MARS CLIMATE DATABASE v2.0 DETAILED DESIGN DOCUMENT (ESTEC Contract 11369/95/NL/JG)

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Abstract

This is the Detailed Design Document for version 2.0 of the Mars Climate Database (MCD) and replaces Collins and Lewis (1997b) which described version 1.0. Version 2.0 of the MCD incorporates several improvements, outlined in this document, but should appear almost identical to the user in terms of operating procedure, unless low-level use is being made of the large-scale variability model. This document reproduces and updates material from Collins and Lewis (1997b), where it is still relevant, as well as adding sections on the new features. The diagrams and data examples given have been prepared using the version 2.0 database. The MCD User Manual (Lewis and Collins, 1999a) should be consulted for more information on how to compile and use the software supplied with the database to access the data.

Contents

1 Introduction

The Mars Climate Database (MCD) is a database of atmospheric statistics compiled from state-of-the art General Circulation Model (GCM) 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 which govern the atmospheric circulation and surface conditions on the planet.

This document provides the user of the MCD with a detailed description of the database structure and of the access software. Descriptions of the models and of the validation procedure are available in other documents relating to the project.

The MCD can also be accessed in a variety of data formats using the World Wide Web at `http://www.lmd.jussieu.fr/mars.html`.

2 Differences Between Version 2.0 and Version 1.0 of the MCD

The principal difference between version 2.0 and 1.0 of the MCD is that the large-scale variability model now makes use of two-dimensional, multivariate Empirical Orthogonal Functions (EOFs), which describe correlations in the model variability as a function of both height and longitude (rather than solely of height as in version 1.0). The 2-D EOFs allow realistic variability to be modelled for trajectories which span a range of longitudes. As in version 1.0, EOFs are stored for a range of latitude bands, but instead of retaining 6 1-D EOFs at each horizontal location for each of 12 seasons, now 72 2-D EOFs are stored for each latitude band and their amplitude is modelled by a set of principal components tabulated once per day (669 times) throughout the model Mars year. This procedure is no more costly to the end-user in terms of either disk storage or CPU time, but gives a much improved description of the variability as a function of both space and time and a larger variance capture.

A second difference is that two parallel datasets are now included in the climate database distribution. The first has been compiled with the same set of model properties as the version 1.0 database, although the GCMs which were used to compile the database have been extensively validated as a result of the first study and improved in several respects (Forget *et al.*, 1999). This dataset is refered to as the “standard dust” dataset. A second complete database has also been prepared with an increased dust single scattering albedo in the models (see Forget *et al.*, 1999, for details) and is refered to as the “bright dust” dataset. The main systematic difference between these datasets is that the “bright dust” data tend to have temperatures which are cooler by up to 10K in the lower atmosphere (between about 5km and 30km altitude). Differences elsewhere are less marked and are often smaller than the intrinsic model variability. An example of the differences can be seen in Lewis and Collins (1999a). The “bright dust” properties tend to give a better fit to a few previous observations of Martian atmospheric temperatures (Lewis *et al.*, 1999) and could be used if only a single dataset is required. The “standard dust” dataset gives a better correspondance with the previous version of the database. Both may be used to check warmer and cooler extremes.

There have also been numerous small improvements and error corrections to the climate database access software since version 1.0 was released, which are now all incorporated into version 2.0. These are listed in a `Changes` file supplied with the software.

3 Database Structure

3.1 The Data Retrieval and Storage (DRS) System

The data in the MCD are 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.

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 if the data are read on a "little endian" machine but is effectively ignored on a "big endian" machine. Hence, the binary data files for the Mars Climate Database are portable between any type of computer, 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.

3.2 Database Grid Structure

3.2.1 Horizontal Structure

Variables in the database are written on an equally spaced horizontal grid of 96 longitude points numbered from 0° to 356.25° East in steps of 3.75° and 48 latitude points numbered from -88.125° to 88.125° in steps of 3.75° (latitudes South of the equator are indicated by negative numbers). See Figure 1.

