MARS CLIMATE DATABASE v1.0
DETAILED DESIGN DOCUMENT
(ESTEC Contract 11369/95/NL/JG)

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1 Introduction

The Mars Climate Database (MCD) is a database of atmospheric statistics compiled from state-of-the art Global Circulation Model simulations of the Martian atmosphere. The models used to compile the statistics have been extensively validated using available observational data and represent the current best knowledge of the state of the Martian atmosphere given the observations and the physical laws that govern the atmospheric circulation and surface conditions on the planet.

This document provides the user of the MCD with a detailed description of the data, how it is written in the database and of the access software. Detailed descriptions of the models and of the validation procedure are available in other documents relating to the project.

Note: This document refers to the first release of the Mars Climate Database (MCDv1.0). Future releases will contain updates to the database, to the access software and to the documentation. If you have any queries, or if you want to find out if this is the latest version of the MCD please email `euromars@lmd.ens.fr`.

2 Database Structure

2.1 The Data Retrieval and Storage (DRS) System

The data in the MCD is written using the Data Retrieval and Storage (DRS) library developed for the Program for (Terrestrial) Climate Model Diagnosis and Intercomparison (PCMDI). The library is available (pre-compiled for common platforms or as source code) from the Lawrence Livermore National Laboratory World Wide Web server at `http://www-pcmdi.llnl.gov/drach/DRS.html`.

DRS was developed as part of the Atmospheric Model Intercomparison Project (AMIP) to facilitate the transfer of data between platforms which may have different representations of floating point numbers. It also has a number of features to enable easy updating of model history files both in terms of temporal extension and in the addition of new diagnostic variables. It is a widely used data format and can be read by many data handling and graphical packages such as GrADS and Freuds.

One of the advantages of the DRS data format which has been used for the database is that the actual byte ordering of the data (often called "big endian") is independent of the type of machine that is used to read and write the data, provided the DRS library routines are used. Hence the binary database files are portable and can be read on any type of machine with programs which make use of DRS subroutines. When accessing the DRS files using GrADS from a "big endian" machine (such as a Sun or HP) this also presents no problem. However, if GrADS is run on a "little endian" machine (such as a DEC or IBM PC) it is still straightforward to read the database files owing to the presence of a record, `options big_endian`, near the head of the `.ctl` file corresponding to the `.dat` file which is being read. This record causes GrADS to swap the byte order as the data is read on a "little endian" machine but is effectively ignored on a "big endian" machine, though it is sensible to retain the record in case a little endian machine is used in future. Hence, the binary data files for the Martian Climate Database are portable between any type of computer which adopts the IEEE internal representation of real numbers (this includes most modern computers), whatever the details of byte ordering, provided that one of the three access methods (the MCDGM interface, program subroutines calling the DRS library, or GrADS with the `.ctl` files supplied) described in the user manual is adopted. Files ending in `.dat` can be transferred between machines in binary format and files ending in `.ctl` can be transferred as plain text: no further conversion is necessary.

2.2 Database Grid Structure

Horizontal Structure

Variables in the database are written on an equally spaced horizontal grid of 96 east longitude points

