from the MCS measured radiance is extensively covered in Kleinböhl et al. (2009) and briefly detailed in this section. It uses 3 channels of the MCS instrument (A1-3) in the far-infrared. The radiative transfer equation is inverted to determine the temperature from the radiance using an iterative method. For this process, a ‘first guess’ is needed for the temperature profile, although the success of this retrieval method is shown to be insensitive to this initial guess (Kleinböhl et al., 2009). The algorithm is processed for each limb profile with 30 iterations, to converge on the final vertical profile of temperature. The error on the retrieval is reduced in the lower atmosphere (0.5 K) and increases at higher altitudes due to the reduction in signal-to-noise ratio (> 1 K above 40 km) and in situations where the atmosphere is opaque.

Figure 2 displays the number of MCS temperature profiles that are assimilated into the MGCM to form part of the final reanalysis product. An increased number of MCS temperature profiles are noticeable at the end of MY 28, as a result of a dedicated campaign to observe as much as possible of the Martian atmosphere during a high dust loading dust storm season. Periods in which there are no data at all (e.g. at the end of MY 29) are as a result of the MCS instrument being switched off during this time period.

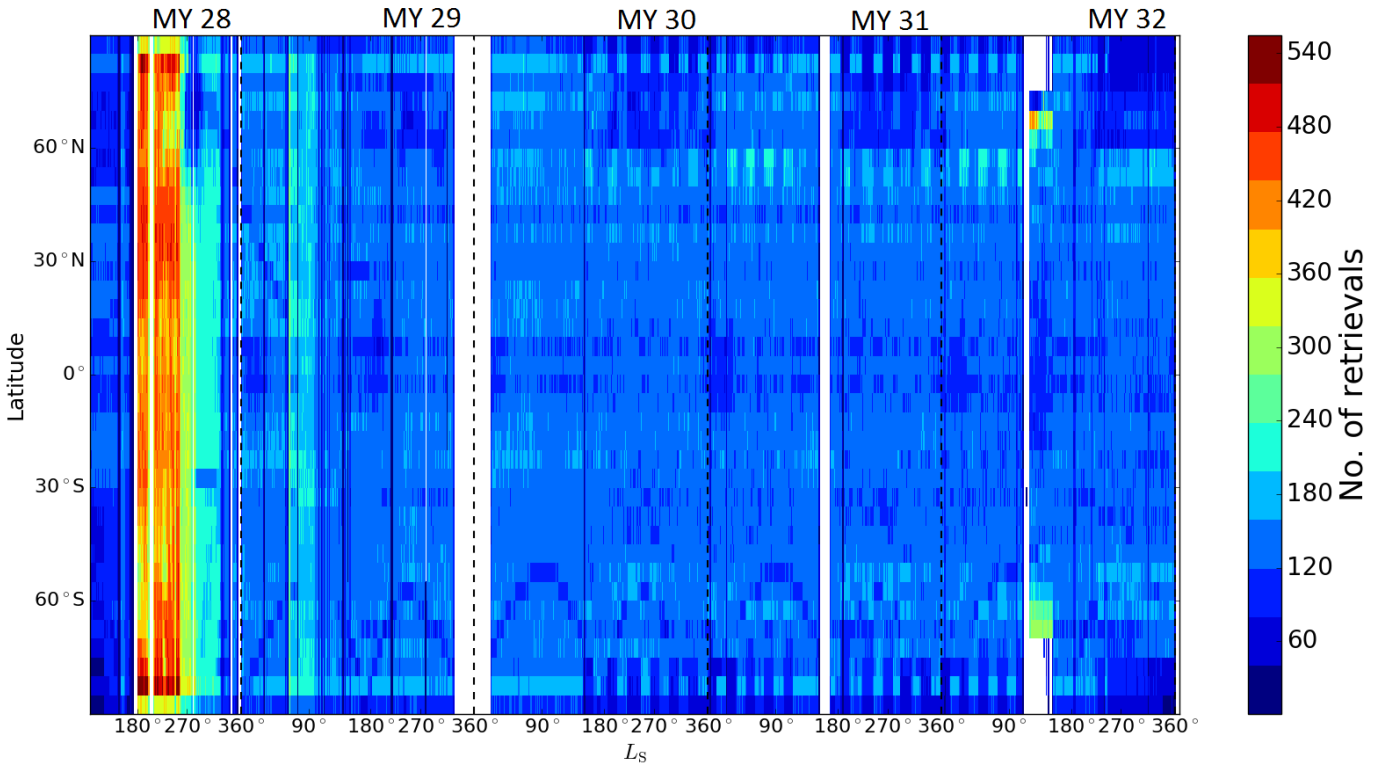

Figure 2 - Number of MCS temperature profiles in 2 sol by 5˚ latitude bins. Dashed vertical lines indicate the end of a Mars year. White indicates no data available in this particular bin.

MCS dust opacity retrievals

The retrieval of dust opacity profiles from the MCS measured radiance is also extensively covered in Kleinböhl et al. (2009). Details of how the column dust optical depth is retrieved are presented in Montabone et al. (2015) and briefly detailed here. For any given successful limb retrieval, the full profile of dust extinction opacity produced by the retrieval algorithm (MCS retrievals from version v4.3 are used for this reanalysis) is integrated to produce a column dust optical depth. The profile is extended upward and downward under the assumption of well mixed dust, based on the last valid value.