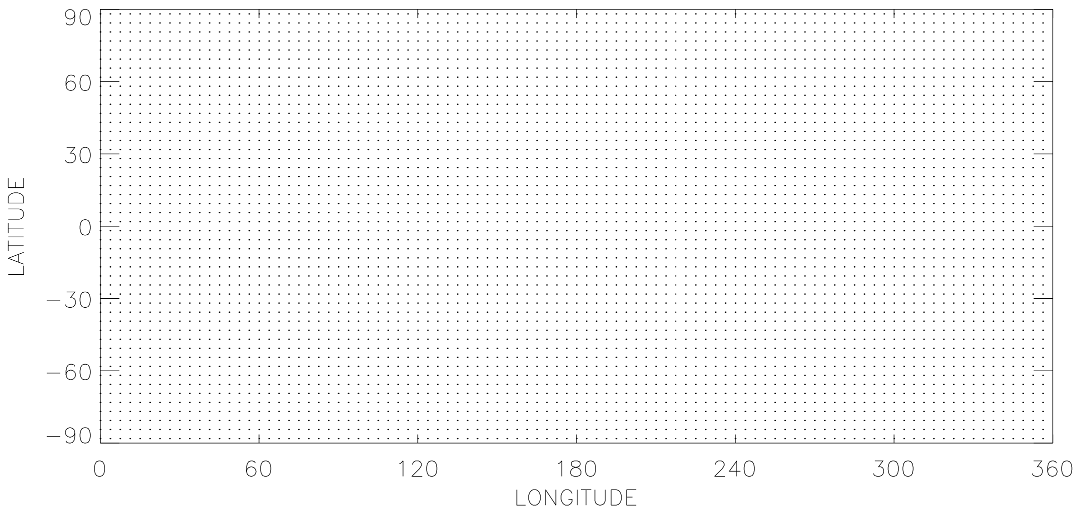

Figure 1: The database horizontal grid of 90 longitude and 48 latitude points.

3.2.2 Vertical Structure

The database vertical coordinate is defined as

$$\sigma = \frac{p}{p_s} \tag{1}$$

where p is the atmospheric pressure and p_s is the surface pressure. Thus σ is 1 at the surface, 0 at infinite height and the σ levels follow the model orography. The sigma levels are arranged as in Table 1 and illustrated 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 $-10\ln(\sigma)$km.

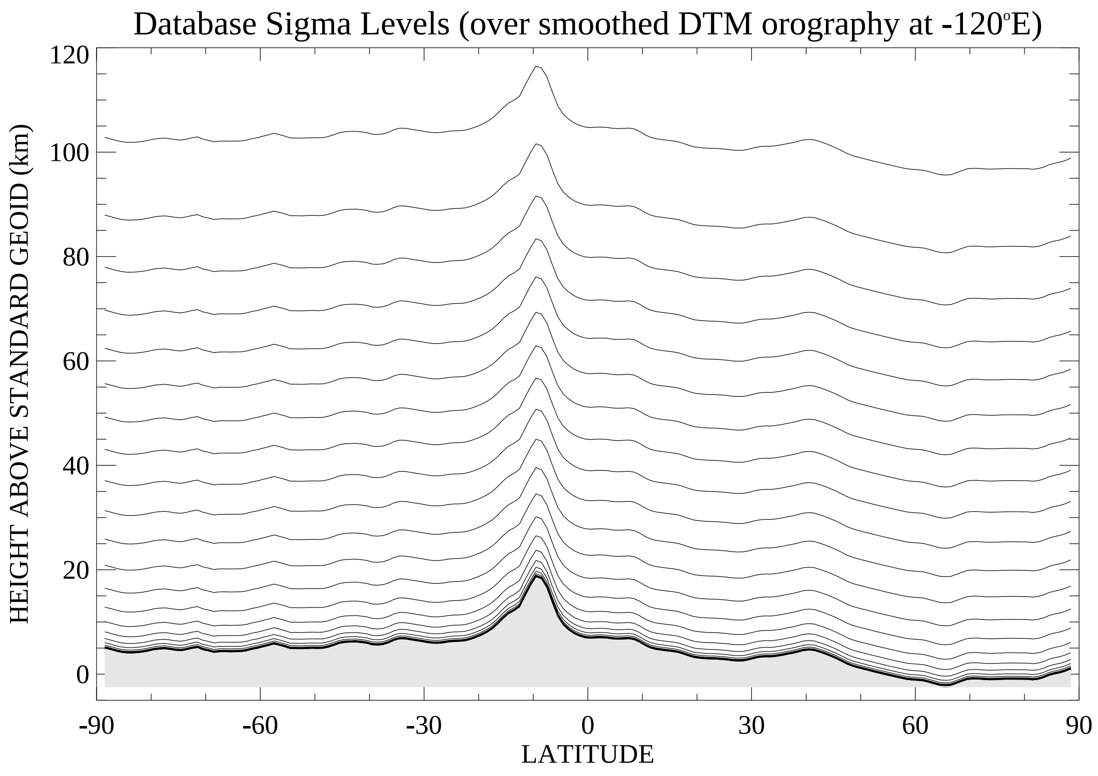

Figure 2: The database σ levels in a region with large topographic features; a section through Olympus Mons is the main peak visible. An isothermal atmosphere with a scale height of 10 km has been assumed for this simple illustration.

