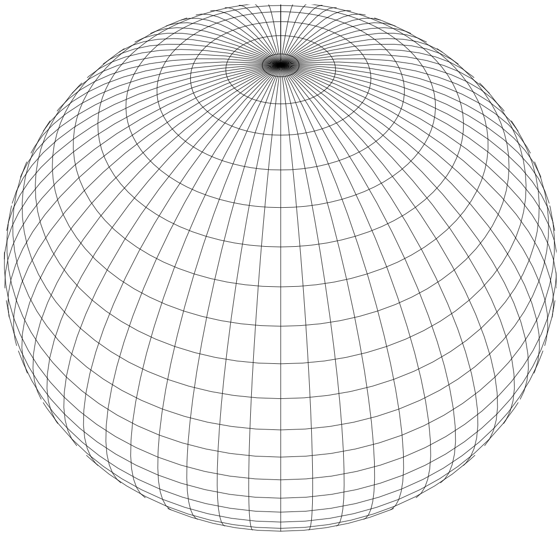
THE EUROPEAN
MARS CLIMATE DATABASE
for mission planning & for scientific studies



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http://www.lmd.jussieu.fr/mars.html

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Contents

1 What is the Mars Climate Database ?

Purpose

When planning spacecraft missions to Mars, detailed information about environmental conditions on the planet is vital to reduce the chances of mission failure and to aid in the optimization of the design process. For example, aerobraking or aerocapture maneuvers 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 and mechanical failures. Similarly, climatological statistics are also of great value and interest for members of the scientific community who need realistic data to study any subject related to the Martian atmosphere and climate. For example, the database has been used to study cloud microphysics, chemistry, geodesy, meso-scale circulation, spacecraft data interpretation, etc.

Contruction

Previous so-called "engineering models" (e.g. "MarsGRAM") used for mission design were based on compilations of observational statistics with simple interpolation schemes to provide estimates of climate variables at any time and any geographical location. Unfortunately, the available observational data on Mars are sparse and incomplete in both space and time, leading to great uncertainties for locations, times, seasons and years for which no data is available.

A different approach has been used here. **The database has been produced from a set of numerical simulation of Mars's climate and atmospheric circulation conducted with a General Circulation Model** (GCM). GCMs are widely used for weather forecasting and climate studies for the Earth. The Mars GCMs have been extensively validated using available observational data and we believe that they 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.

Contents

The MCD contains simulated data (temperature, wind, density, pressure, radiative fluxes, etc. See Table 1) stored on a $5^\circ \times 5^\circ$ longitude–latitude grid[1] from the surface up to an approximate altitude of 120km (above 120 km, pressure and density can be estimated using the database access softwares).

The vertical coordinate for the 3D variables is defined as

$$\sigma = \frac{p}{p_0} \tag{1}$$

[1]The general circulation models used to compile the database run with a higher resolution of $3.75^\circ \times 3.75^\circ$. For simplicity and to reduce the size of the database, the data were stored on $5^\circ \times 5^\circ$ grid.

Mean variable	symbol	units	2-D or 3-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
Surface pressure	ps	Pa	2-D
Surface temperature	tsurf	K	2-D
LW (thermal IR) radiative flux to surface	fluxsurf_lw	W m^{-2}	2-D
SW (solar) radiative flux to surface	fluxsurf_sw	W m^{-2}	2-D
LW (thermal IR) radiative flux to space	fluxtop_lw	W m^{-2}	2-D
SW (solar) radiative flux to space	fluxtop_sw	W m^{-2}	2-D
CO_2 ice cover	co2ice	kg m^{-2}	2-D
Surface emissivity	emis	none	2-D

Table 1: *Variables stored in database mean data files.*

where p is the atmospheric pressure and p_0 is the surface pressure. Thus σ is 1 at the surface and 0 at infinity and the σ levels follow the model orography. There are 32 sigma levels, with the first four level are at about 5, 20, 50 and 115 m whereas the upper level is around 120 km.