The MCS dust profiles cannot be retrieved down to the surface using only limb observations, and the dust in the un-retrieved part of the profile can potentially account for a significant fraction of the total dust column. Therefore estimates of column dust optical depth from MCS observations are likely to introduce errors attributable to either the extrapolation to the surface under the well mixed assumption or the use of dust opacity values at altitudes where the fit to observed radiances is not within the standard threshold.

Figure 3 displays the number of MCS column dust optical depth retrievals that are assimilated into the MGCM to form part of the final reanalysis product. The retrieval method allows for a reliable measurement of dust optical depth during the daytime and nighttime during polar winter over this time period. As with the MCS temperature profiles, more retrievals are available at the end of MY 28 as a result of the dedicated campaign to observe as much as possible during the high dust loading dust storm season.

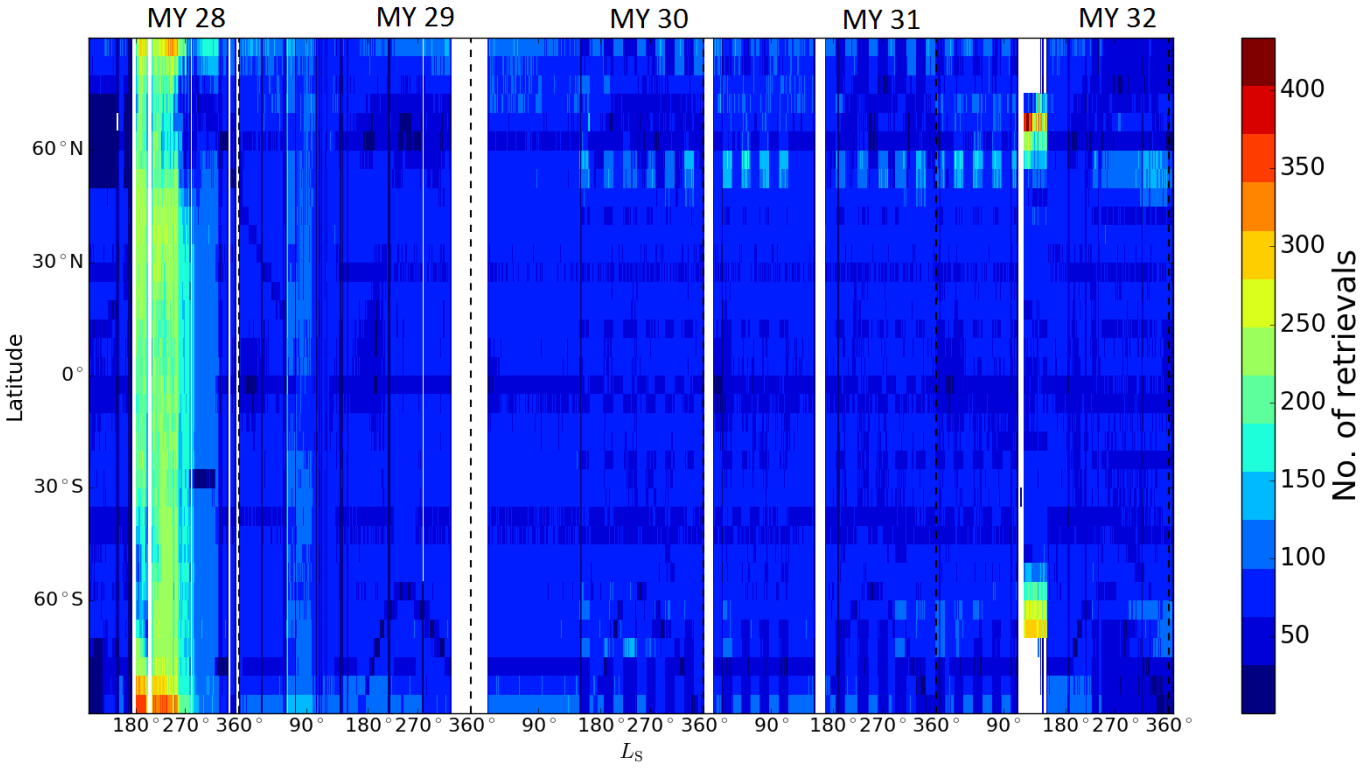

Figure 3 - Number of retrievals of MCS column dust optical depth in 2 sol by 5˚ latitude bins. Dashed vertical lines indicate the end of a Mars year. White indicates no data available in this particular bin.

Quality control

The quality control applied to the MCS temperature profiles is 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. After quality control, around 7.5 million temperature profiles retrieved by the MCS instrument are available for assimilation into the MGCM.

Quality control for the derived MCS column dust optical depth retrievals is fully described in Montabone et al. (2015) and briefly detailed here. Estimates of the MCS column dust optical depth can be fairly inaccurate if the lowest retrieved level of dust opacity is above ~20 km altitude, depending on the time of the year and the dust/water ice conditions. The dataset therefore largely consists of nighttime retrievals that correspond to dust extinction profiles with valid values at or below 25 km altitude, and only retrievals with local times between 12 p.m. and 6 p.m. when the corresponding extinction profile has valid values at or below 8 km altitude are accepted. Finally, estimates of column dust optical depth where the temperature profile dropped below the condensation temperature of carbon dioxide at some pressure levels are rejected, because CO_2 ice opacity is currently not taken into account in the retrieval algorithm but can affect retrievals of dust opacity at those levels. During the time period covered by the MCS instrument, around 4 million column dust optical depth retrievals are assimilated into the MGCM to produce the final reanalysis product.

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

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

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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