3.2.3 Temporal Structure

Data are stored in the database 12 times per Martian day using prime meridian 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.. All times are True Solar Times, not Mean Solar Time. Prime Meridian 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
pmtime=float(iut)
if (iut.eq.13) pmtime=1.0
```

3.3 Database File Structure

3.3.1 Documentation Files

- `mcd/docs` This directory contains PostScript files which can be used to print further copies of the User Manual (`um.ps`) and the Detailed Design Document (`ddd.ps`). It also contains subdirectories (`um` and `ddd`) which have hypertext versions of these documents, suitable for viewing in a WWW browser. Open the file `mcd/docs/index.html` in your browser to view these.

3.3.2 Software Files

- `mcd/mcdgm` This contains FORTRAN source code for the MCDGM interface (see Lewis and Collins, 1999a). Instructions for building the software, to produce the `mcdgm` executable, are given in the User Manual.

  Issuing the unix command `ls mcd/mcdgm` should produce the following list of files (or something very similar):

```
Changes        cospa.f    grid4.f    min2d.f    profi.f
Changes-1.0-4  ctime.f    grwpb.f    mount.f    solls.f
Makefile       dstep.f    ltime.f    ner2d.f    var2d.f
Makefile.DEC   eofpb.f    max2d.f    ner3d.f    var3d.f
Makefile.SGI   gasdv.f    mcdgm.f    opend.f
atime.f        getsi.f    mgthm.f    orbit.f
```

- `mcd/grads` Some sample GrADS scripts which plot MCD data (see Lewis and Collins 1999a). Descriptions of the scripts are given in the User Manual.

  Issuing the unix command `ls mcd/mcdgm` should produce the following list of files:

