A GCM CLIMATE DATABASE FOR MARS: FOR MISSION PLANNING AND FOR SCIENTIFIC STUDIES

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ABSTRACT

The construction of a new database of statistics on the climate and environment of the Martian atmosphere is currently under way, with the support of the European Space Agency. The primary objectives of this database are to provide information for mission design specialists on the mean state and variability of the Martian environment in unprecedented detail, through use of a set of carefully validated simulations of the Martian atmospheric circulation using comprehensive numerical general circulation models. The formulation of the models used are outlined herein, noting especially new improvements in various schemes to parametrize important physical processes, and the scope of the database to be constructed is described. A novel approach towards the representation of large-scale variability in the output of the database, using empirical eigenfunctions, derived from statistical analyses of the numerical simulations, is also discussed. It is hoped that the resulting database will be of value for both scientific and engineering studies of Mars' atmosphere and near-surface environment.

INTRODUCTION

Information on the climatological state of Mars' atmosphere and surface environment is generally required for two very different kinds of activity relating to space research and planetary exploration. The motivation underlying most studies derives (a) from the 'science' community, concerned with the task of understanding the physical and dynamical processes controlling the environment and climate, atmospheric motions and transport, and for studies of comparative planetology between the Earth and other planets. In pursuit of many of these goals, however, another community (b), consisting mainly of aerospace engineers and instrument designers (the 'mission design' community), requires guidance on the range of physical conditions likely to be encountered during a spacecraft mission designed e.g. to land on the Martian surface and to operate there for long periods of time. Such information is a necessary input to the efficient and robust engineering design of spacecraft structures and systems, as well as for the specifications of instruments for making scientific measurements.

The respective requirements of these two communities are quite different, and have led in the past to the development of quite different methodological approaches to the representation of climatological information. The 'science' community, for example, has tackled its requirements for in-depth, dynamically self-consistent, global information through the development of sophisticated time-dependent numerical models (General Circulation Models or GCMs), which explicitly simulate large-scale atmospheric flow, and parametrize a wide range of physical processes active in the climate system, such as radiative transfer, surface-atmosphere interactions and the effects of unresolved turbulent mixing and transport. Such models produce as their primary output a complete three-dimensional time-dependent atmospheric state - a form of 'proxy atmosphere', which can include many details of seasonal and diurnal variations consistent with the dynamical formulation and resolution of the model in space and time. These models are typically validated against observations, in the senses (i) that individual parametrization algorithms are calibrated against known physical constraints, (ii) the schemes are tuned to match available observations, and (iii) parameters in the model simulation are adjusted to ensure that the time- and space-averaged climatological state is consistent with available observations. Such models are, however, computationally sophisticated and expensive, requiring large and powerful computers to run and to analyse their very substantial output.

The 'mission design' community, however, has rather different requirements, not just for realistic estimates of the time-mean state of the atmosphere, but also for details on geographical variations and especially on the range of variability on all scales in space and time. In this respect, dynamical self-consistency is of lesser importance than ensuring that actual observations and experience from past missions are fully represented. This has led to the emergence of a range of 'Global Reference Atmosphere Models', such as MarsGRAM (Justus *et al.* 1990) and GRAM95 (Justus *et al.* 1995) for the Earth. These mainly consist of compilations of observational statistics with suitable interpolation schemes to provide estimates of climate variables of interest to engineers (wind, temperature, density etc.) at any geographical location, together with Monte-Carlo models for synthesising variability about mean states due to motions on both small and large scales. The required output is typically in the form of a set of 'synthetic observations', represented by ensembles of randomly-generated plausible realisations of the atmospheric state along specified trajectories in space and time (e.g. along an entry trajectory to a landing site). These kinds of model are relatively straightforward in concept and computationally inexpensive, being in essence a form of database access system, and will often run on modest PCs or workstations.

In the case of the Earth, GRAM-style models are able to make use of extensive observations of the atmospheric state, acquired over many years. Thus, GRAM95 accesses statistics from global meteorological analyses from the troposphere and stratosphere, while making use of simpler statistical models at higher altitudes. For Mars, however, the available observational data are much more sparse and incomplete in both space and time, so that GRAM-style models based solely on interpolating between available observations are likely to be subject to much greater uncertainties than their terrestrial counterparts.