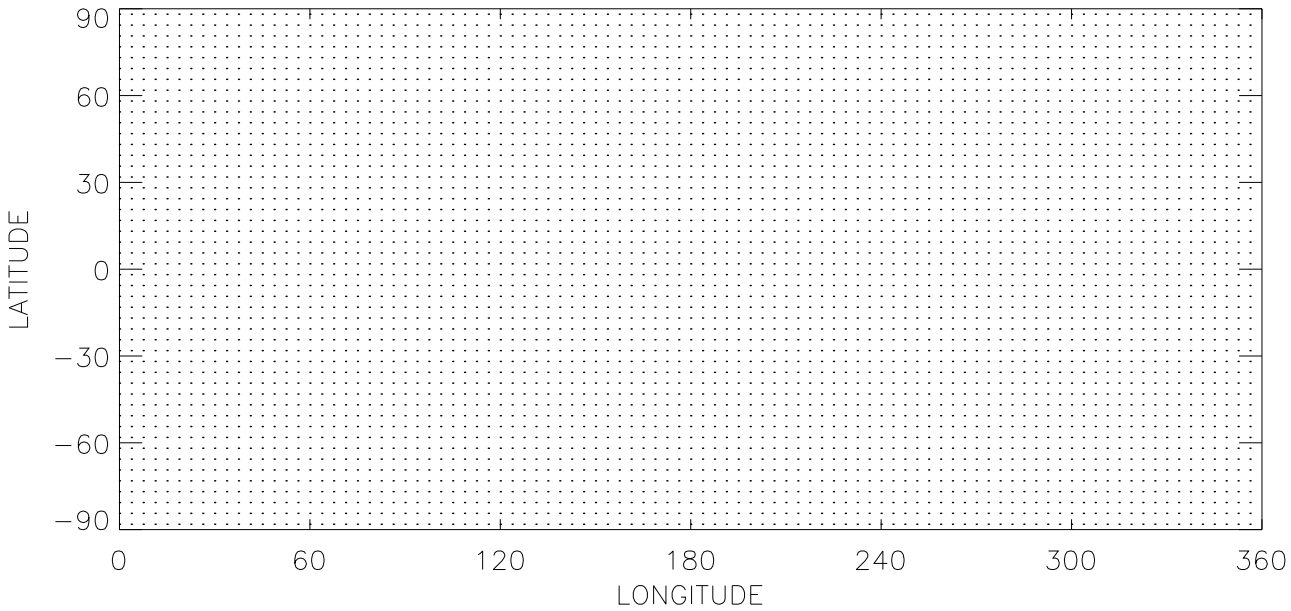

Figure 1: The database horizontal grid of 90 longitude and 48 latitude points.

numbered from 0° to 356.25° in steps of 3.75° and 48 latitude points numbered from −88.125° to 88.125° in steps of 3.75° (south latitudes are indicated by negative numbers). See figure 1.

Vertical Structure

The database vertical coordinate is defined as

$$\sigma = \frac{p}{p_*} \tag{1}$$

where p is the atmospheric pressure and p_* is the surface pressure. Thus σ is 1 at the surface and 0 at infinity and the σ levels follow the model orography. The sigma levels are arranged as in table 1 and a graphical explanation is presented in figure 2.

σ	Approximate Height	σ	Approximate Height
0.9995000	5m	0.2039437	15.9km
0.9980984	19m	0.1235681	20.9km
0.9955622	44m	0.0716660	26.4km
0.9909766	91m	0.0403225	32.1km
0.9827373	174m	0.0221810	38.1km
0.9680972	324m	0.0119545	44.3km
0.9425909	591m	0.0062904	50.7km
0.8996294	1.1km	0.0031992	57.4km
0.8311734	1.8km	0.0015417	64.7km
0.7310061	3.2km	0.0006778	73.0km
0.6009113	5.1km	0.0002497	83.0km
0.4552628	7.9km	0.0000563	97.8km
0.3166897	11.5km		