```
anim_tsurf.gs   map_windt.gs   section_lat.gs  zonal_tuv.gs
map_ps.gs       profile.gs     zonal_sdtuv.gs
```

3.3.3 Data Files

The MCD data are stored in various files in two directories.

- `mcd/data_s` The full MCD dataset derived from model runs with "standard dust" parameters.
- `mcd/data_b` The full MCD dataset derived from model runs with "bright dust" parameters.

To determine which set of dust properties is used, a symbolic link `mcd/data` is created to point to either `data_s` for "standard dust" or `data_b` for "bright dust," e.g.

`cd mcd`
`ln -s data_s data` or `ln -s data_b data`

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, $L_S = 330° - 360°$.
  - `all` indicates that the file contains data for the whole year, e.g. the Empirical Orthogonal Function (EOF) data for the large-scale variability model.
- The next 2 characters indicate the type of data in the file.

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^{-1}	3-D
Meridional (North-South) wind	v	m s^{-1}	3-D
Atmospheric density	rho	kg m^{-3}	3-D
Boundary layer eddy kinetic energy	q2	m^2 s^{-2}	3-D

Table 2: Variables stored in database mean data files.

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^{-1}	3-D
Meridional (North-South) wind	sdv	m s^{-1}	3-D
Atmospheric density	sdrho	kg m^{-3}	3-D
Boundary layer eddy kinetic energy	sdq2	m^2 s^{-2}	3-D

Table 3: Variables stored in database standard deviation data files.

  - `me` indicates mean data.
  - `sd` indicates standard deviation data.
  - `eo` indicates EOF data.

- 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.

Mean data files (`me`) contain 12 seasonal mean values (corresponding to 12 Solar times of day) for the variables shown in Table 2 and standard deviation data files (`sd`) contain seasonal standard deviation values of the variables in Table 3.

EOF data files (`eo`) contain normalized, multi-dimensional EOFs of density, zonal wind, meridional wind, temperature and surface pressure as well as some normalization 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.

In addition there are three files, `mountain.ctl`, `mountain.dat` and `mountain.dic` which contain maps of the topographic height on Mars, smoothed to the resolution at which it is used by the model, and sub-grid scale standard deviation of the topographic height (useful for computing gravity wave perturbations). A final data file, `cospar.dat`, contains the COSPAR reference atmospheric profile, used for some output from the MCDGM interface (see Figure 6).

4 Dust Distribution Scenarios in the MCD

This section outlines the dust distribution scenarios used for the GCM integrations which make up the Mars Climate Database. For the detailed rationale behind these choices, summaries of observational evidence and more references see Forget *et al.* (1999) and Lewis *et al.* (1999).

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

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

with p the pressure, p_0 a standard pressure (700Pa), 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, Equation 2 was developed from a slightly simpler form in common use for Mars modelling, 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 from 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.