Fields are averaged and stored 12 times a day, for 12 Martian "seasons" to give a **comprehensive representation of the annual and diurnal cycles**. Each season covers 30^o in solar longitude (L_s), and are typically 50-70 days long. In other words, at every grid-point, the database contains 12 "typical" days, one for each season. In addition, information on the variability of the data within one season or within one grid-point are also stored in the database. Software tools are provided to reconstruct and synthetized this variability (section 5).

2 How do General Circulation models work ?

The Mars Climate database has been constructed based on output from a set of general circulation models (GCM) developed jointly at LMD and AOPP (Forget et al., 1999). GCMs are a widely used tool in terrestrial weather forecasting, climate forecasting and meteorological research. The basic idea is the following: from an initial state (defined by temperature, pressure, wind fields, etc.), the model uses well known physical laws (e.g. fluid mechanic equations, radiative transfer laws) to compute the evolution of the system timesteps after timesteps.

The General Circulation Models can be schematically divided into two parts.

- The first part is an **hydrodynamical code** dedicated to the time and spatial integration of the equations of hydrodynamics to compute the large scale atmospheric motions. This part, based on a rather general formulation of the equations of fluid mechanics (primitive equations in meteorological dialect) can be used without any change for the other terrestrial planets. Two different kind of hydrodynamical code have been developed so far: 1. finite-differences or grid-points models (on use at LMD) and 2. spectral solver based on a decomposition of the horizontal fields on spherical harmonics (on use at AOPP).

- The second part of the code consists of a set of **physical parametrizations** which are used to force the general circulation and compute the details of the local climate at every grid point. LMD and AOPP use a common set of parameterizations which includes :

  - **Radiative transfer.**
    This is the main source of atmospheric motions (principally the latitudinal variations of the absorption of solar energy). The effects of gaseous carbon dioxide (absorption and emission of radiation) and suspended dust (absorption, emission and scaterring of radiation) are included in the model at solar and thermal infrared wavelengths. To construct the current version of the database and extend the top of the model up to 120 km, a major effort was put in the calculation of the radiative transfer in the upper atmosphere in collaboration with the experts from IAA in Granada. At low pressure above 70 km, one have to consider the fact that the assumption of Local Thermodynamic Equilibrium (LTE) is not valid and that non-LTE effects must be taken into account when computing the radiative heating and cooling budget for the upper CO_2 atmosphere.
  - **Surface Processes.**
    The temperature of the surface is computed from the radiative, sensible and latent heat fluxes at the surface using an 11-level model of thermal diffusion in the soil. Surface properties, i.e. albedo and thermal inertia, are based on Mars Global Surveyor (MGS) and Viking observations. The model also use the accurate topography map obtained by the MOLA altimeter aboard MGS.
  - **Sub-grid scale dynamics.**
    The physical parametrizations must also include representation of small scale motions not explicitly represented by the hydrodynamical code. On the one hand, this includes the representation of vertical exchange of momentum and energy between the surface and the atmosphere due to turbulence and convection, mostly in the so-called Planetary Boundary Layer. On the other hand, the small mountains which are not represented in the GCM smooth grid can influence the model scale flow by (a) producing a form drag on the flow at low levels, and by (b) exciting internal gravity waves which can propagate in the vertical, break, and decelerate the flow far away from the mountains themselves.
  - **CO_2 condensation.**
    a specific parametrization has been developed for Mars to account for the condensation of the CO_2 atmosphere in the polar region during the polar night seasons. CO_2 can condense directly on the surface or up in the

atmosphere. In that last case, the CO_2 ice particles formed in the atmosphere can affect the infrared emissivity of the system as suggested by the oabservations.

3 How are the atmospheric dust variations and dust storms taken into account ?

The major factor which governs the variability in the Martian atmosphere is the amount and distribution of suspended dust. Some years may have low or moderate dust loading throughout the year, while others may have regional or global dust storms which engulf the planet.