Table 1: Database σ levels and approximate heights based on $-10\ln(\sigma)$

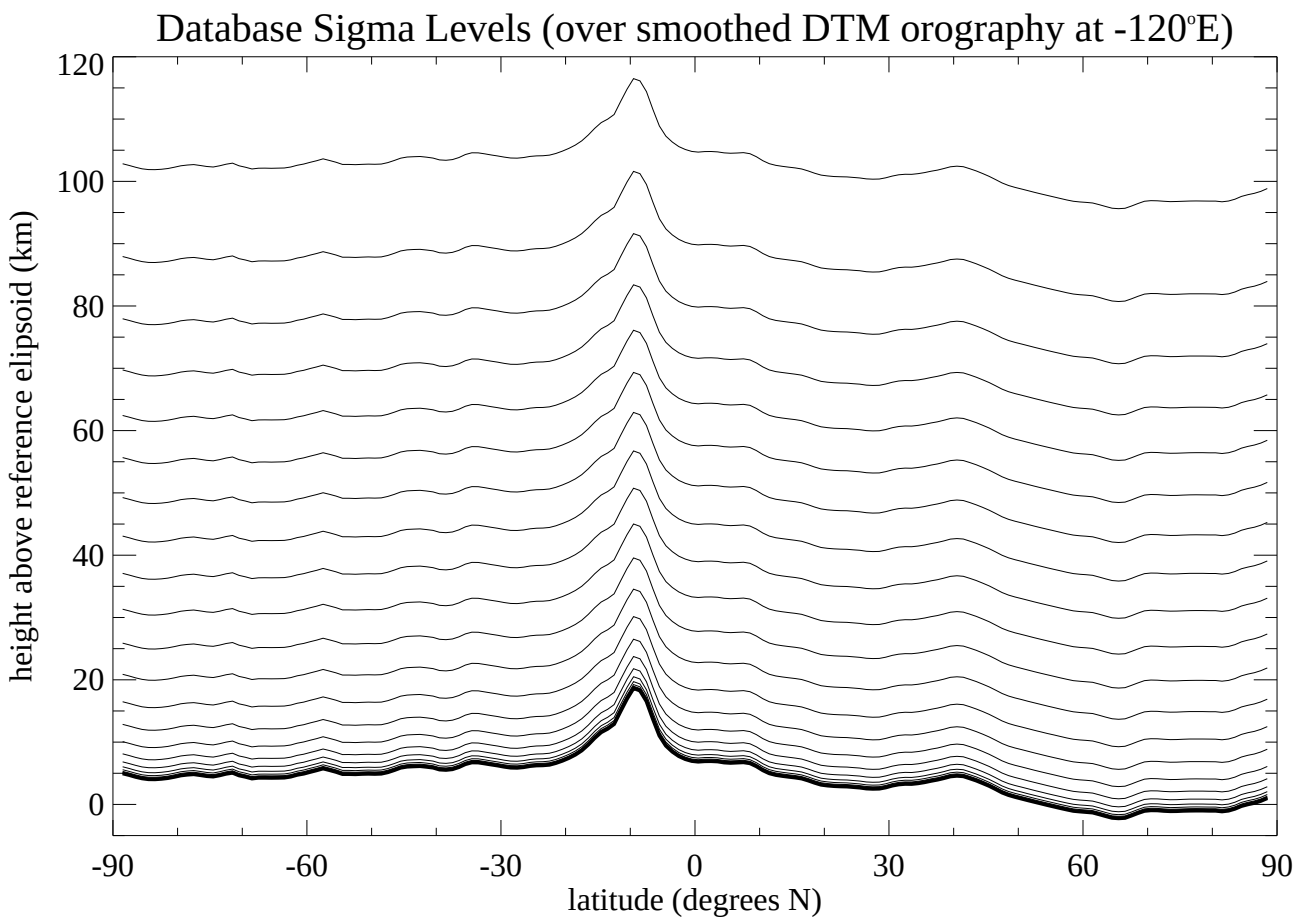

Figure 2: An illustration of the database σ levels.

Temporal Structure

Data is stored in the database 12 times per martian day using universal time, not local time. At universal time level 1 the local time at 0° longitude is 12pm (given that the martian day is 24 'hours' long). Hence at 90° longitude it is 6am, at 180° it is 12am etc. At time level 2 the local time at 0° is 2am etc. Universal time can be computed from local time and longitude using the following FORTRAN commands (see routine `atime.f` in the appended code listing).

```
iut=mod(nint(-longitude/30.+localtime/2.+12.),12)+1
universaltime=float(iut)
if (iut.eq.13) universaltime=1.0
```

2.3 Database File Structure

2.3.1 Software

The MCD software is stored in the directory

`mcd/mcdgm`

Issuing the unix command `ls` should produce the following list of files (or at least something very similar).

```
Makefile data getsi.f max2d.f mount.f orbit.f var3d.f
atime.f dstep.f grid4.f mcdgm.f ner2d.f profi.f vgrad.f
cospa.f eofpb.f grwpb.f mgthm.f ner3d.f solls.f
ctime.f gasdv.f ltime.f min2d.f opend.f var2d.f
```

Files with a `.f` prefix are FORTRAN routines. To compile these routines just issue the command `make` and the `Makefile` will be executed.