- `vik` The standard Viking scenario with data provided for all twelve seasons from multi-annual 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,

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

where ϕ is the latitude. $z_{\max}$ varies between 78km at the equator during the dusty seasons and 20km 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 maximum optical depth 2. Data from these runs are only provided for the seasons when dust storms are most likely to occur; seasons 8, 9 and 10. The dust optical depth was set to double that in the Viking scenario, Equation 4, and the vertical cut-off for the dust was modelled as in the Viking scenario, Equation 5.
- `ds5` A dust storm with maximum optical depth 5. Data from these runs are only provided for the seasons when dust storms are most likely to occur; seasons 8, 9 and 10. The dust optical depth was set to five times that in the Viking scenario, Equation 4, and the vertical cut-off for the dust was modelled as in the Viking scenario, Equation 5.

5 Variability Models

5.1 The Large-Scale Variability Model

In the MCD, data are stored in 12 seasonal bins and at 12 local times of day within each season. Although this captures the main seasonal and diurnal components of variability, any intra-seasonal or day-to-day (synoptic) variations are averaged out. Thus there is a need to simulate this variability, especially if the user wishes to produce an ensemble of realizations of a variable at a particular seasonal date and local time of day which covers a realistic range of variability.

In version 1.0 of the MCD large-scale variability in a vertical profile of a meteorological variable, $D(z)$, was modelled by adding a series of functions to a mean vertical profile, $\overline{D}(z)$,

$$D(z) = \overline{D}(z) + \sum_{i=1}^{N} p_i \mathbf{e}_i(z) \tag{6}$$

where the functions $\mathbf{e}_i(z)$ are eigenvectors of the covariance matrix of all the pre-averaged profiles generated by the GCM 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 to as the Principal Components (PCs) (see, e.g. North, 1984; Mo and Ghil, 1987). The set $\{\mathbf{e}_i\}$ form an optimal linear basis such that the variance capture is high even when the truncation limit is low.

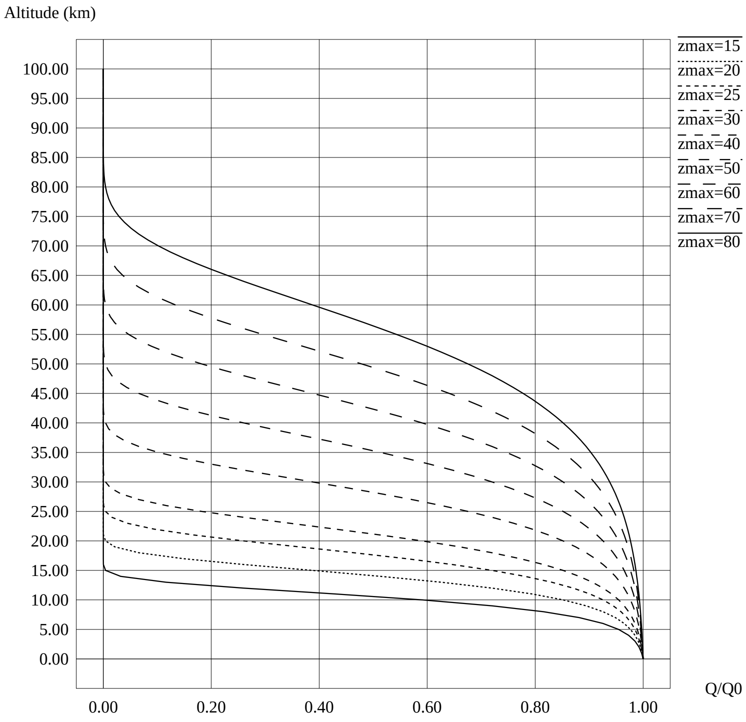

Figure 3: The variation of dust mixing ratio with height for different values of $z_{\max}$ according to the formula (Equation 2) used to compile the Mars Climate Database.

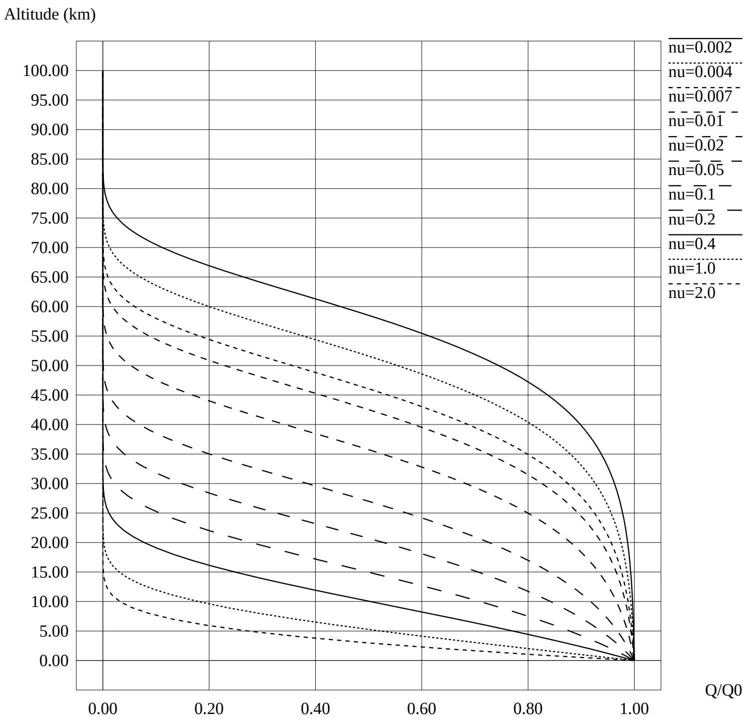

Figure 4: The variation of dust mixing ratio with height according to a formula (Equation 3) previously used in many Mars GCMs, with the ν parameter adjusted to give dust cut-offs at different heights. This function matches that in Figure 3 when $z_{\max} = 70$km and $\nu = 0.007$.

5.1.1 Horizontal Correlations