In the work presented below, therefore, we describe a new approach to this problem, in which we plan to produce a database of climate statistics from a set of carefully validated GCM simulations of Mars' climate and atmospheric circulation. Current generations of Mars GCMs (e.g. Pollack *et al.* 1990; Hourdin *et al.* 1993) are of comparable resolution and sophistication to those used for terrestrial climate simulation and prediction, and have achieved significant progress in quantitatively reproducing many features in the observations from the Mariner and Viking missions. This database is being produced initially for the primary benefit of mission designers, and so will also incorporate a Monte-Carlo model of small and large-scale variability for synthesising realisations along trajectories. Our variability model also includes, however, a novel approach which can represent correlation structures in space and between different variables in a way which preserves the dynamical consistency of the GCM itself. The dynamical self-consistency of such a database is also likely to be of value to the 'science' community.

In the following, we provide an outline description of the GCMs being used to compile the database, including the formulation of several significant improvements in the physical parametrization schemes and their validation (Section 2), while in Section 3 we give a brief description of our approach to modelling variability. Section 4 outlines the climate scenarios to be included in our study and the form likely to be taken by the final database product, and presents a few preliminary examples from an ongoing climate simulation.

MODEL DESCRIPTION

Basic Model

The model used to carry out the climate simulations for use in the database is based on the suite of models developed jointly by the groups at LMD and Oxford. Details of these models are given elsewhere (Hourdin *et al.* 1993, 1995; Collins *et al.* 1996a), but briefly they comprise two distinct formulations of the fluid dynamics of the Martian atmosphere, based on the meteorological primitive equations, (i) using a finite-difference discretisation in the horizontal, based on the terrestrial GCM developed at LMD (Sadourney *et al.* 1982), and (ii) using a pseudo-spectral solver based on the code developed originally at the University of Reading (Hoskins & Simmons 1975). Both these dynamical solvers use terrain-following finite-difference σ-coordinates in the vertical, and make use of a common library of physical parametrization schemes, based on the package developed at LMD (Hourdin *et al.* 1993; 1995). This includes (a) a radiative transfer scheme to represent the effects of solar heating of suspended dust (Fouquart & Bonnel 1980), and infrared cooling due to CO_2 (Hourdin 1992) and dust (represented as a grey absorber/emitter); (b) a surface/soil model, representing the exchange of radiative and sensible heat at the surface and thermal diffusion into the ground (via an 11-level diffusive soil model); (c) a parametrization of turbulent mixing and diffusion (mainly of importance in the planetary boundary layer); (d) a dry convection scheme; and (e) a simple energy-balance representation of CO_2 condensation-sublimation at the surface.

Surface properties (topography, albedo and thermal inertia) are represented at the spatial resolution of the model, based on observations of Mars from Mariner 9 and Viking, and both models have been run at typical resolutions of 64×32 points in longitude and latitude (LMD) or T21 in spectral space (equivalent to $5.6^\circ \times 5.6^\circ$) (Oxford), with up to 20 levels in the vertical up to altitudes of around 80km. Such a resolution is just sufficient to represent most of the major large-scale geographical features of the Martian surface, though substantial local features such as the Tharsis volcanoes and Valles Marineris are heavily smoothed.

Model Enhancements

In preparation for producing the database, a number of enhancements have been made to the earlier model. These include (i) running both versions of the model at higher spatial resolution (96×48 points, or triangular truncation T31 in spectral space, and with 25 levels in the vertical to altitudes of 90 km), in order to represent major local features more accurately, (ii) an improved representation of solar heating and infrared cooling due to dust, (iii) a more sophisticated and accurate representation of turbulent mixing in the planetary boundary layer, (iv) development of a representation of the effects of sub-gridscale topography, including low-level drag and the effects of induced gravity wave drag produced by the presence of topography, (v) a representation of *atmospheric* condensation of CO_2, including the formation of CO_2 clouds, and (vi) a representation of areas of low infrared emissivity in polar regions, recently identified from Viking IRTM observations (Forget *et al.* 1995).

