A Climate Database for the Martian Atmosphere

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ABSTRACT

A database of statistics has been developed in order to describe the climate and surface environment of Mars. The database may be used as a tool for mission planning, and also provides a valuable resource for scientific studies of the Martian atmosphere. This poster presents examples of database output including comparisons with previous observations. The database is based directly on output from multi-annual integrations of two General Circulation Models (GCMs) which were developed jointly at Laboratoire de Météorologie Dynamique du CNRS, Paris, and the University of Oxford, with support from the European Space Agency. The models have been validated against the main features of the meteorology of Mars, as observed by past spacecraft missions. As well as the usual statistical measures used for mission design studies, the database also includes techniques for representing variability. Large-scale variability, captured by the GCMs, is modelled using empirical eigenfunctions derived from an analysis of the full simulations. It is also possible to incorporate some variability on scales smaller than the GCMs can represent explicitly by the use of parameterizations of processes such as gravity wave propagation. The database is continuously updated as new observations become available and the models are improved. A version may be obtained from `http://www.lmd.jussieu.fr/mars.html`.

INTRODUCTION

When planning spacecraft missions to Mars detailed information about environmental conditions on the planet is vital to prevent mission failure and to aid in the optimization of the design process. Aerocapture manoeuvres require detailed knowledge of atmospheric density; when placing landers on the surface of the planet the wind shear can be a crucial factor; and extremes of temperature in the atmosphere and on the surface must be known to prevent electronic failure, for example. However, observations of the environment of Mars are extremely sparse.

In planning previous missions to Mars, environmental statistics have been generated using the Mars Global Reference Atmosphere Model (MarsGRAM, Justus 1990). MarsGRAM uses a combination of observational data and simple physical laws to produce realizations of environmental conditions. For example, temperatures are generated by fitting a series of arbitrary functions to the Mariner 9 and Viking data and winds are derived using thermal wind balance. While MarsGRAM produces reasonable fields of observable variables like surface pressure and temperature for seasons and dust loadings where observations exist, its accuracy is limited by errors in the interpolation between observations and on the assumptions used in the physical laws used to derive the unobserved variables.

Recently, however, there has been considerable effort in developing comprehensive General Circulation Models (GCMs) for Mars (e.g. Haberle *et al.* 1993, Hourdin *et al.* 1995, Collins *et al.* 1996, Wilson and Hamilton 1996) and these GCMs are now at the stage where they can produce realistic simulations of weather and climate. GCMs provide a self-consistent view of the environmental conditions on Mars; that is they are based purely on physical laws and prescribed parameters (e.g. planetary radius, rotation rate, surface roughness, etc.) without reference to function fitting or deriving variables using simplified balance criteria. This was recognized by the European Space Agency who commissioned multi-annual simulations of the martian environment using a state-of-the-art GCM to produce a database of statistics, the Mars Climate Database (MCD).

MARS GENERAL CIRCULATION MODELS

The Mars Climate Database is based upon results obtained from multi-annual integrations of two Mars General Circulation Models developed at LMD and AOPP. GCMs may be divided into two main parts, hydrodynamical code and parameterization schemes.

- The hydrodynamical code computes the large scale atmospheric motions. Two different approaches have been used, in common with Earth GCMs: a) a finite-difference or grid-point model (LMD); and b) a semi-spectral approach based on a decomposition of the horizontal fields into spherical harmonics (AOPP). Using both approaches has allowed a better assessment of model errors to be made.
- The parameterization schemes model physical processes which force the general circulation and are used to compute the impact of processes which are not resolved by the hydrodynamical code. These include the radiative heating and cooling of the atmosphere due to CO_2 gas and dust; the surface thermal balance; the sub-grid scale atmospheric motions (turbulence in the boundary layer, convection, relief drag, gravity waves); and the condensation of CO_2 in the polar regions. These schemes have been developed in parallel by both LMD and AOPP and are common to both models.

DUST DISTRIBUTION SCENARIOS

A major factor which governs inter-annual variability in the martian atmosphere is the amount and distribution of suspended dust. The MCD was compiled with four prescribed dust scenarios, two multi-annual simulations for years with moderate dust loading as observed by the Viking landers or with constant low dust, and two different global dust storm scenarios for appropriate seasons.

- **Viking** The dust optical depth, $\tau(L_S) = 0.7 + 0.3\cos(L_S + 80°)$, varies as a function of time of year to fit the Viking observations with peaks, corresponding to dust storms, removed. The optical depth is uniform in the horizontal, but the cut-off of the dust in the vertical varies as a function of both time and latitude, between 80 km at the equator during the most dusty seasons and 20 km at the pole during the clearer seasons.
- **Low dust** The dust optical depth, $\tau = 0.1$, is invariant in latitude, longitude and time, with a vertical cut-off at 30 km altitude.
- **Dust storm, $\tau = 2$** The dust optical depth has a maximum value of $\tau = 2$, otherwise following the Viking scenario, and with data provided for L_S=210°–300° only.
- **Dust storm, $\tau = 5$** As for the moderate dust storm, except that the maximum optical depth is $\tau = 5$.