2.3.2 Data

The MCD data is stored in various files in the directory

`mcd/data`

e.g.

`mcd/data/viks04me.dat`

The file naming convention is as follows:

- The first 3 characters denote the dust scenario. The various scenarios are explained in an appendix to this document.
  - `ds2` indicates a dust storm with optical depth 2.
  - `ds5` indicates a dust storm with optical depth 5.
  - `low` indicates low dust data.
  - `vik` indicates Viking scenario data.

- The next 3 characters indicate the season number. The northern hemisphere spring equinox is at $L_S = 0°$, with northern summer solstice at $L_S = 90°$, autumn equinox at $L_S = 180°$ and winter solstice at $L_S = 270°$.
  - `s01` is season 1, $L_S = 0° - 30°$.
  - `s02` is season 2, $L_S = 30° - 60°$.
  - `s03` is season 3, $L_S = 60° - 90°$.
  - `s04` is season 4, $L_S = 90° - 120°$.
  - `s05` is season 5, $L_S = 120° - 150°$.
  - `s06` is season 6, $L_S = 150° - 180°$.
  - `s07` is season 7, $L_S = 180° - 210°$.
  - `s08` is season 8, $L_S = 210° - 240°$.
  - `s09` is season 9, $L_S = 240° - 270°$.
  - `s10` is season 10, $L_S = 270° - 300°$.
  - `s11` is season 11, $L_S = 300° - 330°$.
  - `s12` is season 12, $L_S = 330° - 360°$.
- The next 2 characters indicate the type of data in the file.
  - `me` indicates mean data.
  - `sd` indicates standard deviation data.
  - `eo` indicates Empirical Orthogonal Function (EOF) data (for the large scale variability model).
- The last 4 characters (the filename extension) indicate the type of file.
  - `.dat` is a DRS data file.
  - `.dic` is a DRS dictionary file.
  - `.ctl` is a GrADS descriptor file.

Hence the file `mcd/data/viks04me.dat` contains mean data for the Viking dust scenario for season 4.

Contents of Data Files

Mean data files (`me`) contain 12 seasonal mean values (corresponding to 12 universal times of day) for the following variables,

Mean variable	symbol	units	2-D or 3-D
CO_2 ice cover	co2ice	$kg\,m^{-2}$	2-D
Surface emissivity	emis	none	2-D
Surface temperature	tsurf	K	2-D
Surface pressure	ps	Pa	2-D
Atmospheric temperature	t	K	3-D
Zonal (east-west) wind	u	$m\,s^{-2}$	3-D
Meridional (north-south) wind	v	$m\,s^{-2}$	3-D
Atmospheric density	rho	$kg\,m^{-3}$	3-D
Boundary layer eddy kinetic energy	q2	$m^2\,s^{-2}$	3-D

Standard deviation data files (`sd`) contain seasonal standard deviation values of the following variables,

Standard deviation	symbol	units	2-D or 3-D
CO_2 ice cover	sdco2ice	$kg\,m^{-2}$	2-D
Surface emissivity	sdemis	none	2-D
Surface temperature	sdtsurf	K	2-D
Surface pressure	sdps	Pa	2-D
Atmospheric temperature	sdt	K	3-D
Zonal (east-west) wind	sdu	$m\,s^{-2}$	3-D
Meridional (north-south) wind	sdv	$m\,s^{-2}$	3-D
Atmospheric density	sdrho	$kg\,m^{-3}$	3-D
Boundary layer eddy kinetic energy	sdq2	$m^2\,s^{-2}$	3-D

EOF data files (`eo`) contain normalised multi-dimensional EOFS of density, zonal wind, meridional wind, temperature and surface pressure as well as some normalisation factors, eigenvalues and principal component model coefficients. It is recommended that you use the software supplied to access and exploit the data in these files.