Each individual parametrization scheme has been implemented in order to address a particular shortcoming identified in the original models, and full technical details of each scheme will be presented elsewhere. In particular, the new boundary layer scheme, for example, is based on an advanced Mellor-type second-order closure scheme (Mellor & Tetsuji 1982), which can represent many details of the evolution of the planetary boundary layer on diurnal and seasonal timescales. The sub-grid scale orographic scheme makes use of the high resolution Digital Terrain Model (DTM) of Mars topography (Wu 1981), and is based on the new scheme being implemented at the European Centre for Medium Range Weather Forecasts (ECMWF - see Lott & Miller 1996; Collins *et al.* 1996b), including the important effect of gravity wave drag. This is significant at high polar latitudes, and may lead to strong dynamical warming of the upper atmosphere, as suggested from observations (e.g. Deming *et al.* 1986; Théodore *et al.* 1993), much as found in the Earth's middle atmosphere (e.g. Andrews *et. al.* 1987). The new schemes have been tested against a wide range of relevant observational data, and the overall model simulations with all the new schemes in place have been validated against datasets of thermal structure and wind from Mariner 9 IRIS and Viking IRTM and Lander observations.

The main result of this development effort is to produce a comprehensive model of the Martian atmosphere and near-surface environment which faithfully reproduces a wide range of observations, both *in situ* and from remote sounding, where these are available. Since the model is formulated using a wide range of additional information on the physical characteristics of Mars and relevant physical processes, however, the model will also provide a best estimate of the typical state of Mars' climate in places and at times *for which observations are not yet available*. This approach thus enables us to go some way towards making up for the sparseness of the current observational dataset for the planet.

REPRESENTING VARIABILITY

A key element of GRAM-style models of the terrestrial and Martian atmospheres is an ability to estimate not only the time-mean state of the atmosphere along specified trajectories, but also to simulate actual instantaneous realisations along those trajectories which include components representing the variability of the atmosphere in time and space. Recent versions of the GRAM models have developed a range of schemes to add variability to mean fields through the superposition of autocorrelated 'red' noise to the mean profiles of the required variables. The variance and correlation coefficient in space of the 'red' noise are constrained from observations, while the correlations between variables (e.g. between wind, pressure and temperature) at a given location in space are constrained from considerations the equation of state and of elementary dynamical balance considerations (hydrostatic balance etc.) - e.g. see Justus *et al.* (1995) for further details. These models typically distinguish between 'large' and 'small' scales, as representing respectively synoptic and planetary scale phenomena on the one hand and small-scale turbulence and gravity wave phenomena on the other.

This approach is able to generate ensembles of realisations of synthetic 'observations' along specified profiles or trajectories which are superficially plausible, but suffer from a number of drawbacks. Not least of these is their inability to represent correlated structures in profiles between different variables *in space*, in ways which also preserve the details of dynamical balance (including effects of geostrophy and other higher order effects). In an attempt to improve upon this approach, at least on the large scales explicitly resolved by our model, the ESA Mars Environment Model will represent large-scale patterns of variability using multivariate Empirical Orthogonal Functions in the vertical direction. These are patterns derived statistically from the detailed 3D evolution of the model, which are the eigenfunctions of the multivariate covariance matrix along a specified vertical profile. The time-mean covariance of the main meteorological variables in the model (u, v, T, p) is computed at each point along a specified profile, so that the diagonal elements of the matrix represent the autocovariance of each variable at each point along the profile, while the off-diagonal components represent the covariance of variable A at location x_i with variable B at location x_j. Each eigenvector of this matrix represents a pattern which occurs in the data in all variables along the profile, while the eigenvalue spectrum represents the fraction of the total variance 'explained' by each pattern. Although there is no formal balance requirement built into the procedure, by producing the vectors from a dynamically balanced dataset it is likely that the resulting eigenvectors will themselves reflect that balance in their correlated structures between different variables.

Considerable compression of information can be achieved if a relatively small sub-set of the eigenvectors can be shown to capture a substantial fraction of the total variance. In the present work, preliminary analyses of GCM simulations suggest that more than 80% of the observed variance can be captured typically by as few as 7-10 multivariate eignevectors, and that furthermore the form of the most significant of such patterns does not vary strongly from place to place across the planet (at least over a range of latitude and longitude). Fig. 1, for example, shows an eigenvalue spectrum from one such analysis of (u, v, T, p) in a simulation of the northern hemisphere winter circulation at latitude 47°N. From this it is clear that 8 eigenfunctions will capture more than 80% of the total (normalized) variance. Fig. 1 also shows the first three corresponding eigenfunctions as vertical profiles of each variable, together with the corresponding mean profile. The patterns typically show smoothly varying structures with height, with the most substantial variations near the top of the model where the decrease in density leads to a growth in amplitude of most wave-like phenomena in the atmosphere.