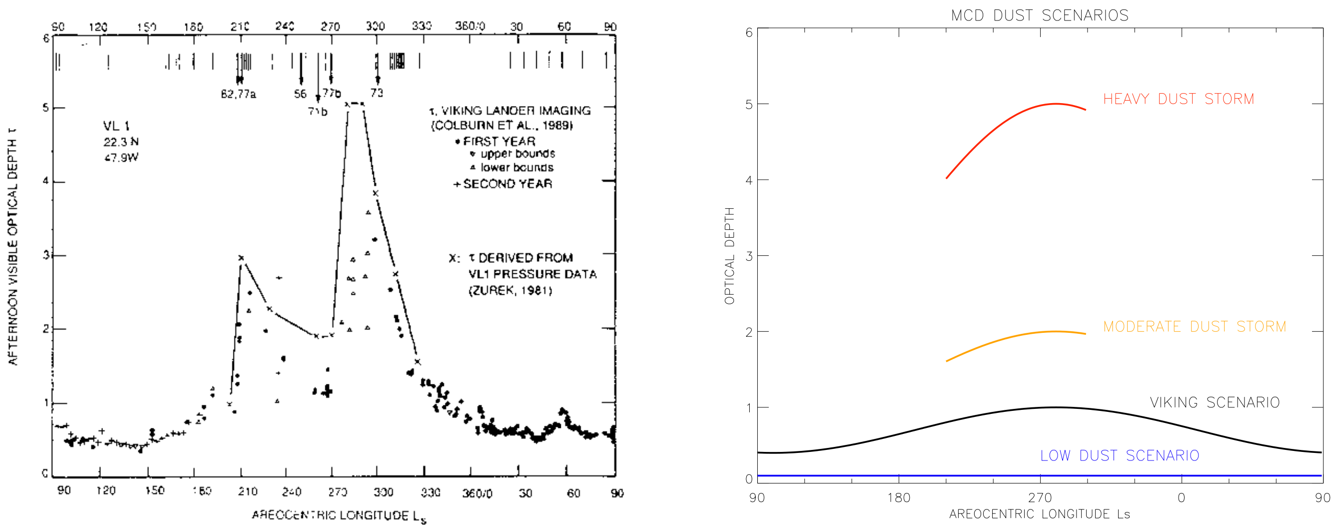

Figure 1: (left) Visible optical depths at Viking Lander 1 (Zurek and Martin 1993); (right) Dust optical depths for the MCD scenarios.

MARS CLIMATE DATABASE

The Mars Climate Database stores means and standard deviations of variables on a regular 3.75° (96×48) horizontal grid with 25 sigma levels in the vertical ranging between 5 m and 95 km altitude (the first eight lie within about 1 km of the surface, to resolve the boundary layer, and the level spacing tends to 5 km higher up). Sigma is a terrain-following coordinate; software is provided to convert the vertical coordinate to pressure or altitude and to interpolate from the grid to any desired location.

Statistics are accumulated over multi-annual experiments for each dust scenario. Fields are stored at 12 times of day for each season, with the year split into 12 seasons to give a comprehensive representation of both the annual and diurnal cycles.

Mean and standard deviation	Units
Atmospheric temperature	K
Zonal (W–E) wind	m s^{-1}
Meridional (S–N) wind	m s^{-1}
Atmospheric density	kg m^{-3}
Turbulent kinetic energy	m^2 s^{-2}
Surface pressure	Pa
Surface temperature	K
Surface emissivity	
CO_2 ice cover	kg m^{-2}

Table 1: Variables stored in the Mars Climate Database.

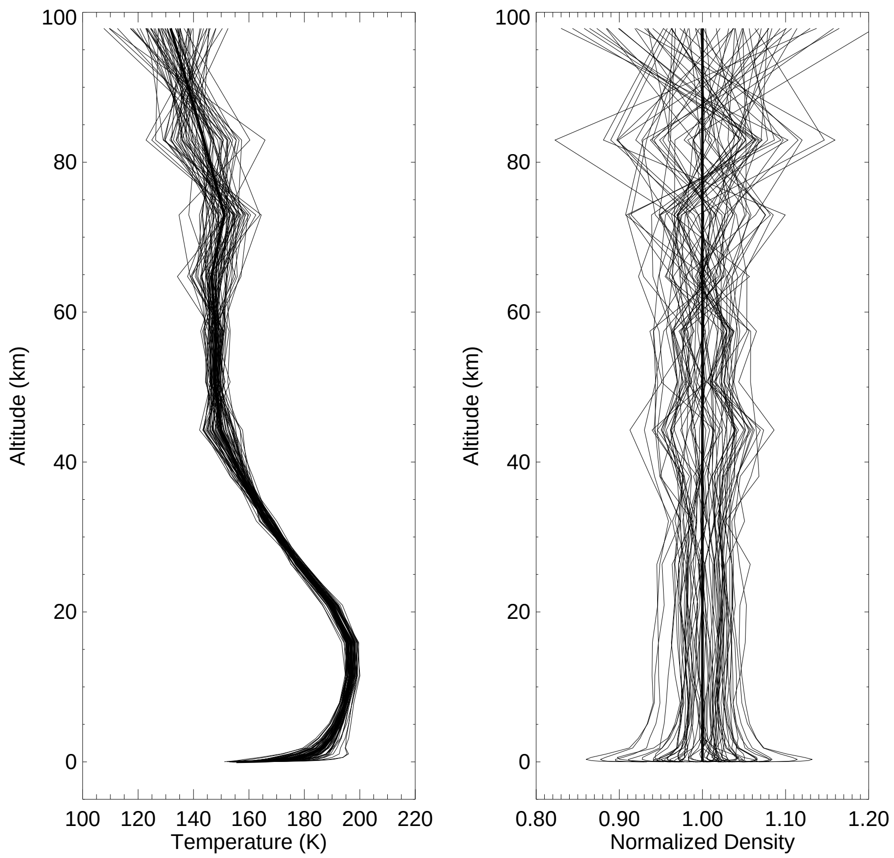

Figure 2: A series of profiles of temperature and normalized density generated by the large-scale variability model.

The large-scale variability model seeks to represent the day-to-day GCM variability within each season, e.g. owing to baroclinic weather systems, which has been lost in the temporal averaging of the model history. This is accomplished by using an approach based on a technique used in meteorological data analysis as well as in other subject areas, namely Empirical Orthogonal Function (EOF) analysis (e.g. North 1984, Mo and Ghil 1987).

EOFs are generally computed for single variables only. Here, multivariate EOFs (of surface pressure, atmospheric temperature, zonal and meridional wind, and density) are computed to account for the significant cross-correlation between dynamical variables. The EOFs form an optimal linear basis such that the variance capture is high even when the number of EOFs retained is low. Details are given in Collins *et al.* (1996).

