Tender submitted
to the European Space Research and Technology Centre
of the European Space Agency

in response to the Invitation To Tender No.
AO/1–2798/94/NL/JG issued on 6 july 1994

MARTIAN ENVIRONMENT MODELS

Tender LMD/AOPP-09/94
September 22, 1994

Authors
Olivier TALAGRAND *
Peter L. READ †
Matthew COLLINS †
François FORGET *
Frédéric HOURDIN *
Stephen R. LEWIS †
Fred W. TAYLOR †

Proposed Contractor:
Centre National de la Recherche Scientifique (France).
Proposed Co–contractor:
The University of Oxford (England).

Total amount requested: 250,000 AU

*Laboratoire de Météorologie Dynamique du CNRS, Ecole Normale Supérieure, 24 rue Lhomond, 75 231 PARIS Cedex 05, France.
† Sub-department of Atmospheric, Oceanic & Planetary Physics, Department of Physics, Oxford University, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom.

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2.1 Introduction

2.1.1 Scope of the Tender

The proposal described herein has been produced jointly by the Laboratoire de Météorologie Dynamique of CNRS/Ecole Normale Superieure, Paris (France - hereafter referred to as LMD), and the Atmospheric, Oceanic and Planetary Physics division of the Dept. of Physics of the University of Oxford (United Kingdom - hereafter AOPP), in response to the recent ESA Invitation to Tender No. AO/1-2798/94/NL/JG - Martian Environment Models. This document describes in detail our tender for this contract, in which we propose to undertake all aspects of the work requested as two parallel contracts, and to provide the required deliverables.

2.1.2 Work Required

Spacecraft missions to a planet such as Mars, which entail soft-landing instrumentation on the planet's surface, are difficult and complex undertakings which require careful preparation and engineering design. An important factor which such designs need to take into account is the range of environmental conditions which the spacecraft and its instruments are likely to encounter, both during the descent phase of the mission and once installed at or near the surface. Until recently, it has been customary to provide such information in the form of a set of simple tables of numerical data, compiled and summarised from a diverse range of observational sources and model simulations of various degrees of complexity (e.g. Kaplan 1988, Justus 1990). With the continuing development both of the observational exploration of Mars, and of man's ability to simulate the atmosphere and surface environment in numerical models, it is clear that such simple tabulated models no longer represent adequately the current state of knowledge of the Mars environment. Also, with the increasing complexity of proposed missions to Mars, the requirements of engineering design for such missions have become much more stringent, so that environmental models now need to provide more detailed and comprehensive information than hitherto. Accordingly, ESA now requires the development of a more complex model of the Mars environment, based around a comprehensive numerical circulation model, providing as complete a representation as possible of most aspects of the Mars environment as needed for mission design studies.

In the present tender, it is proposed to carry out a detailed study and development project, as outlined in the Invitation to Tender Document. The project is anticipated to comprise four distinct stages:

(a) Carry out a survey and review of the current state of knowledge concerning the atmosphere and surface conditions of Mars, and the present status of efforts to simulate the Martian meteorology and climate using global numerical models. This will be presented in the form of a written report.

(b) Develop and validate an advanced global circulation model of the atmosphere of Mars, including representations of surface processes and the effects of unresolved scales of motion, capable of running on a high performance workstation. The code will be made available to ESA.

(c) Perform a systematic set of multi-annual climate simulations, optimized so far as possible against available observations, and compile a database of suitable statistics for use in future engineering studies. The database will be presented both in numerical form and as a documented commentary.

(d) Carry out a critical comparison of the new database with previous generations of engineering models of the Mars environment, and produce a final report.

2.1.3 Expertise of the LMD/AOPP Consortium

The combined groups at Paris and Oxford are particularly well placed within Europe to carry out this study, because of the expertise and facilities which both groups are able to deploy. LMD is one of the principal research institutes in France involved in atmospheric modelling, and has a worldwide reputation for excellence of research in simulation of the Earth's meteorology and climate. AOPP is one of the pre-eminent groups in the United Kingdom for research in many aspects of atmospheric physics, including the design and use of space instrumentation for atmospheric measurements for the Earth and other planets (through collaboration with NASA and ESA), and in data analysis and modelling.