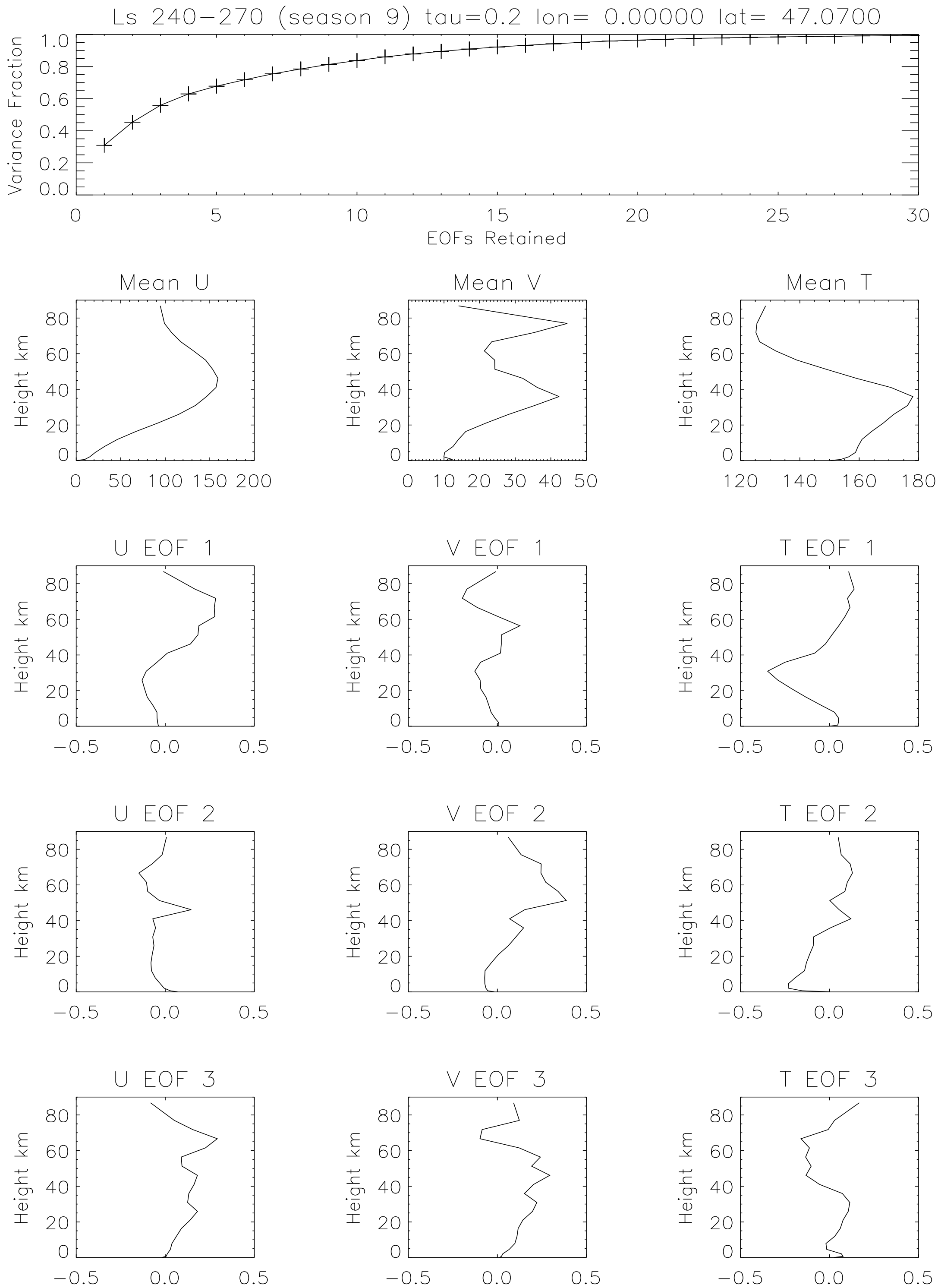


Figure 1: An eigenfunction analysis of a typical mid-latitude vertical profile of wind and temperature during northern hemisphere winter. (a) shows the cumulative variance capture of each eigenfunction, while each row below shows the time mean profile of each variable u, v, T and the first three eigenvectors.

In the implementation of the Environment Model database, synthetic realisations may be produced by a superposition of (i) the time-mean profile of each main variable, valid at the required location, season and time of day, (ii) a sub-set of large-scale eigenfunctions with randomly-determined amplitudes (consistent with the analysed eigenvalue spectrum) and (iii) some correlated noise to represent the effects of variability which is not resolved explicitly by the GCM. In the case of (iii), the required variance may be obtainable from versions of the parametrization schemes within the model, which estimate the intensity e.g. of boundary layer turbulence and topographic gravity wave activity as a function of space and time.