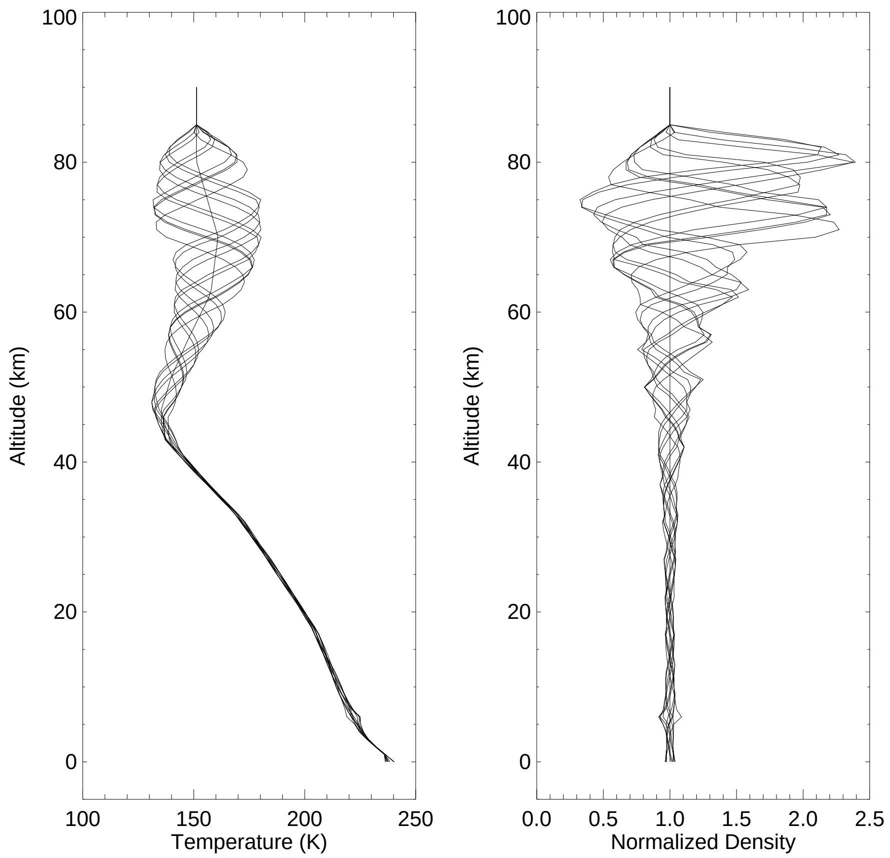

Figure 3: A series of perturbations generated by the small scale variability model added to mean profiles of temperature and density.

The Mars GCM cannot be run at sufficiently high resolution to simulate many small-scale motions, e.g. vertically propagating gravity waves, which can feed back on the large scale circulation of the atmosphere. Thus a parameterization of these effects is used in the Mars GCM (Collins *et al.* 1997). There is also a need to simulate small-scale gravity wave behaviour in the Mars Climate Database. A model which generates perturbations of density, temperature and wind has been developed based on the scheme used in the GCM.