The particular sub-groups within LMD and AOPP concerned with the present proposal have been involved in studies of the Martian atmosphere using large-scale numerical models for more than 5 years, and have been collaborating closely for the past 1-2 years in the development of a suite of comprehensive global circulation models with high spatial resolution and advanced parametrization schemes for a wide range of physical processes. The current version of the model suite comprises a common library of parametrization schemes (developed at LMD and used by both groups) and two types of representation of fluid dynamical processes viz. an advanced gridpoint scheme (developed and used at LMD) and a spectral scheme which represents horizontal fields as truncated series of spherical harmonics (developed largely by Reading University and used at Oxford, with a common heritage to the operational model used at the European Centre for Medium Range Weather Forecasts, and to that used in the UK Universities Global Atmospheric Modelling Program [UGAMP]). The consortium thus employs both the main numerical techniques which are in common use for simulation of the Earth's weather and climate. Both groups are also developing a complementary range of data assimilation schemes, based on methods used operationally for the Earth and intended for use in the analysis of observations to be obtained from future missions to Mars.

For the present project, it is proposed to provide a specific realisation of the joint LMD/AOPP model. Recent studies indicate that the present versions of this model are capable of simulating the atmospheric circulation and surface processes on Mars as realistically as any other model currently available. It is proposed, however, to implement some significant enhancements to the model capabilities in developing the baseline model for delivery to ESA, some details of which are discussed below in Section 2.2.2, and to carry out a more comprehensive optimization and validation of the model performance than has been possible hitherto. It is then proposed to carry out a series of climate simulations jointly by both groups, using the enhanced facilities, which will then form the basis of the required database.

In the following sections, we outline in more detail the tasks envisaged within the proposed project, including the survey and review exercise (Section 2.2.1), the model development and validation (Section 2.2.2) and the database (Section 2.2.3). Financial and management issues are presented in Section 3.

2.2 First iteration of the activities described in the Work Statement

2.2.1 Review on the environmental conditions on Mars

This section is both a first iteration of the review required by the ITT and an introduction to the Martian environment. This review shall be a general survey concerning "all that is known" about the Martian environment. Its scope shall be twofold: (a) we will consider more specifically the data which are of interest for the design and the safety of spacecraft and probes on Mars, and, (b) more generally, the kind of information that should be taken into account for the development of an environmental model and a climate database. These information and data will come primarily from telescopic and spacecraft observations as well as from previous analyses and modelling results.

General information

Such a review should start with general information about the planet : "up to date" facts and figures about the dynamical and physical properties of the planet (orbital characteristics, planetary parameters, etc... ; see Kieffer et al.,1992[1]).

Surface properties

For the review of the geological aspects related to atmospheric environment we will take advantage from the links established between LMD and Philippe Masson (Laboratoire de Geologie Dynamique de la Terre et des Planètes, Université Paris Sud). One of the most impressive aspects of Mars is its large topography, the highest point, Olympus Mons, towering almost 27 km above the mean geoid. The most recent dataset available is the Mars Digital Terrain Model (DTM, Eliason et al., 1991; Davies et al., 1992) but large uncertainties remain concerning the relative altitude of different parts of the planet, and thus on the local surface pressure. From this point of view, landing site selections for instance should consider carefully these large uncertainties. Another topographic map, from the "Consortium" (Mariner 9) is also available. This dataset is

[1] For this first iteration of the review, we do not cite historical papers, but only a selection of "up to date" works or reviews.

somewhat different from the DTM, and, although it is older, it is not clear which one is the best for atmospheric modelling.

For thermal and radiative calculations, which are important for both climate modelling and spacecraft design, we will have to consider surface properties such as ground albedo and thermal inertia of the surface (Kieffer et al., 1977; Paige et al., 1992; Paige and Keegan, 1992) . Here again, we shall lay stress on the range of uses of these data and their uncertainties (Haberle and Jakosky, 1991) .

The physical properties of the ground (particle size, rock abundance, ...) are difficult to measure remotely. Nevertheless, the ground was directly observed around the two Viking Landers, and more general studies have been achieved using orbiter information (Christensen and Edgett, 1994; Simpson et al., 1992) .