In version 1.0 only correlations in altitude between variables were considered when calculating the covariance matrix. However, in order to retain cross-correlations between different variables (zonal wind, meridional wind, temperature, surface pressure and density) all were normalized and combined together to form a set of multivariate functions. Different sets of EOFs were computed for each of the 12 seasons on a low resolution grid ($20°$ longitude $\times$ $20°$ latitude) and the series (6) was truncated at $N = 6$ to reduce the demands on data storage. Even so, typically $80 - 90\%$ of the variance was retained in the version 1.0 variability model at this level of truncation.

In order to improve the model it is desirable to extend the spatial dimension to include correlations between variables in both the horizontal and the vertical. Ultimately it would be desirable to include all the longitude, latitude and vertical grid-points in the analysis. A technical point, however, must be noted here. In computing the EOFs, the eigenvalues and eigenvectors of an $N \times N$ real symmetric matrix must be found. The order, N, of the matrix depends on the number of variables and on the number of spatial points. Since the number of calculations needed to perform the eigenvector problem increases as N^3 there is a limit on the value of N that can be handled practically. The estimated CPU time and storage requirements for calculating the eigenvectors of the full problem (even on the low resolution grid with four three-dimensional and one two-dimensional variables, for which $N = 18\times9\times(4\times25+1) = 16362$) is prohibitive.

We make the choice, therefore, to calculate EOFs in the two-dimensional, height-longitude plane which gives a manageable set of eigenvector problems. There is some physical basis for this choice, in that much of the variability the model must account for is in the form of baroclinic waves which, in general, propagate West to East along lines of latitude.

5.1.2 Statistical Stability and PC Modelling

In version 1.0 of the MCD we calculated separate sets of the variability EOFs for each of the 12 seasons. However, due to the relatively small number of days in each season (50–70), this can lead to poor estimation of the EOFs. Greater statistical stability can be achieved by forming the covariance matrix over the entire annual cycle, although this means that more EOFs must be retained in the series (6) in order to still capture a relatively high fraction of the variance. Fortunately this is possible as there is then no need to store the EOFs at each season. In fact the series can be extended to include 72 ($= 12 \times 6$) EOFs rather than just 6 per season with no increase in the amount of space needed to store the MCD.

This also overcomes a problem which might occur with the version 1.0 implementation of the PC modelling. If a time series of a variable was computed across a seasonal boundary there could be a discontinuity at the boundary where the quadratic fit to the intra-seasonal or trend components did not match. In the improved version 2.0 of the variability model we simply store a smooth version of each PC to represent the seasonal cycle together with a variance to represent synoptic activity. This both simplifies and improves the algorithm.

5.1.3 Calculation of EOFs and PCs