MCD ZONAL-MEAN FIELDS

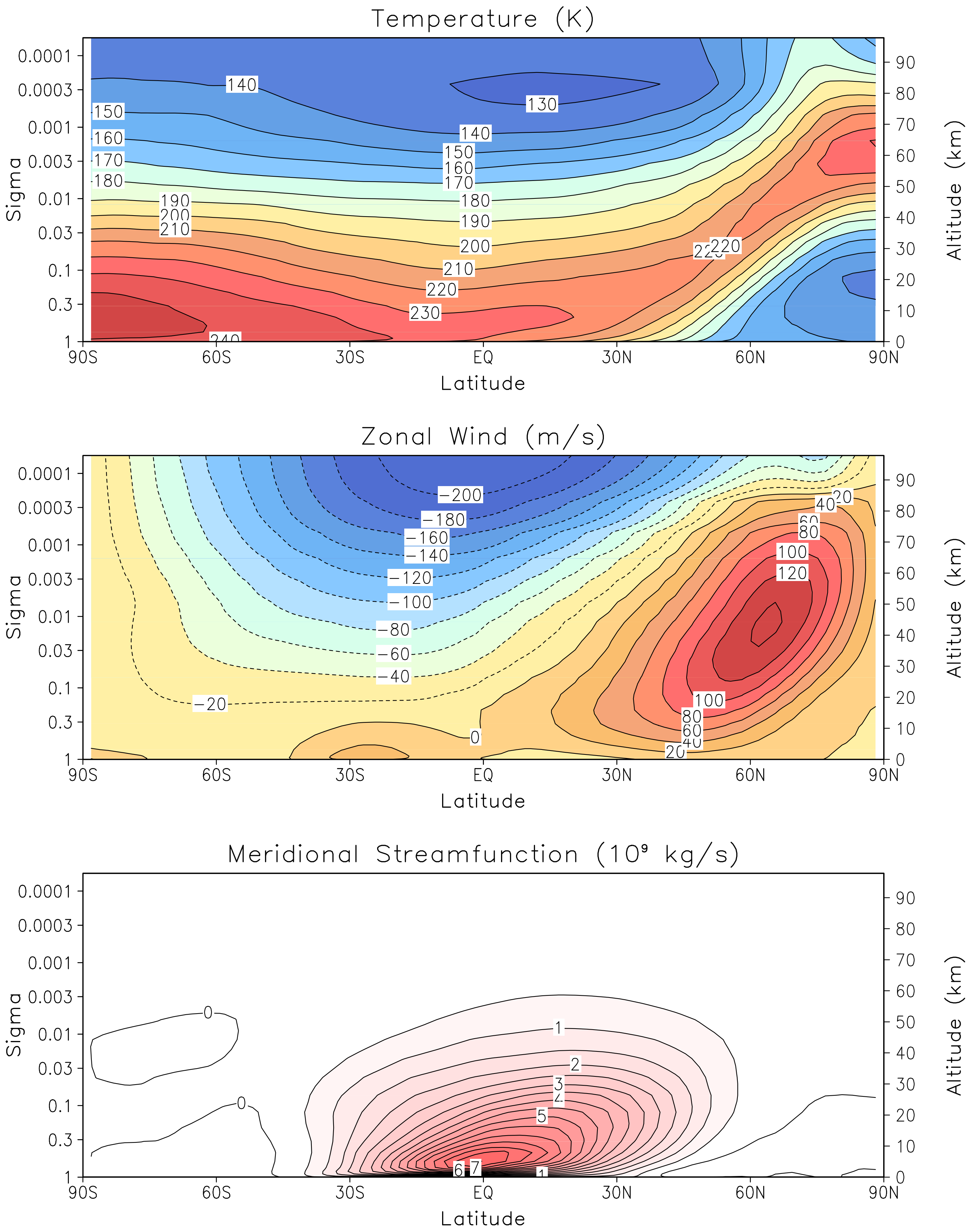

Figure 4: Zonal-mean temperature, zonal (east-west) wind and meridional streamfunction, averaged over all times of day for the period L_S=270°–300° of the Viking dust scenario. The meridional streamfunction was calculated from the meridional velocity stored in the MCD and shows a single, cross-equatorial Hadley cell with the rising branch in the southern hemisphere.

MCD SURFACE TEMPERATURES AND WINDS

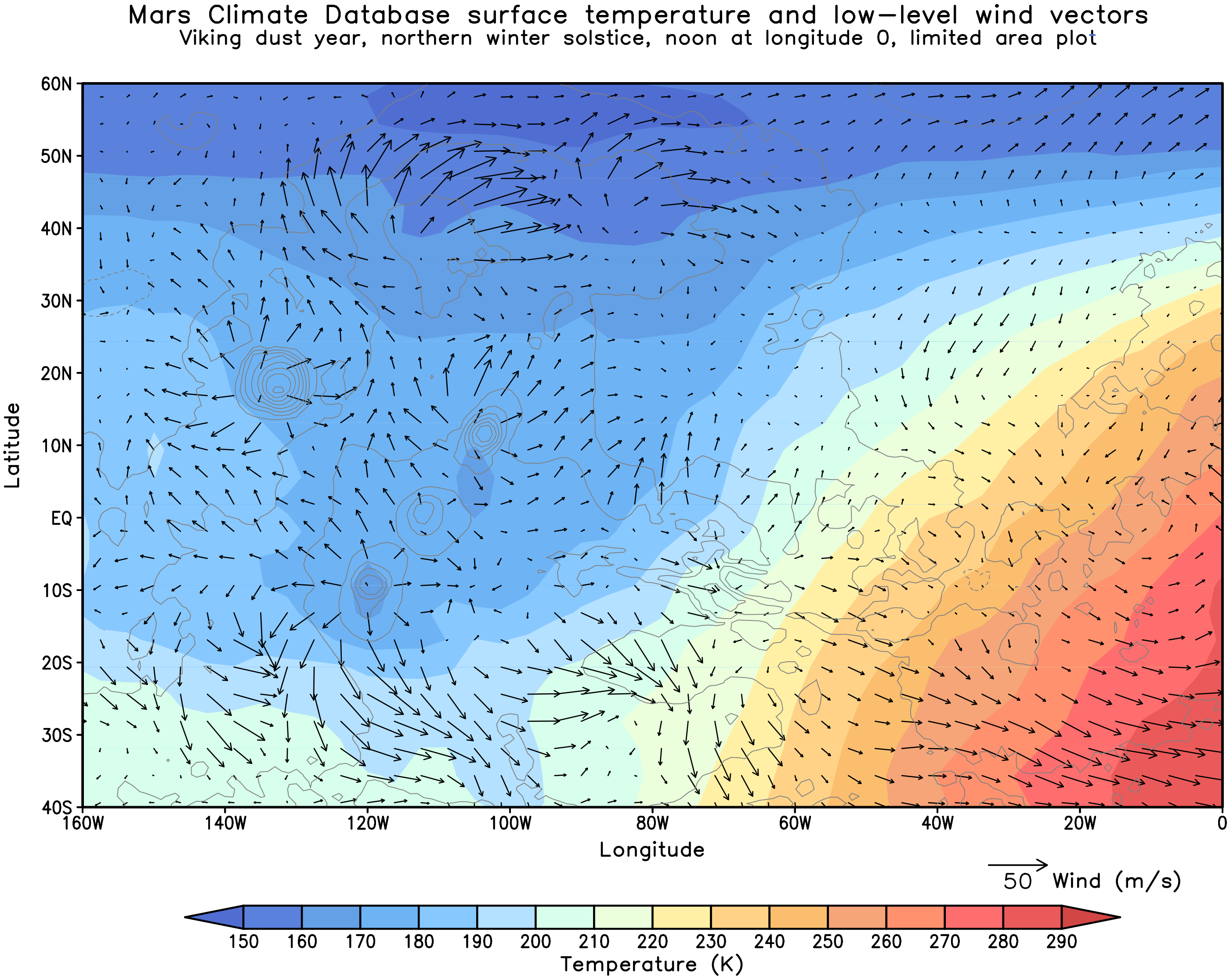

Figure 5: Near-surface (5m) wind vectors and surface temperatures at one time of day (noon at 0° longitude) during the northern winter solstice season, L_S=270°–300°, of the Viking dust scenario. The DTM topography is plotted in grey contours (interval 2 km) for reference. Olympus Mons and the Tharsis ridge are clearly visible on the left side of the region; this area is in darkness at the time of the plot, about 3am local time at Olympus Mons. Winds are predominantly down-slope in this cold region, whereas in the warmer, sunlit areas to the lower right they are mainly up-slope.