Polar caps

A specific review about the permanent and seasonal polar caps shall be provided. On Mars, during the autumn and winter seasons, the local surface and atmospheric temperatures fall to the frost point of CO_2 gas, CO_2 condenses, and seasonal polar ice caps are formed (James et al., 1992) . These seasonal polar caps can extend equatorward to at least 50 degrees latitude, so many potential landing sites are affected. For climate modelling, these condensation processes are of primary importance because, not only do they change the surface properties, but above all they contribute substantially to large seasonal pressure variations at the surface which were observed by the Viking Landers, and create specific atmospheric flows called "condensation flows" (Pollack et al., 1990; Hourdin et al., 1993) .

Aeronomy

We shall review the composition of the Martian atmosphere (Owen, 1992) , and its radiative properties.

Water vapor has its own specific cycle (Jakosky and Haberle, 1992) , creating rare clouds (French et al., 1981) and ground frost, as observed at the Viking 2 site (Svitek and Murray, 1990) .

Airborne dust has a major impact on the Martian environment since it considerably changes the radiative properties of the atmosphere, directly influencing temperatures and winds. The dust composition, size, and optical constants have partially been deduced from observations (Pollack et al., 1979; Clancy et al., 1993) . The spatial and temporal distribution of dust is only partly known from spacecraft and telescopic observations, and is subject to strong interannual variability (Colburn et al., 1989; Martin and Richardson, 1993) . Local dust storms often occur which, some years, extend to the whole planet. These dust storms might well be dangerous for a probe and we shall therefore review the existing data concerning their frequency and probability of occurrence (Martin and Zurek, 1993; Zurek and Martin, 1993) .

Thick CO_2 ice clouds are thought to form in the polar regions. These clouds could have a strong impact on the polar energy balance, and therefore, on the CO_2 condensation rate and the planet's global climate (Forget and Pollack, 1994) .

Given knowledge of the radiative properties of the atmosphere, radiative transfer calculations can be performed in order to provide estimates of the radiative fluxes that have to be taken into account in computing temperatures in an atmospheric circulation model (Hourdin, 1992b) as well as for the design of a probe. In particular, we shall provide information on the ultraviolet (UV) fluxes at the Martian surface, since many kind of instruments can be damaged by this type of radiation.

Meteorology

Spacecraft data have detailed the distribution of surface temperature and have yielded information on atmospheric temperatures, though the temperature field is far from being known systematically from these observations (Leovy, 1982; Leovy, 1985; Martin, 1981; Seiff and Kirk, 1977; Santee and Crisp, 1993) . Direct estimates of wind are extremely sparse for Mars since winds can only be deduced remotely from the rare observations of clouds or from the orientation of aeolian surface features (Kahn, 1983). In-situ local wind measurements were obtained at the Viking Lander sites. Similarly, the two Viking Landers recorded the surface pressure over several Martian years. These pressure measurements contain invaluable information on the global atmospheric circulation. The large amplitude seasonal oscillations of the pressure were due not only to the variations of the atmospheric mass mentioned above but also to internal latitudinal mass redistribution (Hourdin et al., 1993; Pollack et al., 1993) . The more rapid oscillations of the surface pressure were signatures of the transient baroclinic planetary waves which are present, at least in the Northern Hemisphere, during autumn and winter (Barnes, 1981; Barnes et al., 1993) . From such observations, and with the help of GCMs, the main features of the large-scale circulation have been identified (e.g., Zurek et al, 1992). As on Earth, the large scale circulation includes a Hadley-like axisymmetric regime in low latitudes, quasi-stationary planetary waves, and seasonally-varying regions of significant activity due to traveling planetary waves at higher latitudes. The effect of smaller scale components of the flow, like internal gravity waves, must also be considered because of their great potential for altering the large scale flows through momentum transport (Barnes, 1990; Théodore et al., 1993) . Other typical components of the Martian atmospheric circulation, such as large scale atmospheric tides, the condensation flows that we mentioned above, or strong topographic effects should be considered as well (Joshi et al., 1994) . All these components must be taken into account for the design of a space mission. But because of the high variability of the atmospheric system, we shall review more specifically the mechanisms that cause this variability at different scales.

Near the ground, where most probes will have their working environment, the atmospheric environment is characterized by the effect of the Planetary Boundary Layer (hereafter PBL). A good parametrisation of the PBL is also required to model the atmosphere general circulation.