DATABASE CLIMATE SCENARIOS

The overall intention of the Environment Model is to provide guidance on the typical state of the Martian climate system and its associated variability, in a way which represents knowledge not only from direct observations, but also from *a priori* knowledge of the dynamics and physics of the Martian atmosphere and surface. Despite the sparseness of observations, it is already clear that the Martian climate system at present exhibits a range of quite different states, ranging from the very clear and cold conditions encountered during the recent Phobos mission to the very dusty and disturbed conditions prevalent during a major dust storm. In order to represent these long-term variations, the Environment Model database will include three main scenarios, to be derived from separate series of climate simulations using the LMD and Oxford GCMs.

Scenario A represents the clear and relatively undisturbed conditions typical of the Phobos mission (e.g. Chassefière *et al.* 1995), and is being run with a constant distribution of dust in both space and time (i.e. with dust mixing ratio varying only with height) with a uniform optical depth of 0.1.

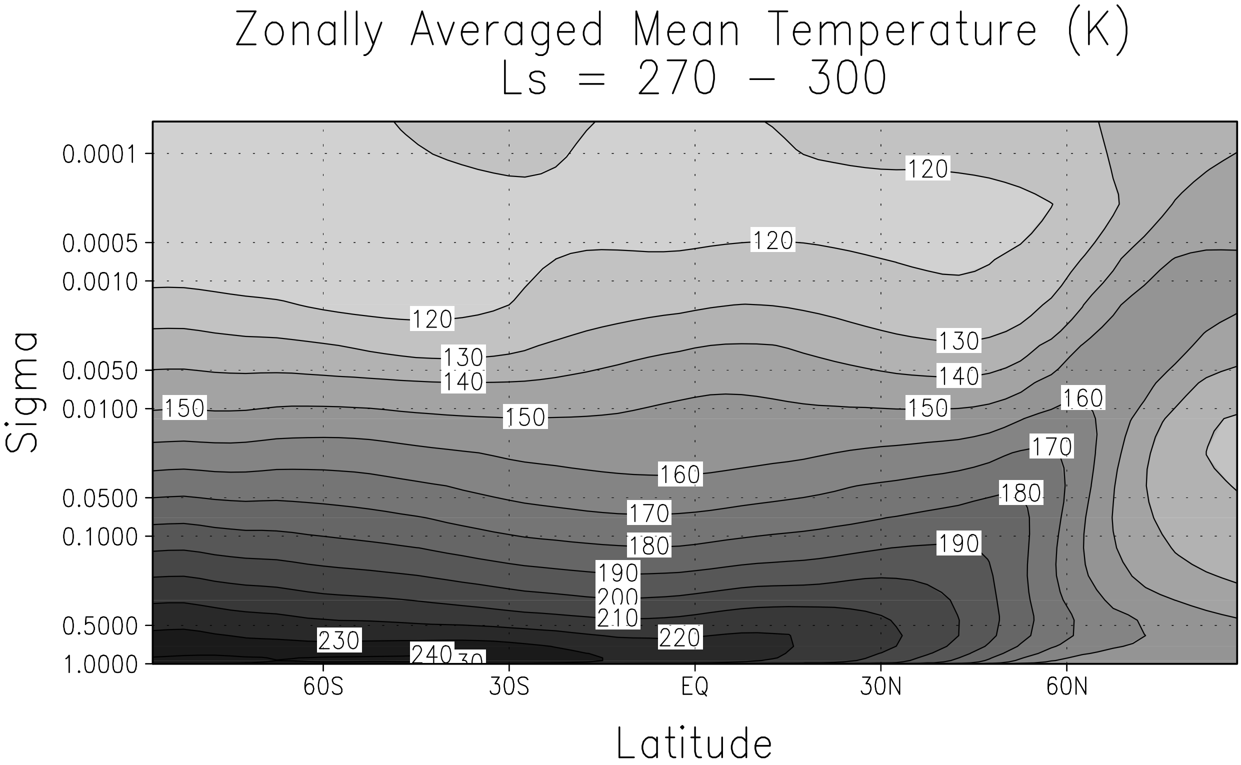
Scenario B represents the somewhat more dusty conditions typical of those prevailing around the time of the Viking missions in the 1970s, outside of major dust storms. For this case, the dust distribution varies in both latitude and with season (as well as in height) over the range $0.5 < \tau < 1.0$, in a manner which is consistent with observations during the Viking era.