Because of this variability, and since even for a given year the details of the dust distribution and optical properties can be uncertain, multi-annual model integrations were carried out for the database assuming various "dust scenarios", i.e. prescribing various amount of airborne dust in the simulated atmosphere.

Five dust scenarios have been used :

- A first scenario, named *Mars Global Surveyor Dust Scenario* based on recent spacecraft observations, which should be used for most aplications. It is our current "best guess" thought to represent the moderately dusty planet Mars as observed by Mars Global Surveyor.
- Two additional annual scenarios which are provided to bracket the possible global conditions on Mars (Figure 1) outside global dust storms.
  - The *"Viking Lander" Dust Scenario* : a relatively dusty year made by generalizing the Viking Lander dust opacity observations to the entire planet, but with the large dust storms removed.
  - The *Low Dust Scenario* : a very clear year (visible optical depth $\tau = 0.1$).
- Two additional dust storm scenarios which are provided only during the period during which such global events are known to occur (southern spring and summer) :
  - *Dust Storm Scenario ($\tau = 2$)* : a moderate global dust storm
  - *Dust Storm Scenario ($\tau = 5$)* : A severe global dust storm

Further details on the dust scenario can be found in Lewis et al. (2001b).

4 Are numerical models a reliable source of information on the Martian environment ?

One particular strength of using a GCM to compile such a database is that it provides a physically consistent estimate of the environmental conditions on Mars for seasons and

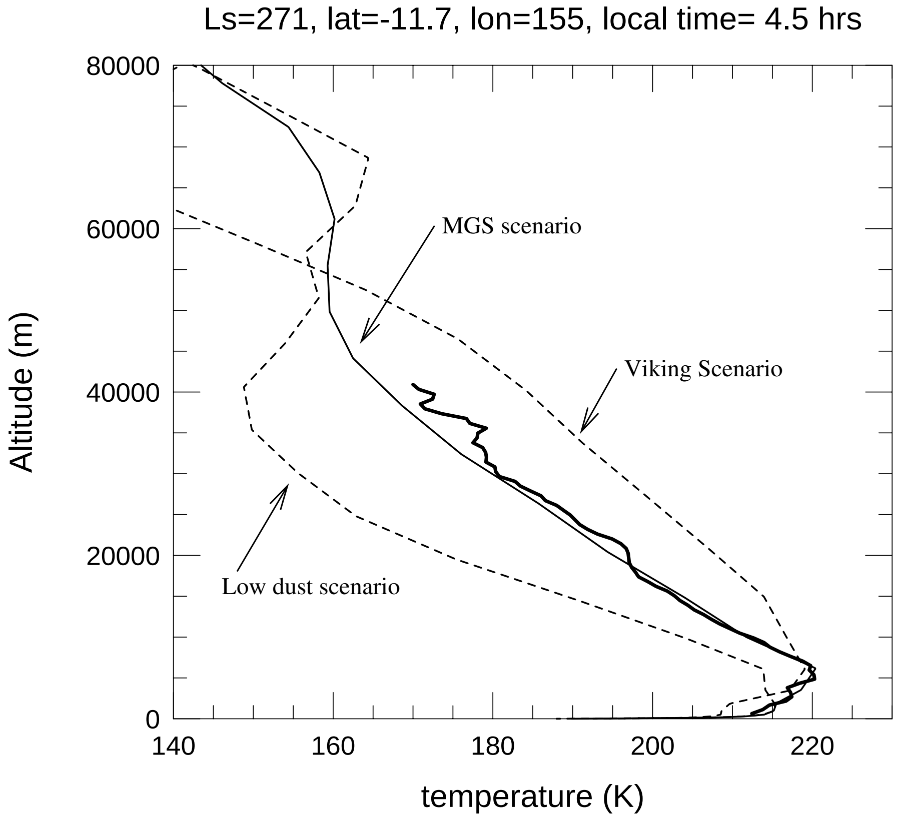

Figure 1: *A typical temperature profile observed by radio-occultation (thick solid line, february 1998,* $L_s = 271^o$*,* 11.7^o*S-*155^o*E, local time : 4:30) compared to temperature profiles predicted by the database at the same time and location. Profiles from the "MGS" scenario are usually very close to the MGS observations, whereas the "Viking" and "low dust" scenarios yield warmer and colder temperatures profiles in the lower atmosphere, respectively. MGS data courtesy of D. Hinson, Stanford University.*