In general, PBL fields cannot be fully resolved from orbit, but the *in-situ* Viking Lander data has been the subject of several important studies (Sutton et al., 1978; Tillman et al., 1994) . In fact, most modelling work for Mars has parametrized the PBL using relationships extrapolated from terrestrial experience, though theoretical models with high-order closure schemes for nonlinear moments (Mellor and Tetsuji, 1982) can now be applied for the study of Mars (Haberle et al., 1993a) .

General Circulation Models

As mentioned above, our relatively comprehensive knowledge of the Martian meteorology is due in large part to the results obtained from atmospheric General Circulation Models (GCMs). The usefulness of GCMs in this particular instance is certainly due in great part to the similarity of the atmospheric circulations of Earth and Mars. As early as the late 1960s, the then recently developed terrestrial GCM of UCLA was successfully adapted to Mars (Leovy and Mintz, 1969) . The same model was gradually improved over the following period, and was later used both for the preparation of the Viking mission and for many studies of Martian meteorology performed at the NASA/Ames Research Center by J. B. Pollack and collaborators (Pollack et al., 1981, 1990, 1993, Haberle et al., 1993b, Barnes et al., 1993).

Since 1989, a new version of the terrestrial GCM of Laboratoire de Météorologie Dynamique in Paris has been adapted to Mars (Hourdin, 1992b, Hourdin et al., 1994). The LMD model was the first self-consistent Martian GCM to simulate the Martian atmospheric circulation over more than a year.

The British Mars modelling effort began in 1990 with a joint project between the Department of Meteorology at Reading University and AOPP Oxford. The project at first concentrated on theoretical research into dynamical processes in the Martian atmosphere using a version of the Oxford spectral GCM that employed the full dynamical part, a highly simplified physical parametrization package (Collins, 1993; Joshi et al., 1994) , and an accurate representation of surface topography (based on the United States Geophysical Survey DTM). This model was further developed in the lead-up to the ill-fated Mars Observer mission, with a view to the application of data assimilation methods for the analysis of remote sounding measurements from the orbiter spacecraft (Lewis and Read, 1994) . In 1993, the Martian physical parametrization package adapted by Frédéric Hourdin from LMD (Hourdin et al., 1993) was interfaced to the Oxford spectral dynamical code, allowing the process-modelling studies that initially used the simplified models to be extended to fully realistic simulations (Collins et al., 1994) .

In connection with the preparation of the Mars Observer Mission, several other teams started their own GCM modelling projects during the years 1992-1993, based on the adaptation of existing terrestrial GCMs, for instance at NASA/GISS (Allison et al., 1993) and GFDL, Princeton (Wilson, 1993) . Since the demise of Mars Observer, however, the fate of these efforts remains uncertain.

These various modelling efforts will be systematically and critically reviewed.

2.2.2 The Martian atmospheric General Circulation Model

Introduction

One of the two major objectives of the present proposal is the improvement and validation of an atmospheric General Circulation Model (GCM) of the Martian atmosphere. This model will be used on the one hand for the generation of a complete atmospheric database which will be provided to ESA. On the other hand, we will provide a user-friendly version of the GCM which ESA may use to perform series of supplementary numerical experiments to prepare future Martian missions.

GCMs are classical tools for the study of the terrestrial atmospheric circulation, both for weather forecasting and for climate studies. Schematically, atmospheric GCMs consist of two parts:

(1) The "dynamical part" is dedicated to a temporal and spatial integration of the hydrodynamical equations for the explicitly resolved scales (generally of the order of few hundred km in the horizontal for classical terrestrial applications). Terrestrial models are generally based on the "primitive equations of meteorology" (e.g., Holton, 1979) which are valid for Earth-like planets (a solid body covered by a shallow atmosphere assumed to remain vertically in hydrostatic balance). This part of the code can thus be used for various different planets by simply changing appropriate parameters such as the gravitational acceleration, rotation rate or certain boundary conditions such as the specification of the surface orography.

(2) The "physical part" is dedicated to the diabatic forcing of the atmospheric circulation by radiative and other processes, and to the modelling of sub-grid scale processes. This part must be significantly modified depending on the planet under consideration.

For Mars, in addition to previously existing dynamical codes developed for terrestrial studies, we already have a rather complete and relevant physical package. We will thus concentrate on the tuning and validation of existing models in addition to a few model developments and refinements.

The pre-existing Martian GCM

For several years, two European teams have been involved in independent efforts to model numerically the global atmospheric circulation of the Martian atmosphere.