I addition there are three files, `mountain.ctl, mountain.dat` and `mountain.dic` which mountain maps of the topographic height on Mars and sub-grid scale standard deviation of the topographic height (useful for computing gravity wave perturbations).

3 Dust Distribution Scenarios in the Martian Climate Database

This section outlines the dust distribution scenarios used for the GCM integrations which make up the Martain Climate Database. For the detailed rationale behind these choices, summaries of observational evidence and more references see the relevant sections of The Martian Environment Review and the Database Critical Review which have been compiled under this contract.

For all the scenarios, the vertical distribution of dust was calculated according to the formula,

$$\frac{Q}{Q_0} = \exp\left(0.007\left(1 - \max\left[\left(\frac{p_0}{p}\right)^{(70\,km/z_{\max})}, 1\right]\right)\right) \tag{2}$$

with p the pressure, p_0 a standard pressure ($700\,Pa$), Q and Q_0 the dust mixing ratio at the pressure levels p and p_0, and $z_{\max}$ the altitude of the top of the dust layer (where the dust mixing ratio is one thousandth of its value at p_0). This formula gives a rapid decay up to the height of the top of the dust layer and almost homogeneous dust mixing in the lower regions of the atmosphere. The function is illustrated for several different values of $z_{\max}$ in figure 3.

In fact this formula was developed from a slightly simpler form in common use for Mars, namely,

$$\frac{Q}{Q_0} = \exp\left(\nu\left(1 - \left(\frac{p_0}{p}\right)\right)\right) \tag{3}$$

where ν is now a parameter which determines the dust cut-off. This function is illustrated in figure 4. Equation 3 matches equation 2 when $z_{\max} = 70\,km$ and $\nu = 0.007$, which were roughly the conditions under which equation 3 was derived to model the distribution of dust at the time of the IRIS observations form Mariner 9. The reason for modifying the formula to the form in equation 2 was that it gives much more desirable properties in terms of the total dust contained below the cut-off threshold (with a broader region of homogeneity) and the vertical gradient of the dust is not so steep near the surface, especially when the dust is mostly low in the atmosphere, compare figure 3 with figure 4 when $z_{\max} = 20\,km$ and $\nu = 1.0$. While having these desirable properties the function still matches the limited available observations when the dust is high in the atmosphere.

Baseline multi-annual model integrations were carried out for the database under two main scenarios: (a) seasonally-varying dust as observed during the Viking Lander years, but with the large dust storms removed; and (b) low uniform dust, perhaps appropriate to more recent observations of a clearer, colder Mars. In addition, scenarios were conducted for several seasons with much higher dust loadings, appropriate to dust storm conditions. The details of the scenarios follow.

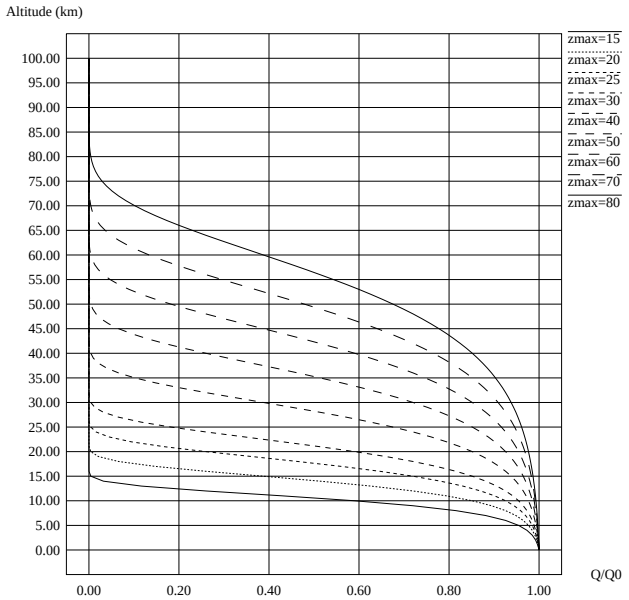

Figure 3: The variation of dust mixing ratio with height for different values of $z_{\max}$ according to the formula (equation 2) used to compile the Martian Climate Database.