Consider a time series of longitude-pressure vectors of zonal wind, $\mathbf{u}(\phi, p, t)$, meridional wind, $\mathbf{v}(\phi, p, t)$, temperature, $\mathbf{T}(\phi, p, t)$, density, $\rho(\phi, p, t)$ and surface pressure $p^*(\phi, t)$ at M discrete time points and on L spatial points. We form a time series of vectors $\mathbf{D}(t)$, where

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

and the hat $\hat{}$ denotes a removal of the series mean and normalization of variance operator,

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

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

where the m denotes time and the l denotes spatial point. Hence, with this normalization, 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

$$\mathbf{C} \;=\; \frac{1}{N}\mathbf{D}\mathbf{D}^T \tag{10}$$

where N = (number of horizontal points) $\times$ (4 $\times$ number of vertical points + 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 ith 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 ith eigenvalue.

The ith principal component (PC) at time m, p_{mi} is defined as

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

and we note the result

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

Each principal component has 669 values during one year (one per day). From the PCs we calculate a 30 day running mean, ps_{mi}, and a variance departure from that mean, pv_{mi}. The modelled PC, p'_{mi}, at time m is then

$$p'_{mi} \;=\; ps_{mi} + \Phi pv_{mi} \tag{15}$$

where Φ is a normally distributed random variable with unit standard deviation.

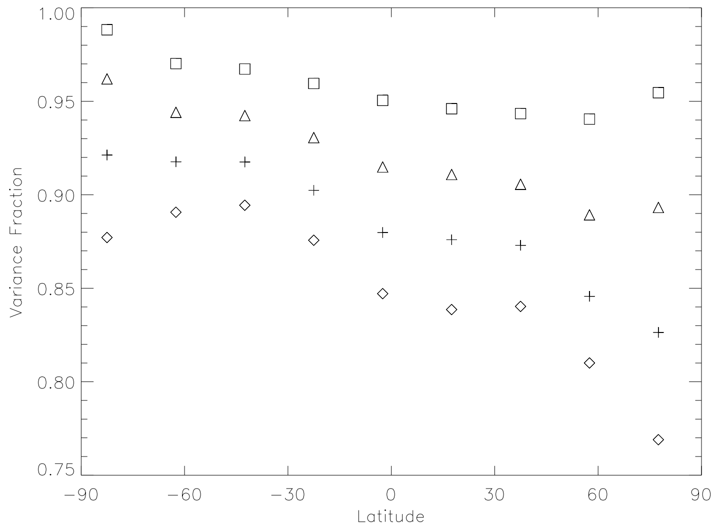

Figure 5: The fraction of variance captured by 72 EOFs (squares), 36 EOFs (triangles), 18 EOFs (plus signs) and 9 EOFs (diamonds) at different latitudes for the Viking scenario run. 72 EOFs capture more than 95% of the variance at most latitudes.

5.1.4 Variance Capture

In version 1.0 of the variability model only 6 EOFs per location per season were retained in the series in Equation 6 to limit the amount of data storage required. Because, in the improved version, a single set of EOFs are calculated for the whole year, 72 EOFs can be retained in the series with no greater storage overhead, to give a potentially greater overall variance capture. Figure 5 shows the fraction of variance captured by retaining 72, 36, 18 and 9 EOFs at different latitudes. By retaining 36 EOFs approximately 90% or greater of the variance is captured and by retaining 72 EOFs approximately 95% or greater of the variance is captured. Including more EOFs gives relatively little increase in variance capture but increases the storage requirements considerably. Thus 72 EOFs seems to be a good compromise between variance capture and data storage.

5.1.5 Examples of Cross-Sections

Density is one of the most important variables used by engineers in mission planning (e.g. when calculating entry trajectories or aerobraking manoeuvres). Hence the new variability model is illustrated using this field. Because density varies exponentially with height it is useful to compare any density profile with some ‘standard’ profile. Figure 6 shows the northern hemisphere COSPAR standard atmospheric density profile from the surface to approximately 90 km. All density profiles are referenced to this profile by expressing the density as a percentage difference, d, from the COSPAR profile. i.e.