Scenario C is intended to represent conditions prevailing during the mature phase of a major dust storm. The statistics for this scenario will be derived from a series of short simulations covering the observed dust storm seasons, utilising a range of plausible dust distributions with peak values of optical depth up to around 5.0.

With the exception of Scenario C, each scenario will be derived from several years of continuous simulations, in order to include effects of interannual as well as intraseasonal variability in the statistics. Statistics will be compiled for twelve distinct seasons, based on a sub-division of the Martian year into suitable increments of solar longitude L_S, and within each season, for twelve distinct times of day for each longitude. This is in order to ensure that the statistics held in the database can adequately represent the full seasonal and diurnal variation (including explicit representation of the thermal tide) in the mean fields. Fields will be held at the spatial resolution of the GCM, ensuring that much of the geographical variability of the Martian environment is captured in the database. Such a collection of data will amount to a substantial dataset, though of a size (several hundred Mb) which is manageable for current generations of workstations.

Some preliminary results from a simulation in the low-dust Scenario A are shown in Figs 2 and 3 for illustration. Fig. 2 shows the zonal mean temperature and zonal velocity fields during the northern hemisphere winter season. The strongly stable stratification over the winter pole is clearly evident, as is the significant warming at high northern latitudes around $\sigma = 0.07$, associated with breaking gravity waves. The zonal wind field is broadly in thermal wind balance with the thermal field, with a strong 125 m s^{-1} jet at high northern mid-latitudes and a weaker easterly jet in the summer hemisphere.

Fig. 3 shows a typical low-level horizontal wind field at $\sigma = 0.98$ (an altitude around 200 m above the ground), superimposed on the corresponding surface pressure field (in practice a proxy for surface topogra-