- `vik` The standard Viking scenario with data provided for all twelve seasons from multiannual experiments. The total dust optical depth for the Viking case varied as a function of time to fit the Viking observations with peaks representing dust storms removed,

$$\tau(L_S) = 0.7 + 0.3\cos(L_S + 80^\circ) \tag{4}$$

  where τ is the optical depth and L_S the solar longitude of Mars. The optical depth was uniform in the horizontal for the Viking baseline run. However, the cut-off of the dust in the vertical varied as a function of both time and latitude,

$$z_{\max}(L_s, \phi) = \left(60 + 18\sin(L_s - 158^\circ) - 22\sin^2\phi\right)\ km \tag{5}$$

  where ϕ is the latitude. $z_{\max}$ varies between $78\,km$ at the equator during the dusty seasons and $20\,km$ at the pole during the clear seasons.

- `low` The low dust scenario with data provided for all twelve seasons from multiannual experiments. The low dust case was conducted with a dust distribution which was invariant in latitude, longitude and time, with an optical depth of $\tau = 0.1$ and a cut-off at $z_{\max} = 30\,km$ altitude.

- `ds2` A dust storm with optical depth 2. Data from these runs is only provided for the seasons when dust storms are most likely to occur; seasons 8, 9 and 10. In fact the scenario was initialized from a Viking scenario restart state at the beginning of season 7 and the season 7 data was then discarded. The dust optical depth was set to a constant value of $\tau = 2$, and the vertical cut-off for the dust was modelled as in the Viking scenario, equation 5.

- `ds5` A dust storm with optical depth 5. Data from these runs is only provided for the seasons when dust storms are most likely to occur; seasons 8, 9 and 10. In fact the scenario was initialized from a Viking scenario restart state at the beginning of season 7 and the season 7 data was then discarded. The dust optical depth was set to a constant value of $\tau = 5$, and the vertical cut-off for the dust was modelled as in the Viking scenario, equation 5.

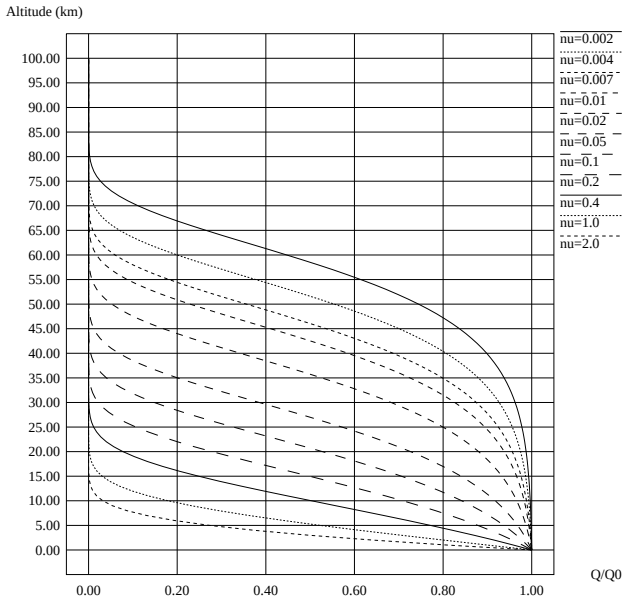

Figure 4: The variation of dust mixing ratio with height according to a formula (equation 3) previously used in many Martian GCMs, with the ν parameter adjusted to give dust cut-offs at different heights. This function matches that in figure 3 when $z_{\max} = 70\,km$ and $\nu = 0.007$.