MCD ENTRY PROFILES

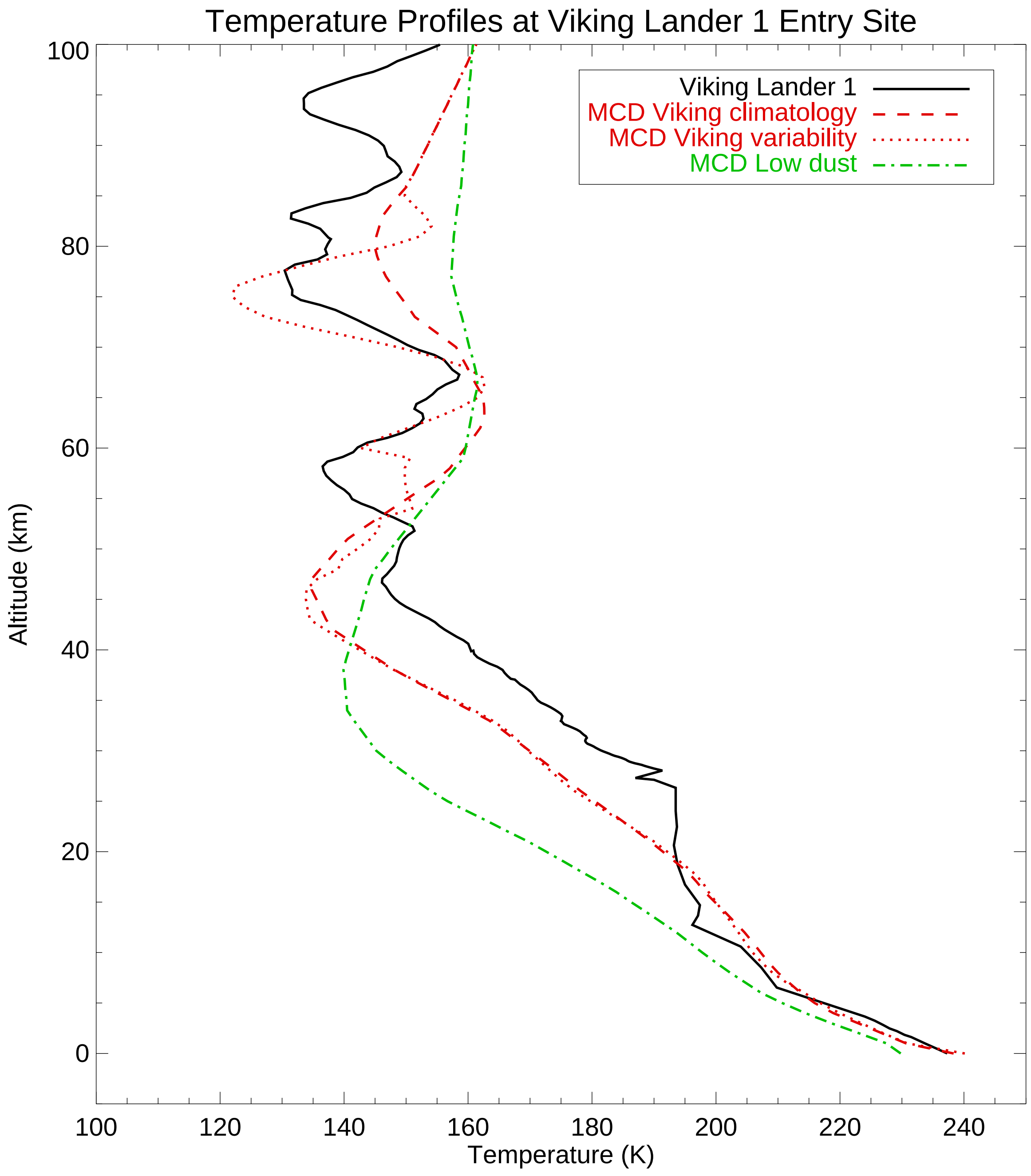

Figure 6: Temperature profiles at the Viking Lander 1 entry site (22°N, 48°W, L_S=96°, 4pm local time) showing the climatological mean with and without the addition of the large-scale and small-scale variability models. The variability model profile is just a single realization and in practice a larger ensemble of profiles might be generated. The low dust climatology is also shown in comparison. The real entry profile observed is shown in black.