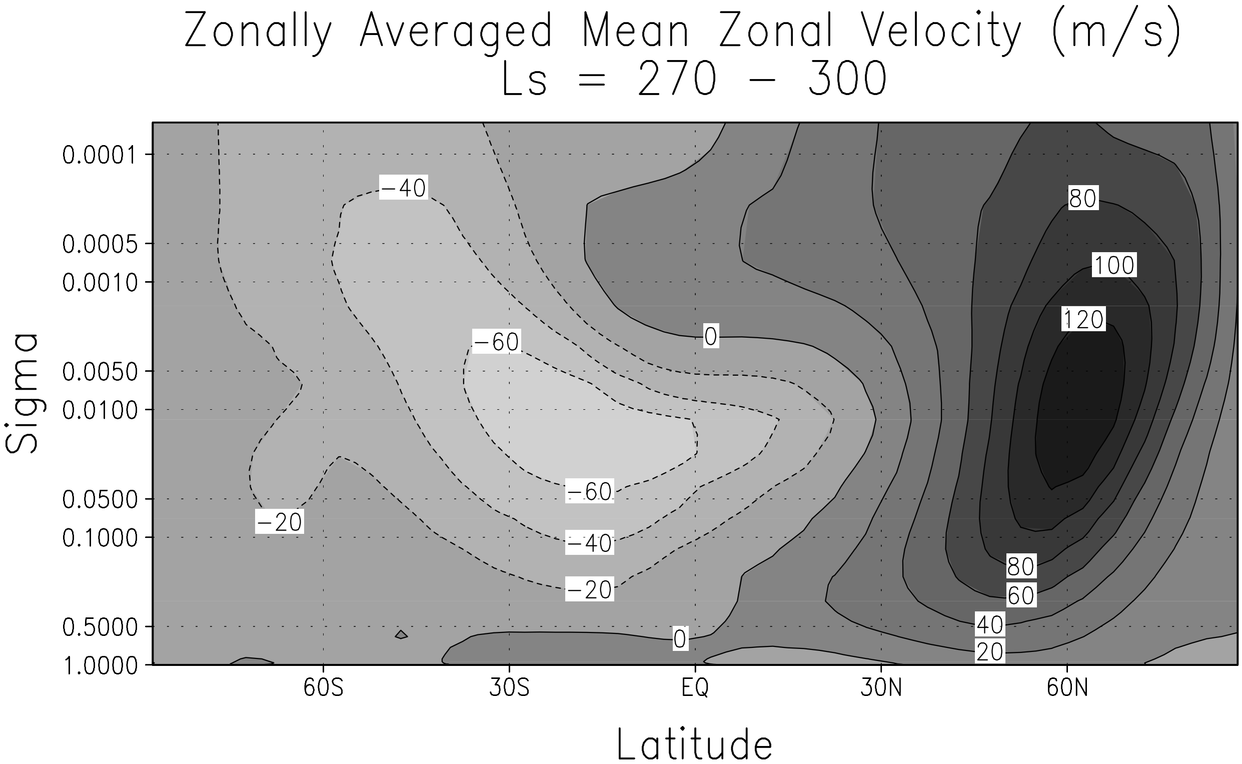


Figure 2: Seasonally-averaged zonal mean fields of temperature and zonal wind for the northern hemisphere winter case of Scenario A (low dust).

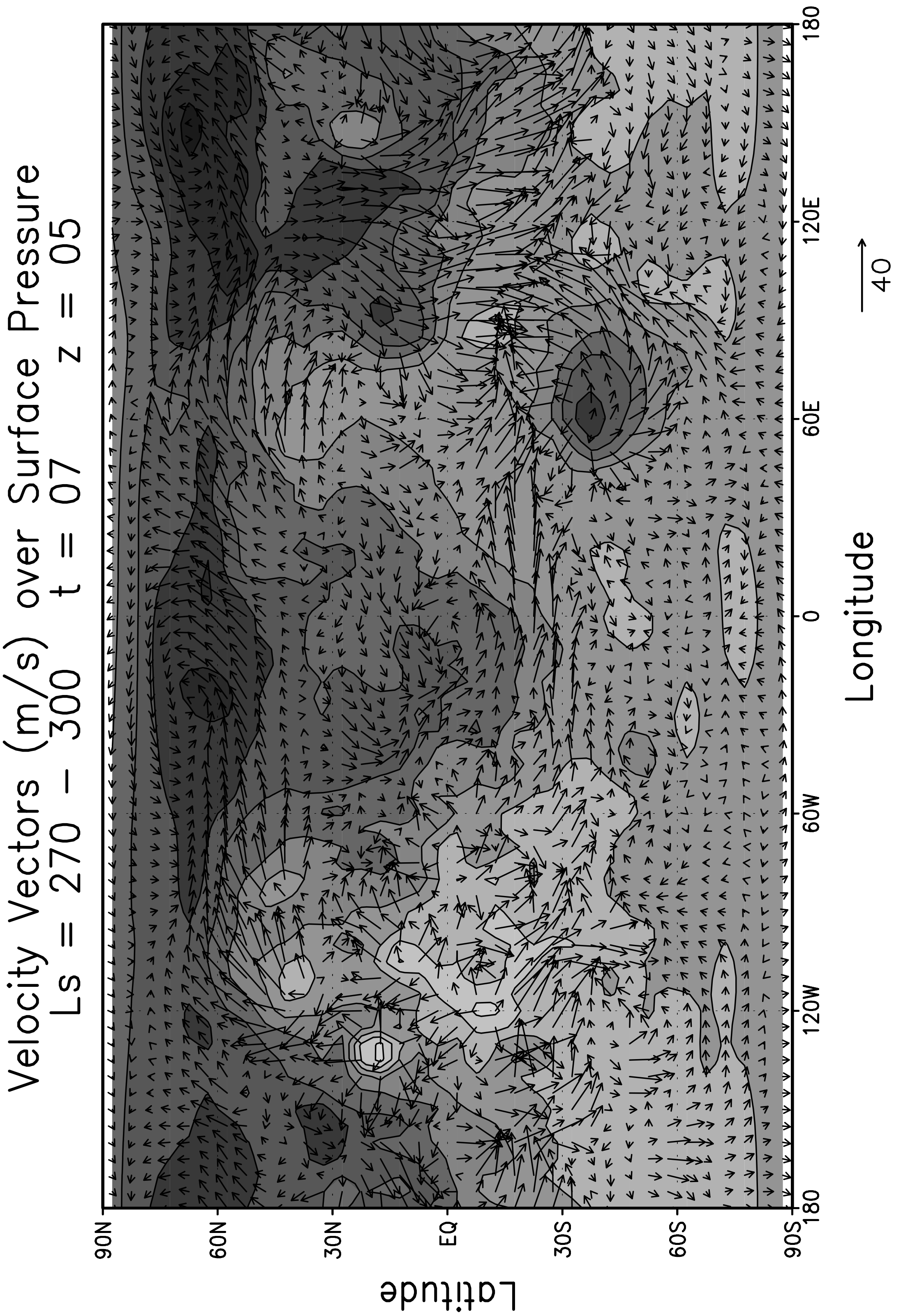


Figure 3: Map of seasonal mean low-level wind at $\sigma = 0.98$ during northern hemisphere winter, superimposed on surface pressure contours. Plot is taken at a local time of 18h at longitude 0, (i.e. the sun is overhead at longitude 90E).