dust loadings which are not covered by the observations. But is the climate database consistent with the available observations ?

First, several key parameters (pressure, dust scenario) of the General Circulation models have been tuned to match the observations. For instance, the GCM does a very good job in reproducing the seasonal pressure variations recorded by Viking Lander 1 and 2 because the total atmosphere mass and polar caps albedo were chosen for this purpose. On this basis, we are extremely confident in the ability of the database to predict the surface pressure elsewhere on the planet, something only a GCM can do !

Second, the MCD has been validated against most of the available observations. In most cases, it is found that the model is able to predict the observations with a very good accuracy. Figures 1, 2, 3, 4 and 5 show such comparison for recent observations from the Mars Global Surveyor and Mars Pathfinder mission. Further comparisons can be find in Lewis et al. (1999) and in Forget et al. (2001b). This validation processes has also shown that some problems remain in some locations and seasons. For instance, the GCMs do not simulate the large temperature inversions which are sometime observed in the tropics in summer ; polar night profiles seems to be slightly colder in reality than in the database during southern winter ; there is no permanent southern CO_2 ice polar caps in the database...

Nevertheless, the agreement between the database and the observations should be good enough for most applications, and we believe that the database is the best tool available for most purpose.

5 How is the small scale variability of the atmosphere represented in the database ?

Mean fields are stored in the database once a season. 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, using Empirical Orthogonal Functions (EOFs). Let $D(z)$ be the database mean vertical profile of a meteorological variable. We add a series of functions to the mean vertical profile,

$$D(z) \ = \overline{D}(z) \ + \ \sum_{n=1}^{N} p_i e_i(z) \tag{2}$$

where the functions e_i are eigenvectors of the covariance matrix of the modelled profiles (the EOFs) and p_i are the amplitudes of the functions (the Principal Components). The e_i form an optimal linear basis such that the variance captured 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