VIKING PRESSURE CURVES

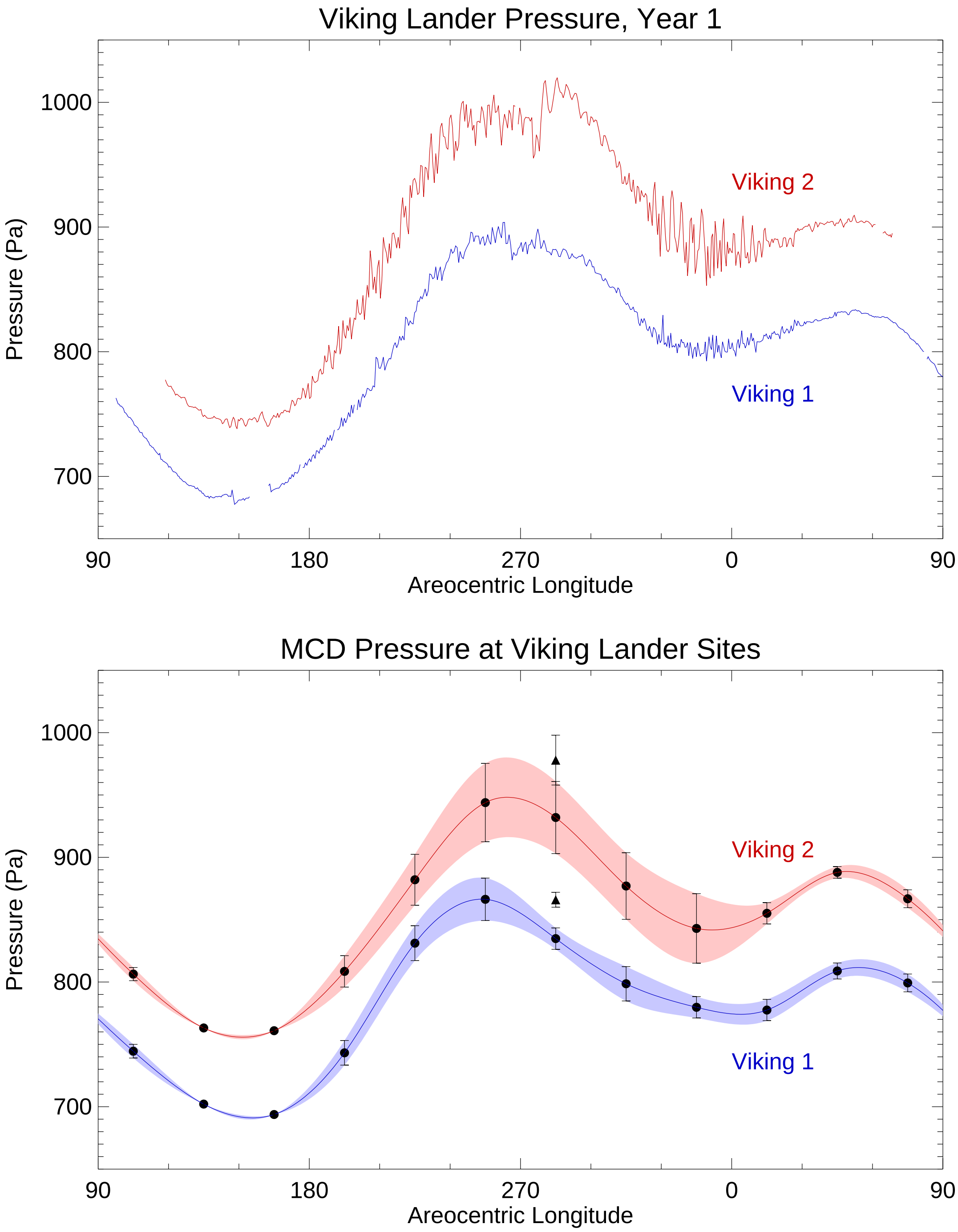

Figure 7: **Upper:** Observed Viking surface pressure for the first martian year of observations, averaged to remove the diurnal tide. The high frequency oscillations are caused by weather systems passing over the landers. The jump in pressure, and modulation in the amplitude of the weather signal, close to $L_S = 280°$ was caused by a global dust storm. **Lower:** Pressure at the Viking sites (22°N, 48°W and 48°N, 226°W) for the MCD Viking dust scenario. The black circles show the diurnally-averaged, seasonal values at intervals of $30° L_S$ and the smooth curve is a cubic spline fit. The error bars and shaded region indicate the non-diurnal variability (2σ) of the surface pressure with the seasonal trend component removed. The triangles and error bars at $L_S = 285$ show the pressure and non-diurnal variance at this time in the $\tau = 5$ dust storm scenario; pressures are higher and variance lower, consistent with observations.

MARS PATHFINDER

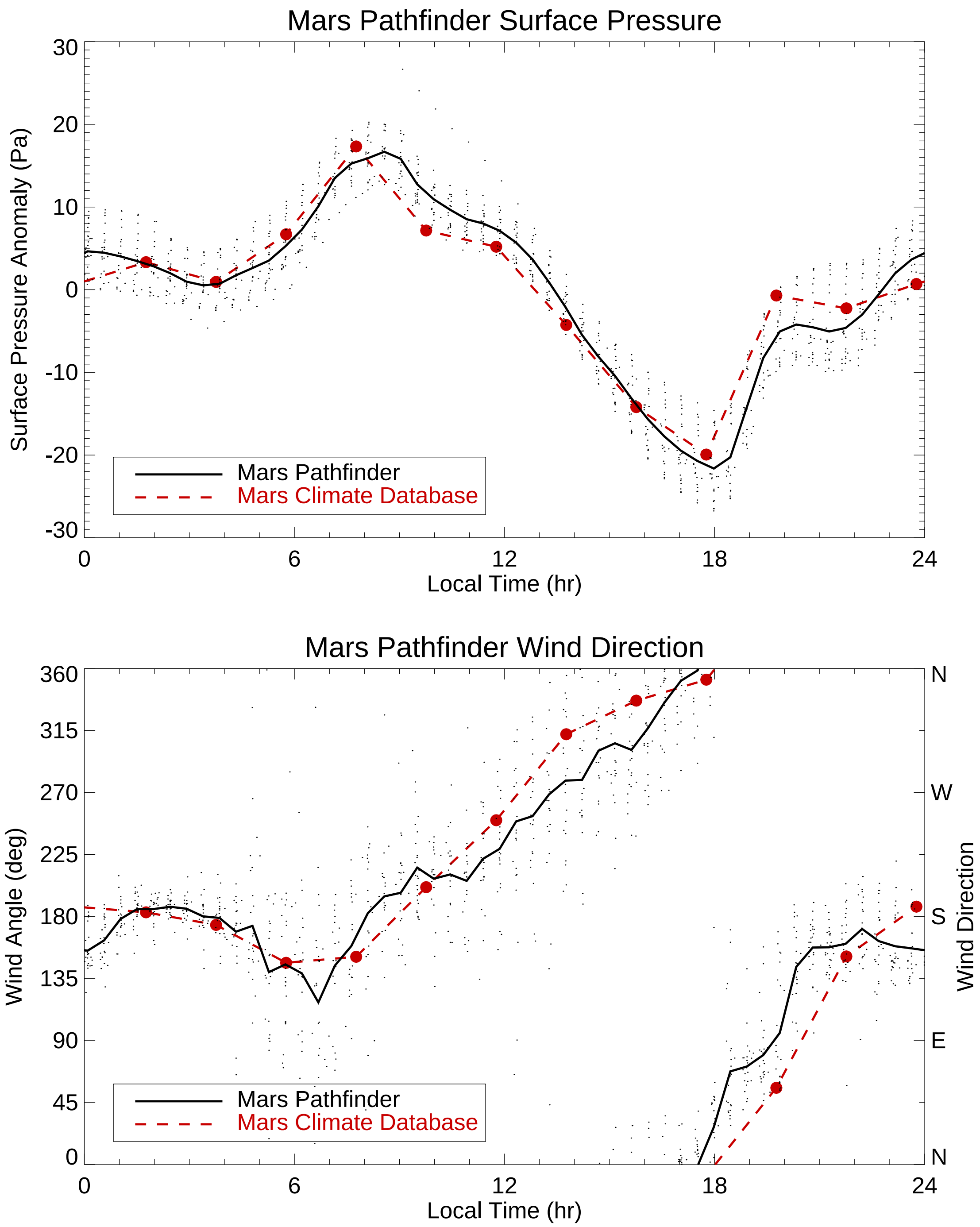

Figure 8: **Upper:** Observed Mars Pathfinder surface pressure anomaly as a function of local time of day for the first thirty days of the mission (individual observations are shown as dots, the line is the mean cycle) compared with the MCD mean diurnal cycle for the Viking scenario at the same location and time of year (19°N, 33°W, L_S=142°). **Lower:** Observed Mars Pathfinder wind direction on the 1m meteorological mast compared with the MCD mean diurnal cycle as above.