phy), again for the northern hemisphere winter case illustrated in Fig. 2. This case corresponds to $t = 18$h at latitude $\phi = 0$. A wealth of local detail is seen at this resolution, showing broadly westerly flow at high northern latitudes with pronounced deflections around major topographic features. The effects of local slope winds are also much in evidence, e.g. with strong katabatic downslope drainage flow down Olympus Mons and the Tharsis plateau (during the night at this time) and with strong spiralling upslope flow in the Hellas basin during local afternoon in the summer hemisphere.

It is intended that the final database will be made widely available to both the Mars science and engineering communities. By ensuring full dynamical and physical self-consistency through the use of GCMs in deriving the input data, it is hoped that the Environment Model will be of value in a wide range of studies of the Martian environment and climate system.

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REFERENCES

Andrews, D. G., Holton, J. R. & Leovy, C. B., *Middle Atmosphere Dynamics*, Academic Press (1987).

Chassefière, E., Drossart, P. & Korablev, O., Post-Phobos model for the altitude and size distribution of dust in the low Martian atmosphere. *J. Geophys. Res.*, 100, 5525-5539.

Collins, M., Lewis, S. R., Read, P. L. & Hourdin, F., Baroclinic wave transitions in the Martian atmosphere, *Icarus*, 120, 344-357 (1996a).

Collins, M., Lewis, S. R. & Read, P. L., Gravity wave drag in a global circulation model of the Martian atmosphere: parametrization and validation. *Adv. Space Res.*, this issue (1996b).

Deming, D. J., Mumma, F., Espenak, F., Kostius, T. & Zipoy, D., Polar warming in the atmosphere of Mars. *Icarus*, 66, 366-379 (1986).

Forget, F., Pollack, J. B. & Hansen, G. B., Low brightness temperatures of Martian polar caps: CO_2 clouds or low spectral emissivity? *J. Geophys. Res.*, 100, 21119-21234 (1995).

Fouquart, Y & Bonnel, B., Computations of solar heating of the Earth's atmosphere: a new parametrization. *Contrib. Atmos. Phys.*, 53, 35-62 (1980).

Hoskins, B.J. & A.J. Simmons, A Multi-Layer Spectral Model and the Semi-Implicit Method. *Quart. J. R. Met. Soc.*, 109, 771-783 (1975).

Hourdin, F., A New Representation of the Absorption by CO_2 15 μm Band for a Martian General Circulation Model. *J. Geophys. Res.*, 97(E11), 18319-18335 (1993).

Hourdin, F., P. Le Van, F. Forget & O. Talagrand, Meteorological Variability and the Annual Surface Pressure Cycle on Mars. *J. Atmos. Sci.*, 50, 3625-3640 (1993).

Hourdin, F., Forget, F. & Talagrand, O., The sensitivity of the Martian surface pressure to various parameters: a comparison between numerical simulations and Viking observations. *J. Geophys. Res.*, 100, 5501-5523 (1995).

Justus, C., 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., Jeffries, W. R., Yung, S. P. & Johnson, D. L., The NASA/MSFC Global Reference Atmosphere Model - 1995 version (GRAM-95). *NASA Technical Memorandum* (1995).

Lott, F. & Miller, M. J. A new sub-grid scale orographic drag parametrization: its formulation and testing. *Quart. J. R. Met. Soc.*, in press (1996).

Mellor, G. L. & Tetsuji, Y., Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Sci.*, 20, 851-875 (1982).

Sadourney, R. & Laval, K., New Perspectives in Climate Modelling (ed. A. Berger & C. Nicolis), Elsevier, pp. 173-197. (1982).

Théodore, B., Lellouch, E., Chassefiere, E. & Hauchecorne, A., Solsticial temperature inversions in the Martian middle atmosphere: observational clues and 2-D modelling. *Icarus*, 105, 512-528 (1993).

Wu, S. S. C., A method of defining topographic datums of planetary bodies. *Annal. de Geophys.*, 1, 147-160 (1981).