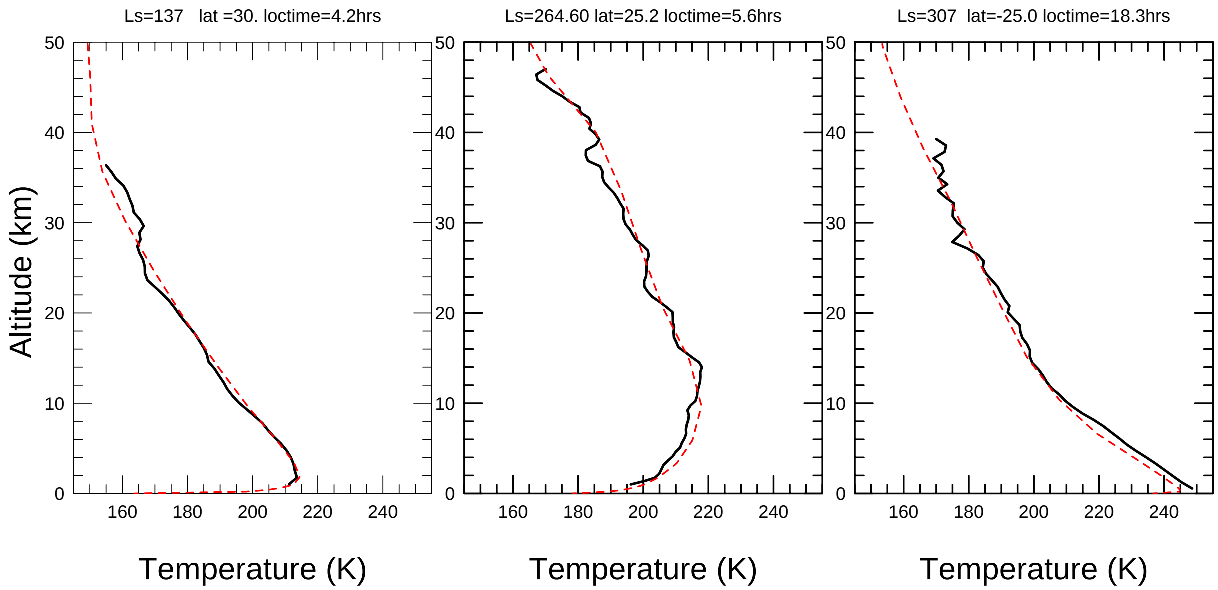

Figure 2: *Example of very good fits to the observations that can be obtained with the database MGS scenario at various seasons. The black solid lines show temperature profiles measured by radio-occultation with Mars Global Surveyor. The red dashed lines are the MCD predictions at the same locations and times. The model is usually able to simulate accurately the variations of the temperature profiles due to change in dust loading and insolation.*

together and form a set of multivariate functions. In practice the series (2) is truncated to 6 EOFs which, on average, capture around 80-90% of the variance.

- A **small scale variability model**, simulating perturbations of density, temperature and wind due to the upward propagation of small scale gravity waves have been included in the database system. The model is based on the parametrization scheme used the numerical models that simulated the data in the database.

Further details on the variability models can be found in Lewis et al. (1999, 2001b)

6 How to access the database ?

For moderate use : the World Wide Web site.

For anyone having access to internet, A **World Wide Web** site has been developed at LMD (`http://www.lmd.jussieu.fr/mars.html`). In adition to a complete documention, this interactive site offer a direct and convenient access to the data in a variety of graphical and numerical formats. However, the variability models are not available on the web-site.