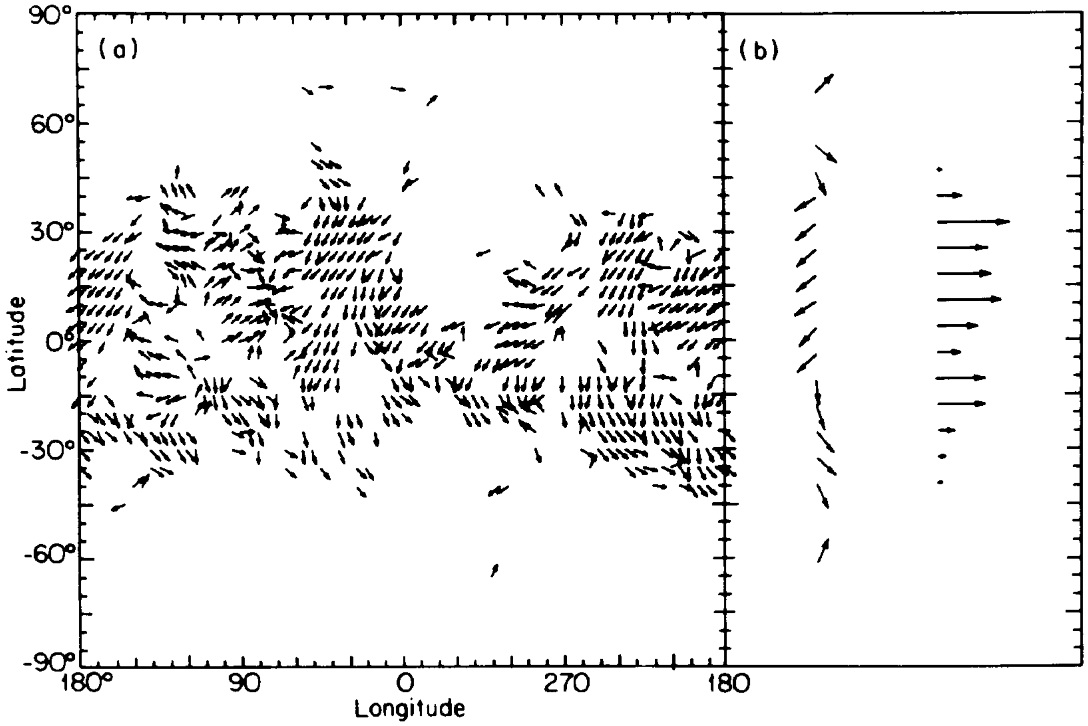

Figure 9: Distribution of "Type I(b)" surface streak orientations derived from Viking Orbiter mosaics (from Magalhaes 1987): (a) average azimuths for 5°×5°bins; (b) zonally averaged azimuths in 2°bins (every fourth bin shown), with horizontal arrows representing the relative number of streaks in each bin, the longest of which represents 700 streaks. The "Type I(b)" streaks are thought to indicate the directions of near-surface winds during the decay of the global dust storms in 1977.

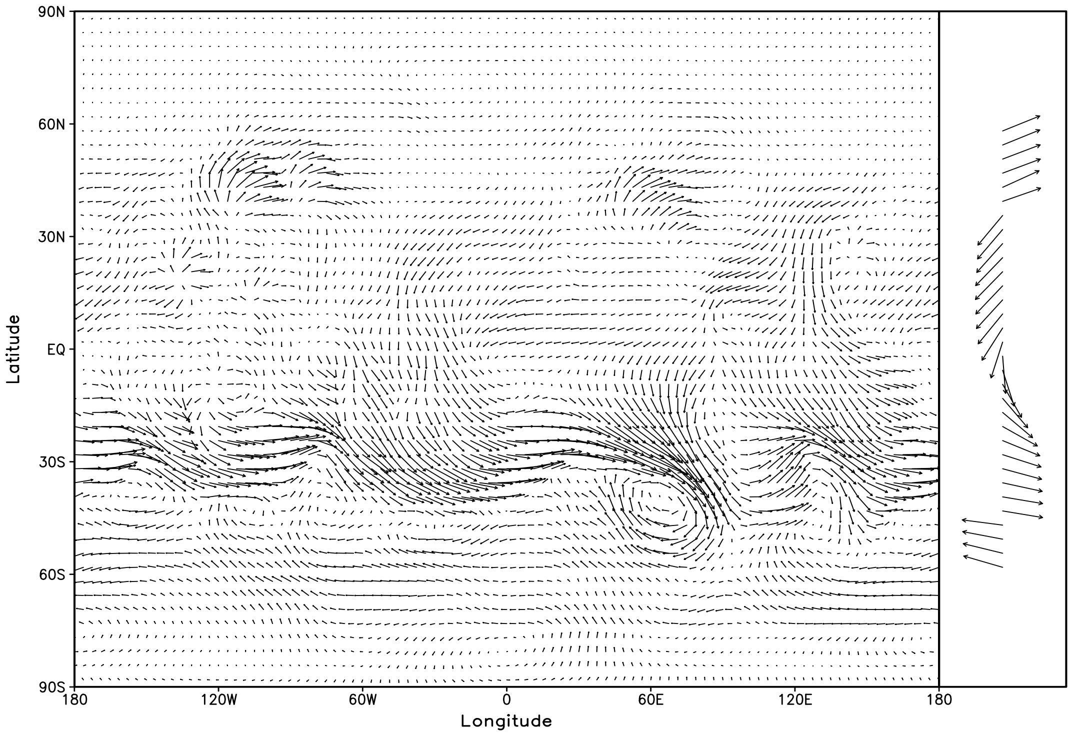

Figure 10: Wind directions taken from the lowest level of the MCD and diurnally-averaged over season 10 (L_S= 270°– 300°) of the $\tau = 2$ dust storm scenario. The right panel shows the zonal-mean wind direction between 60°S and 60°N, to be compared with Fig. 9(b).