$$d = 100 \times \frac{\rho_{COSPAR} - \rho}{\rho_{COSPAR}} \tag{16}$$

Figure 7 shows a selection of instantaneous longitude-height fields of density (referenced to

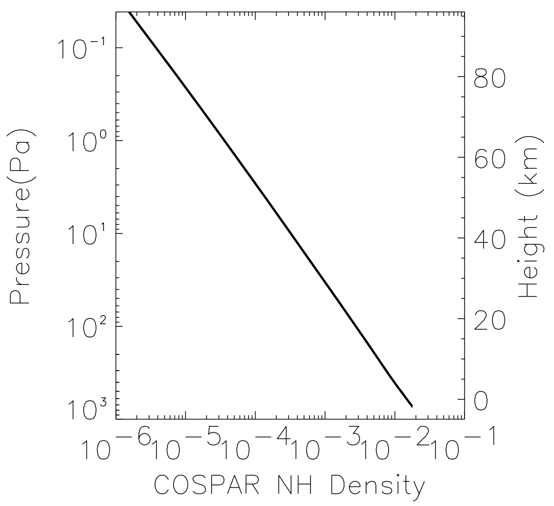

Figure 6: COSPAR northern hemisphere mean density ($\mathrm{kg\,m^{-3}}$) for Mars. Note the logarithmic scale on the abscissa.

the COSPAR profiles) taken directly from the Viking scenario GCM run at $L_S = 0°$, $L_S = 90°$, $L_S = 180°$ and $L_S = 270°$. The variability model simulations of these fields are shown in Figure 8. On a large scale the variability model captures the seasonal cycle of density variability well. Small differences between the GCM and the variability model simulated fields are due to the random nature of the PC model (Equation 15).

5.2 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 parameterization scheme used in 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

$$\tau_0 \;=\; \kappa \rho_0 N_0 |\mathbf{v_0}| \sigma_0 \tag{17}$$

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

$$\tau_0 \;=\; \kappa \rho_0 N_0 |\mathbf{v_0}| \delta h^2. \tag{18}$$

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,

$$\delta h \;=\; \sqrt{\frac{\rho_0 N_0 |\mathbf{v_0}| \sigma_0}{\rho N |\mathbf{v}|}} \tag{19}$$

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

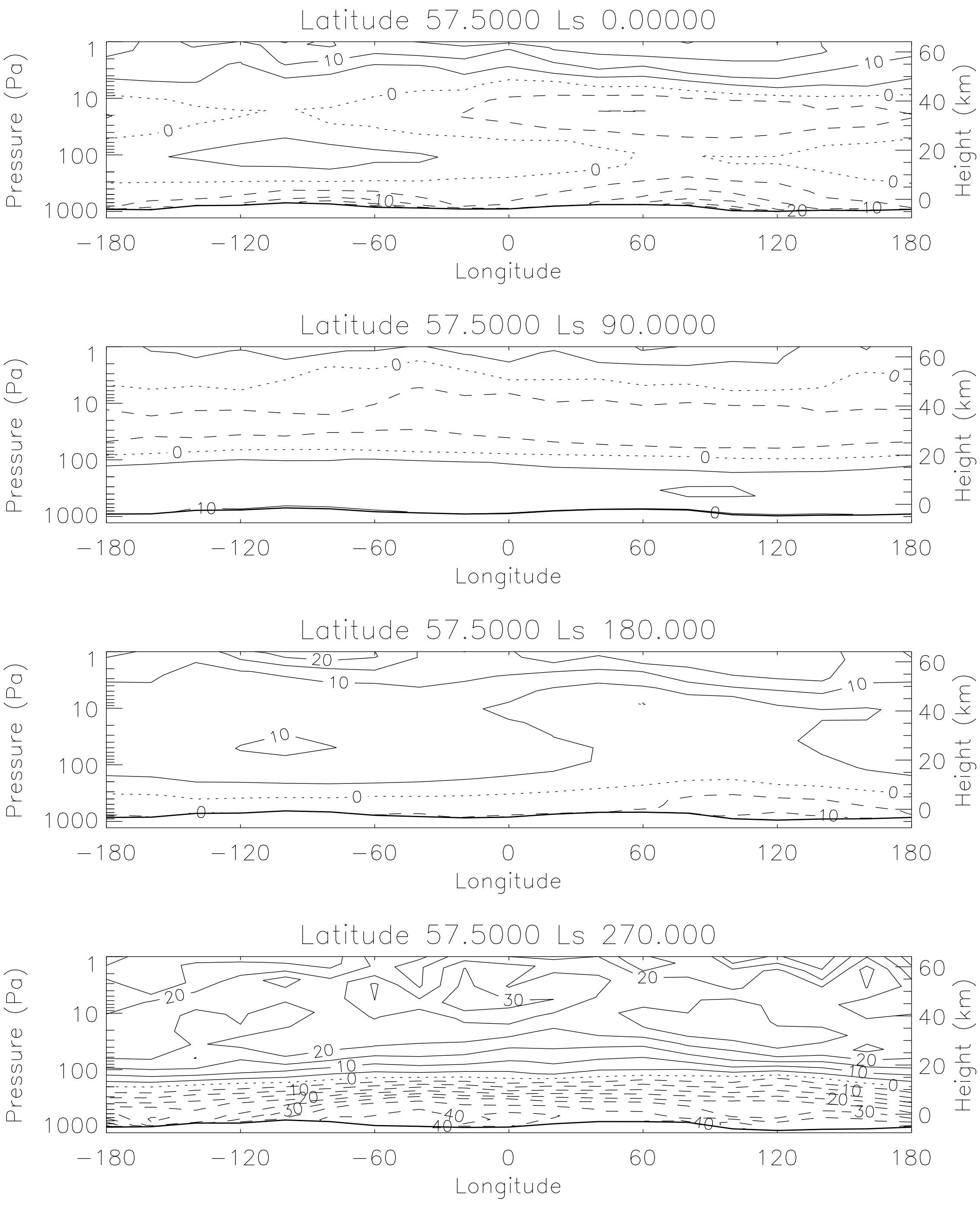

Figure 7: Longitude-height cross sections of density at 57.5°N expressed as a deviation from the COSPAR northern hemisphere reference profile at several seasonal dates. The fields are instantaneous and have been taken from the Viking scenario GCM run.

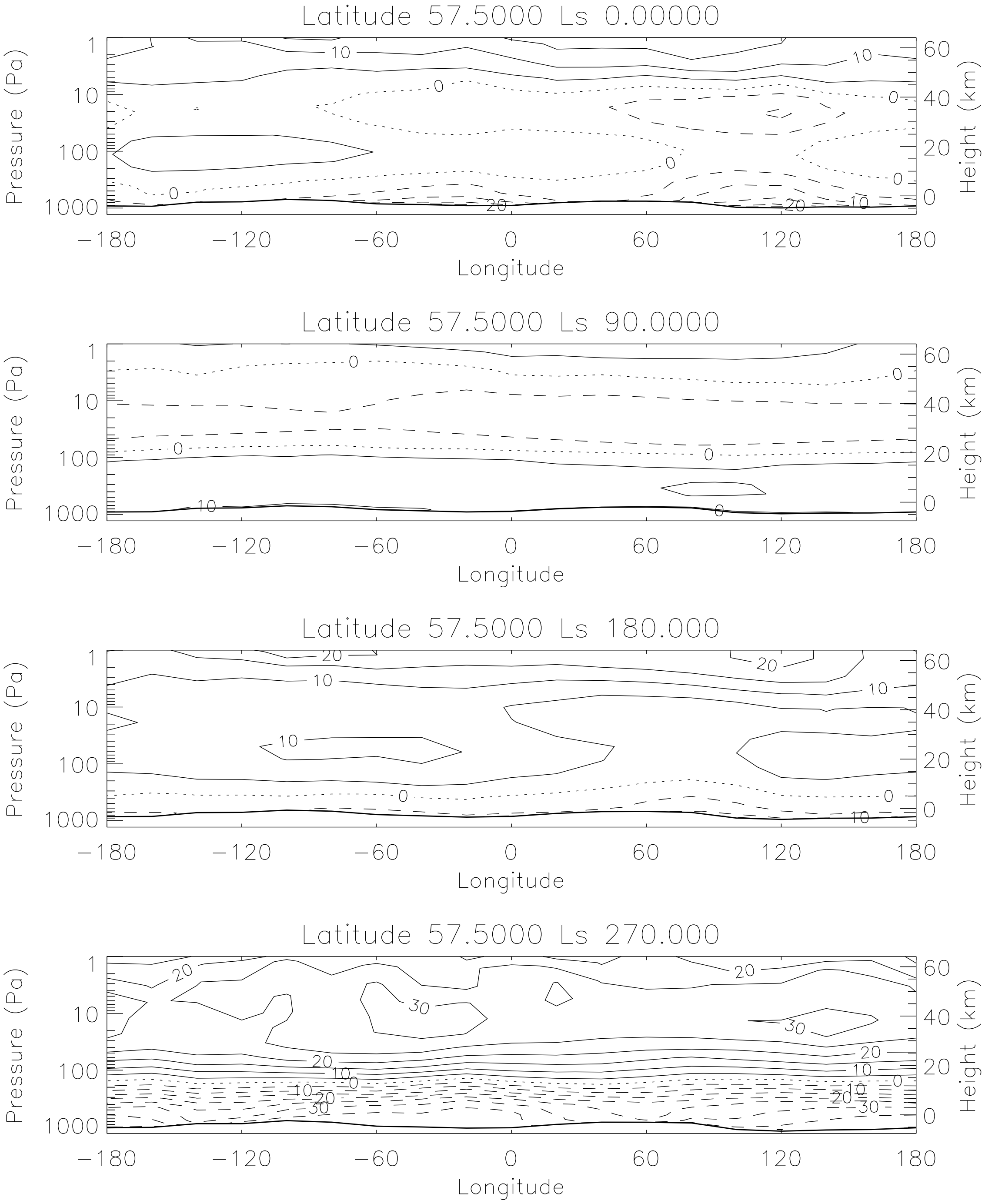

Figure 8: Longitude-height cross sections of density at 57.5°N simulated using the new variability model and expressed as a deviation from the COSPAR northern hemisphere reference profile.

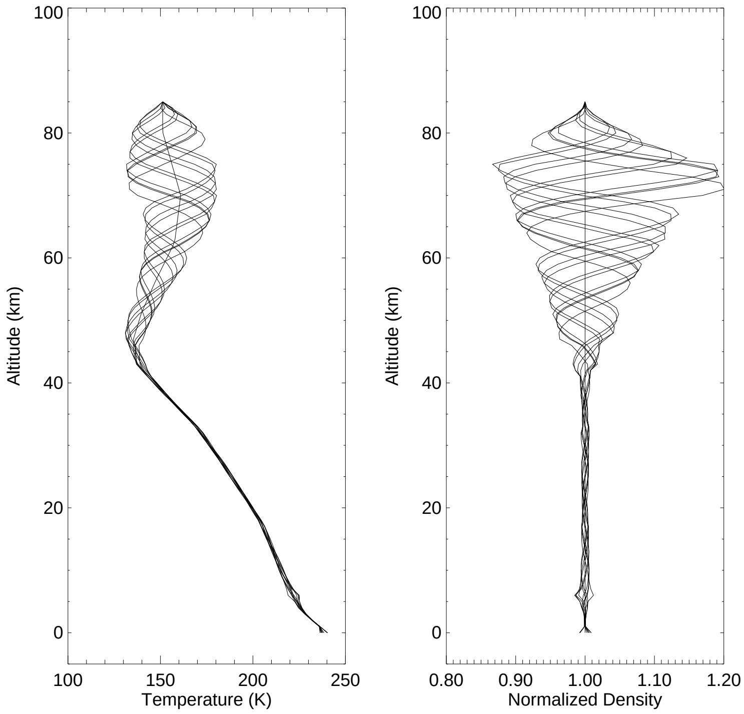

Figure 9: A series of ten perturbations generated by the small scale variability model added to mean profiles of temperature and density from the MCD; these correspond to the Viking Lander 1 entry location and time.

The gravity wave perturbation to a meteorological variable is calculated by considering vertical displacements of the form

$$\delta z = \delta h \sin\left(\frac{2\pi z}{\lambda} + \phi_0\right) \tag{20}$$

where λ is a characteristic vertical wavelength for the gravity wave and ϕ_0 is a randomly generated surface phase angle. Perturbations to temperature, density and wind at height z are then found by using the value at $z + \delta z$ on the background profile, with the perturbations to temperature and density calculated on the assumption of adiabatic motion to the valid height. A value can be chosen for λ to provide a reasonable comparison with the observed Viking entry temperature profiles above 50 km; we take $\lambda = 16$ km. An example of several small scale perturbations is shown in Figure 9.

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