TES data and MGS scenario at $L_S = 270°$

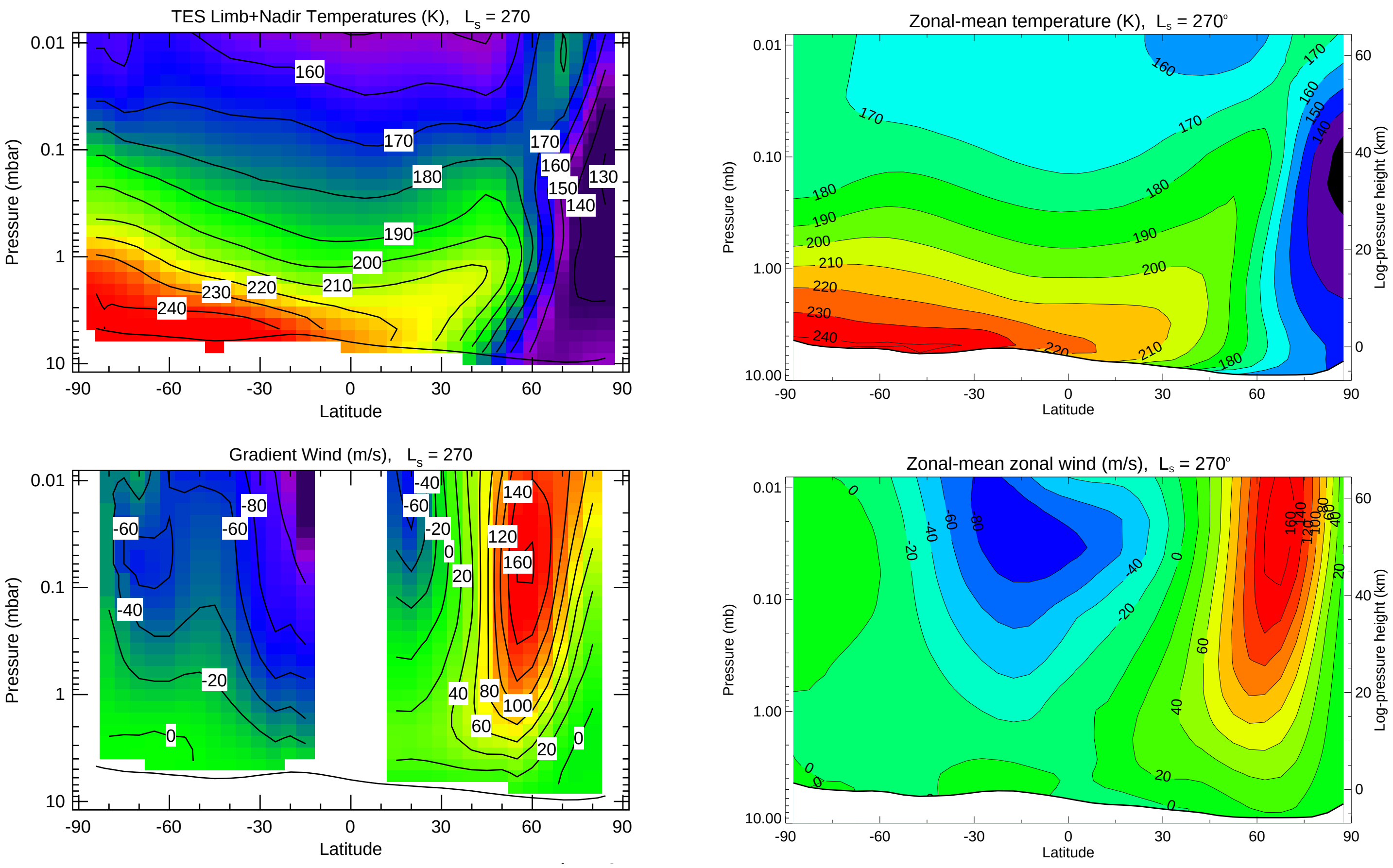

Figure 3: *Mean meridional cross-sections of atmospheric temperatures retrieved from the MGS Thermal Emission Spectrometer observations (top, left pannel) and corresponding gradient winds (bottom, left pannel) at $L_s = 270^o$ compared to time-mean zonal-mean plots from the Mars Climate database using the MGS scenario for the same season. One can notice that the simulated summer pole atmosphere at $L_s = 270^o$ is slightly cooler than in the TES inversions, resulting in weaker or absent simulated easterly winds high in the summer hemisphere. This discrepency is probably due to the occurence of a regional dust storm between $L_s = 260^o$ and $L_s = 272^o$ at the edge of the south polar cap during the year observed by MGS. TES figure from Smith et al. (2001).*