4 Variability

4.1 The Large Scale Variability Model

Mean fields are stored in the database once a season, a season being typically 50-70 days long. Although the main variability, which is due to the diurnal cycle, is captured by storing the fields 12 times a day there may still be significant variation about the mean due to, for example, motions of baroclinic weather systems.

Large scale variability in the database is represented using a novel approach based on a technique that is widely used in meteorological data analysis as well as in other subject areas.

Let $D(z)$ be the database mean vertical profile of a meteorological variable. We add a series of functions to the mean vertical profile,

$$D(z) \; = \overline{D}(z) \; + \; \sum_{n=1}^{N} \; p_i e_i(z) \tag{6}$$

where the functions $\mathbf{e_i}$ are eigenvectors of the covariance matrix of the modelled profiles and p_i are the amplitudes of the functions. The eigenvectors $\mathbf{e_i}$ are often called Empirical Orthogonal Functions (EOFs) and the p_i are referred too as the Principal Components (PCs) (see e.g. Mo and Ghil (1987)). The $\mathbf{e_i}$ form an optimal linear basis such that the variance capture is high even when the truncation limit is low. In order to retain cross-correlations in altitude between different variables we combine all the variables together and form a set of multivariate functions.

In practice the series 6 is truncated to 6 EOFs which, on average, capture around 80-90% of the variance. The PCs are modelled using a second order polynomial fit, to capture any seasonal trend, plus some white noise, to capture any oscillatory phenomena.

The full mathematical details are given below.

Consider a time series of vertical profiles of $\mathbf{u}(p,t)$, $\mathbf{v}(p,t)$, $\mathbf{T}(p,t)$, $\rho(p,t)$ and surface pressure $p^*(t)$ at M times and at L levels. We form a time series of vectors $\mathbf{D}(\mathbf{t})$ where

$$\mathbf{D}(t) \;=\; (\hat{\mathbf{u}}(p,t), \hat{\mathbf{v}}(p,t), \hat{\mathbf{T}}(p,t), \hat{p^*}(t), \hat{\rho}(p,t)) \tag{7}$$

and the hat $\hat{}$ denotes a removal of the series mean and normalisation of variance operator e.g.

$$\overline{u} \;=\; \frac{1}{ML}\sum_{m=1}^{M}\sum_{l=1}^{L} u_{ml} \tag{8}$$

$$\hat{u}_{ml} \;=\; \frac{u_{ml}-\overline{u}}{\sqrt{\frac{1}{ML}\sum_{m=1}^{M}\sum_{l=1}^{L}(u_{ml}-\overline{u})^2}} \tag{9}$$

where the m denotes time and the l denotes vertical level. Hence the variance of the entire time series of $\mathbf{D}(t)$ is unity.

We then form the $(N \times N)$ covariance matrix, $\mathbf{C}$, such that

$$\mathbf{C} \;=\; \mathbf{D}\mathbf{D}^T \tag{10}$$

where $N = 4L+1$, $\mathbf{D}$ is the $(N \times M)$ matrix whose rows are the vectors $\mathbf{D}(t)$ and the superscript T indicates the transpose.

The matrix $\mathbf{C}$ is real symmetric and we can find the eigenvectors and eigenvalues and order them in decreasing eigenvalue magnitude. We note that if $\mathbf{E}_i$ is the i'th eigenvector then

$$|\mathbf{E}_i| \;=\; 1 \tag{11}$$

where $|\cdot|$ is the Euclidean Norm, and

$$\sum_{i=1}^{N}\lambda_i \;=\; 1 \tag{12}$$

where λ_i is the i'th eigenvalue.