The first model was developed in 1989 at LMD, based on the finite-difference dynamical model developed and used at LMD for climate studies (Sadourny and Laval, 1984) . A full set of physical parametrizations was specifically developed or adapted to Mars. Around 1990, a similar kind of activity was started jointly at Reading and Oxford, in which a simple spectral dynamical model, originally used for the Earth, was adapted for idealised model studies of the Martian atmosphere, and in the development of a data assimilation scheme. In 1993, the LMD and Oxford teams decided to join their efforts in closer collaboration, and the physical package of LMD has now been successfully interfaced with the Oxford spectral dynamical code.

Thus the numerical tool we intend to use as a basis for the present proposal is an ensemble composed of a common Martian physical package and of two dynamical codes: the finite-difference model of LMD and the spectral solver. This suite of models is described in details in Appendix A. This is especially attractive since the two dynamical codes in fact cover the range of existing dynamical model types as employed in the global modelling of atmospheric circulations (for Earth as well as for Mars; cf. the AMIP project). By using both versions of the dynamics in the generation of the database, we will not only provide information on the variability of the Martian atmospheric circulation as produced by a given GCM, but also an estimate of the likely uncertainty arising from modelling errors.

Note that in addition to the explicit representation of the large scale dynamics, the two dynamical codes include similar representations of the non linear exchanges between resolved and unresolved (subgrid-scale) motions.

The LMD physical package includes:

1. an efficient radiative transfer scheme adapted from the one developed for the LMD climate model by Fouquart and Bonnel (1980) and Morcrette et al. (1986) and later-on introduced in the operational code of European Centre for Medium-Range Weather Forecasts (ECMWF). The original terrestrial code already included the representation of scattering and absorption of visible sun-light by dust. Particular care has been given to the accurate representation of absorption and emission by carbon dioxide and dust in the thermal infrared (Hourdin, 1992b) . This part of the code has been very carefully validated by comparisons with line-by-line computations up to 70 km altitude (Hourdin, 1992b) .

2. a simple but physically-based parametrization for the representation of turbulent mixing has been adapted to Mars from the planetary boundary layer scheme of the LMD climate GCM. The efficiency of the mixing depends on both the vertical wind shear and the vertical static stability of the atmosphere. The model also includes a simple parametrization for convection where unstable vertical temperature profiles occur.

3. an energy balance model at the surface, including an 11-layer model of thermal conduction in the soil which allows accurate computation of the response of the surface temperature to oscillatory forcing with periods ranging from a fraction of a day up to a few Martian years.

4. a simple zero-order parametrization for the condensation and sublimation of carbon dioxide.

Model improvements

The main improvement of the currently existing model will be the increase of its spatial resolution. The LMD model has been extensively used (in a multi-annual simulation and in a number of one-year simulations) at a very low horizontal resolution with 32 points in longitude and 24 points in latitude. A few one-year simulations have also been performed with a higher resolution: 64 longitudes and 48 latitudes. The Oxford dynamical code has been mainly used with a T21 truncation (a triangular truncation of spherical harmonics with a maximum total wavenumber of 21) which may correspond to an intermediate resolution of the LMD grid-point model. The resolution we need to fulfill the ESA requirements is much higher. We intend to perform test simulations with 96 longitudes $\times$ 48 latitudes and 128 longitudes $\times$ 64 latitudes for the LMD finite-difference dynamics. For climate integrations the Oxford spectral code will be run principally using a T42 truncation. This corresponds to a dynamical grid of 128 $\times$ 64 points for calculating the nonlinear interaction terms and 96 $\times$ 48 points for calculating contributions from the physical parametrization schemes, and is effectively intermediate between the LMD resolutions (the maximum grid spacing for the coarser physical grid at this resolution is about 225 km at the equator). It is also feasible to run the Oxford spectral code at a higher resolution (T63) which gives a physical grid close to the higher LMD resolution and a dynamical grid of 192×96 points, although the computational cost is significantly increased.

The direct impact of increasing the horizontal resolution is that it gives better information on the local atmospheric conditions. It may also strongly influence the large scale dynamics and variability, especially because of the more accurate representation of the surface orography (e.g. Joshi *et al.* 1994). The model coverage will also be extended in height to 70 km; some additional viscous layers may be required above 70 km to act as a 'sponge' and absorb vertically propagating waves before they reflect from the model lid. Tests must also be performed in order to ensure that the required vertical discretization based on 20 layers (plus up to 5 'sponge' layers) is well suited for the generation of the atmospheric database.