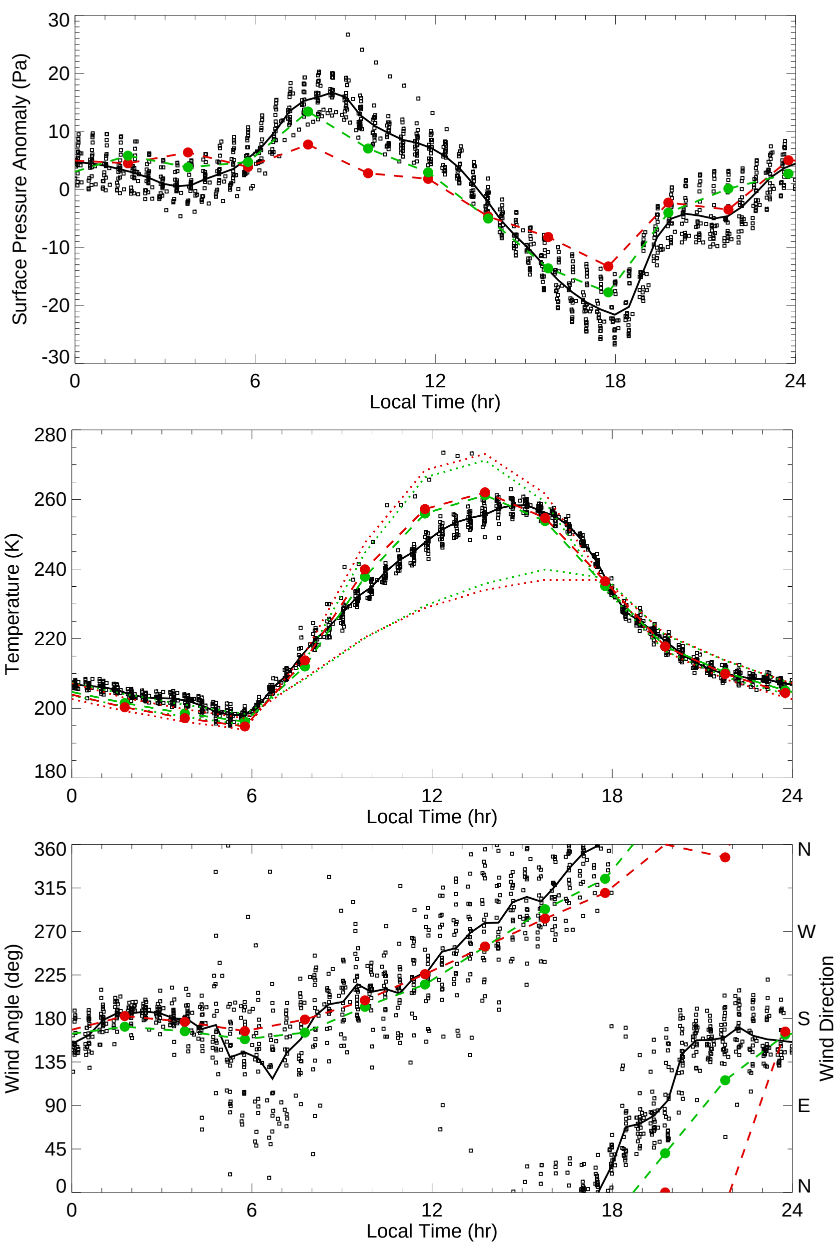

Figure 4: *A comparison of the Mars Pathfinder surface measurements with the MCD. The small squares show the Mars Pathfinder measurements and the solid line is the mean of the observations taken over the first 30 days of the mission. The large circles connected by dashed lines show the MCD predictions interpolated to the Mars Pathfinder location. Red lines: MGS "dust scenario" (the low dust scenario gives very similar results). Green line: Viking scenario.* **Top pannel:** *The pressure diurnal cycle : the MGS scenario appears to underestimate the total amplitude of the surface pressure tide, whereas the Viking dust scenario appears to give a better fit.* **Middle panel:** *the temperature at the top of the 1 m meteorological mast (about 1.27 m above the surface). The dotted lines are the MCD surface temperature (top line at midday) and the MCD lowest atmospheric level (5 m) temperature (bottom line).* **Bottom panel:** *The wind direction axis, indicated by the compass point from which the wind is blowing from (0^o is a northerly). The general sense of rotation is determined by the passage of the diurnal thermal tide; the details, such as the small rotation toward an easterly near dawn before the subsequent rotation to a westerly, are a consequence of the local topography.*