Figure 11: Visible images of the martian north polar cap taken by the Hubble Space Telescope (`http://oposite.stsci.edu`).

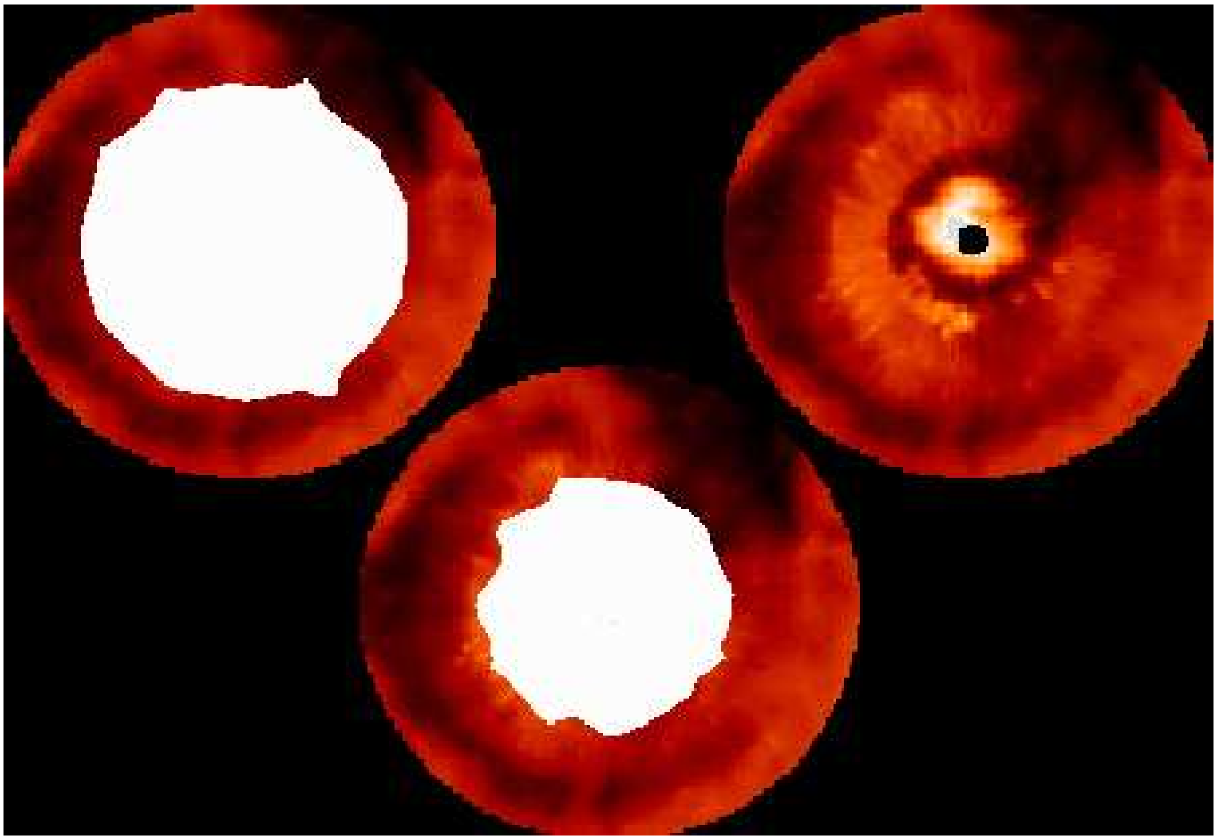

Figure 12: CO_2 ice fields from corresponding seasons of the MCD Viking scenario, superimposed on the GCM albedo field. Areas shaded white indicate a CO_2 ice cover of greater than 50 kg/m^2.

DISCUSSION

The Mars GCM parameters have been tuned where possible to be consistent with most of the available observational data for the atmosphere of Mars, obtained primarily by the Mariner 9 and Viking spacecraft. However, such observations are sparse in both spatial and temporal coverage. One strength of using a GCM to compile the database is that it provides a physically consistent view of the environmental conditions on Mars for seasons and dust loadings which are not covered by the observations.

Although the Mars GCM provides one of the best current estimates of the environmental conditions on Mars, large uncertainties in our understanding and representation of the Martian environment remain. In particular, the Martian topography has not yet been accurately measured and the dust distribution in the atmosphere is poorly known. This situation will change with the arrival of new data from missions such as Mars Global Surveyor and Mars Climate Orbiter. With the analysis of these data the Mars GCMs will be improved and the Mars Climate Database will be updated.

In future versions of the models, the lifting, transport and deposition of dust will be modelled explicitly and the altitude of the model top will be increased to at least 120 km. The representation of variability within the Mars Climate Database itself will also be improved. The next version to be released will include a large-scale variability model based on two dimensional, multivariate EOFs which can describe the longitudinal propagation of baroclinic waves and allow a greater fraction of the variability to be represented with realistic horizontal, as well as vertical, correlations.

The MCD can be distributed on various media, requiring about 1Gb for a full installation, which is recommended for serious use and for access to the variability models. The data are distributed in a portable binary format and can be accessed via a complete interface, via user-written programs which call subroutines supplied with the data or via a range of data visualization tools, e.g. GrADS. Access to the database fields in a variety of formats is possible through a WWW interface, `http://www.lmd.jussieu.fr/mars.html`, which also gives contact details to request a full copy on other media.

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