The i'th principal component at time m, p_{mi} is defined as

$$p_{mi} \;=\; \sum_{n=1}^{N} D_{mn}E_{in} \;=\; \mathbf{D}\cdot\mathbf{E}_i \tag{13}$$

and we note the result

$$\frac{1}{MN}\sum_{m=1}^{M}(p_{mi})^2 \;=\; \lambda_i \tag{14}$$

Each principal component has M values but for the database we choose to model them as

$$\mathbf{q}_i \;=\; a_i \;+\; b_i\mathbf{x} \;+\; c_i\mathbf{x}^2 \;+\; \phi \tag{15}$$

where

$$\mathbf{x} \;=\; \frac{1}{M}(1,2,...,M) \tag{16}$$

and ϕ is a normally distributed random variable chosen so that

$$\frac{1}{MN}\sum_{m=1}^{M}(q_{mi})^2 \;=\; \lambda_i \tag{17}$$

i.e.

$$P(\phi) \;=\; \frac{\sigma}{\sqrt{2\pi}}\exp\left(\frac{-\phi^2}{2}\right) \tag{18}$$

where

$$\sigma \;=\; \sqrt{\frac{1}{M}\sum_{m=1}^{M}(q_{mi} \;-\; p_{mi})^2} \tag{19}$$

4.2 The Small Scale Variability Model

The small scale variability model simulates perturbations of density, temperature and wind due to the upward propagation of small scale gravity waves. The model is based on the parametrisation scheme used the numerical models that simulated the data in the database (see collins *et. al*, 1997).

The surface stress exerted by a vertically propagating stationary gravity wave can be written

$$\tau_0 \;=\; \kappa\rho_0 N_0 |\mathbf{v_0}| \sigma_0 \tag{20}$$

where κ is a characteristic gravity wave horizontal wave number, ρ_0 is the surface density, N_0 is the surface Brunt Väisälä frequency, $\mathbf{v_0}$ is the surface vector wind and σ_0 is a measure of the orographic variance. In this case we choose the model sub-grid scale orographic variance.

This surface stress can be related to the gravity wave vertical isentropic displacement, δh by

$$\tau_0 \;=\; \kappa\rho_0 N_0 |\mathbf{v_0}| \delta h^2. \tag{21}$$

We then assume that the stress, τ, above the surface is equal to that at the surface. This leads to an expression for δh at height z i.e.

$$\delta h \;=\; \sqrt{\frac{\rho_0 N_0 |\mathbf{v_0}| \sigma_0}{\rho N |\mathbf{v}|}} \tag{22}$$

where ρ, N and $\mathbf{v}$ are the density, Brunt Väisälä frequency and vector wind at height z.

The gravity wave perturbation to a meteorological variable A is modelled by

$$A' \;=\; \delta h \sin\left(\frac{2\pi z}{\lambda} + \phi_0\right) \frac{\partial A}{\partial z} \tag{23}$$

where λ is a characteristic vertical wavelength for the gravity wave and ϕ_0 is a randomly generated surface phase angle. The vertical derivative of A is calculated using simple finite differences.

5 Extraction Software

Appended at the end of this document is a listing of all routines in the extraction software. A description of what each routine does is included in the comment at the top of each routine. Variables input into and output from each routine are also commented.

The software can be compiled as a whole by typing `make` which executes the unix `Makefile` and produces the executable `mcdgm`. This can be run interactively by simply typing `mcdgm` or in batch mode using the unix script `mcdbj`. Please see the user manual for more help.

Alternatively individual subroutines can be compiled into the users software. Note however that some routines rely on others so these dependents will require compilation too.

Also included is a listing of the GrADS scripts that can be used to produce various types of graphical output. A description of what each script does is included in the comment at the top of each script.

6 References

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Justus, C. G., 'A Mars Global Reference Atmosphere Model (Mars-GRAM) for mission planning and analysis', *AIAA Paper No. 90-0004*, 28th Aerospace Sciences Meeting, 1990.

Justus, C. G., Alyea, F. N., Cunnold, D. M., Jeffries, W. R. III, and Johnson, D. L., 'The NASA/MSFC Global Reference Atmosphere Model - 1995 Version (GRAM-95)', *NASA Technical Memorandum*, 1995.

Mo, K.C., and Ghil, M., 'Statistics and dynamics of persistent anomalies', *J. Atmos. Sci.*, **55**, 877-901, 1987.