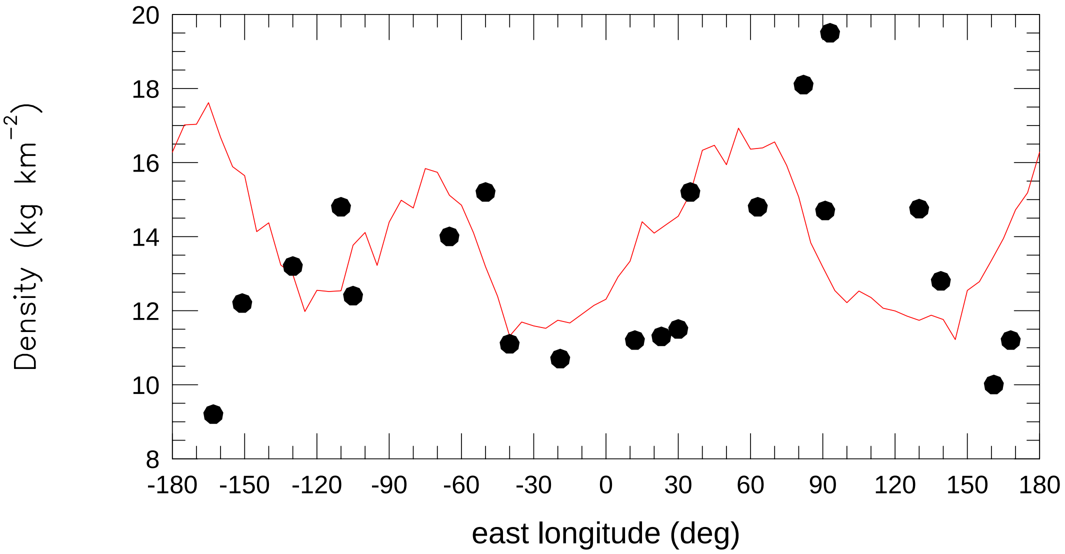

Figure 5: *A comparison of the density measured in-situ (red dots) by the Mars Global Surveyor accelerometer during aerobraking around 125 km during northern winter (Keating et al., 1998) with the densities predicted at about the same location by the Mars Climate Database (MGS scenario). The absolute value of the density is well predicted in spite of the extreme sensitivity of density to the entire atmosphere below. In addition, the MCD predicts longitudinal variations comprising wave-like wavenumber 1 and 2 structures which are quite similar to the observations.*

For intensive or precise work : the CD-ROMs

The MCD is available for distribution on a couple of CD-ROMs that can be obtained from LMD. In its current version The data are distributed in portable binary formats, such as the Data Retrieval and Storage (DRS) library developed for the Program for (Terrestrial) Climate Model Diagnosis and Intercomparison to facilitate the transfer of data between different platforms (Lewis et al., 2001a).

Bearing in mind the potentially diverse range of users of the MCD, including engineers involved in the design of spacecraft missions, scientists specializing in GCM studies who are familiar with manipulating similar data sets and scientists from other areas who may require information on environmental conditions on Mars, the data may be accessed by several methods :

- If you know FORTRAN, the best way to retrieve environmental data from the Mars climate database is to use the **subroutine mode** of the software supplied with the Mars Climate Database. In practice, one only has to call a main subroutine named `atmemcd` from within any program written in FORTRAN to get environmental data at any given locations and times. A simple example of such a program (`test_emcd`), which can be easily modified, is provided. This mode was developped with a particular attention to trajectory simulation application, but It should also be used for other purpose. A programmer's guide is available (Forget et al. 2001a).

- An interface, MCDGM, is supplied with the Mars Climate Database. The MCDGM interface performs in a very similar way to MarsGRAM version 3.5. It is intended to make the database as easy to use as possible for those with prior experience of MarsGRAM as well as providing possible access for all users to the complete database, It can be run in interactive or batch mode.
- It is possible to access the database directly from within any program, written in FORTRAN or C, by using the **DRS library**.
- Control files, instructions and example scripts are provided for accessing the database using **GrADS**. GrADS is a freely available package for access, manipulation and display of earth science data which runs on many computing platforms.

7 Key References

(available on the web-site : `http://www.lmd.jussieu.fr/mars.html`)

Technical documentation

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Scientific articles

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