We also intend to improve the existing model by developing and introducing two new parametrization schemes.

We first plan to introduce a parametrization for the effects of gravity waves on the large scale dynamics. It has been suggested by Barnes (1990) that, as in the case of the terrestrial atmosphere, gravity waves with horizontal scales of order 10^2-10^5 m are excited in the lower atmosphere by various processes, including topographic interactions, fronts and local instabilities. These waves may propagate vertically, and grow in amplitude as the ambient density decreases at high altitudes, finally breaking and depositing their horizontal momentum at upper levels. Such effects have been observed directly in the Earth's atmosphere, and it is now widely accepted that gravity waves exert a strong influence on the momentum budget of the large-scale circulation. The parametrization of such momentum deposition has lead to significant improvements in the climate simulations of terrestrial global circulation models (e.g., McFarlane, 1987).

Similar effects have also been inferred in the atmosphere of Mars (Theodore *et al.* 1993), where high altitude temperature inversions have been attributed to the effects of breaking gravity waves, possibly excited by interactions with the massive underlying topography. Joshi (1994) has recently carried out a feasibility study of the effect of a modified form of the well known Lindzen parametrization scheme for topographically-induced gravity wave drag (Lindzen, 1981) in a simplified version of the AOPP GCM, and obtained some encouraging initial results. Accordingly, we propose to develop a further modified version of this scheme for inclusion in the joint LMD/AOPP physical parametrization package, and to validate it against ground-based observations e.g. of Theodore *et al.* (1993).

We also plan to test simple parametrizations for the CO_2-ice clouds. Until now, we have assumed in our Martian model that all the CO_2 ice-crystals formed in the atmosphere instantaneously precipitate onto the surface. It is, however, much more plausible that those crystals form CO_2-ice clouds, as suggested by thermal infrared observations from spacecraft. These clouds are thought to have a strong impact on the thermal balance of the polar regions and the thermal atmospheric structure, reducing the amount of CO_2 that condenses during the autumn and winter seasons (Forget and Pollack, 1994) .

In view of the very poor knowledge and few observations we have of the Martian CO_2-ice clouds, the parametrization to be developed must be as simple as possible. Nevertheless, we plan to simulate the condensation and possible sedimentation or sublimation of the CO_2 ice particles in the GCM. This treatment will be based on the calculations of the condensation rates of the CO_2 in the cold polar atmosphere by the GCM and on cloud microphysical considerations. We shall also derive a simple parametrization of the simulated polar cloud radiative properties from thermal infrared observational analyses.

In order to fulfill the ESA requirements, we will also develop special tools for the representation of small-scale turbulent motions. In fact, the model in its present state already computes estimates of the turbulent kinetic energy in the PBL which is directly related to the intensity of the subgrid-scale motions. One additional development in that respect could be the inclusion of a more sophisticated parametrization including a prognostic equation for the turbulent energy such as that developed for terrestrial oceanic and atmospheric models by Mellor and Yamada (1974) (see also, Mellor and Tetsuji, 1982; Myakoda and Sirutis, 1977) .

Choice of parameters and tuning

The Martian atmospheric general circulation model of course depends on a number of parameters and boundary conditions (surface orography, visible albedo and thermal inertia) some of which are only poorly constrained from observations. We will take care in the choice and tuning of those parameters, taking advantage of the extensive work which has already been conducted at LMD on the sensitivity of the Martian model to some of the uncertain parameters (Hourdin et al., 1994) . Without going into the detail of each parametrization, we would like to underline some of the major problems and the solutions we propose.

1. The ITT requires the use of the DTM orography data-set which is generally used as a basis for the preparation of spacecraft missions (it is in particular preferred to the older Consortium data-set). However, the DTM orography is not without problems: for instance, the DTM altitude of the Viking 2 landing site is higher than that of Viking 1 in contradiction with the local pressure measurements. Infrared measurements on the caps also suggest surface temperatures on the condensing caps compatible with much more elevated terrains than given in the DTM data-set (Forget and Pollack, 1994) . The choice of a surface orography is crucial in the determination of the surface pressure which can be essential for the preparation of in-situ missions. We think that it is important for the purpose of this proposal to perform a sensitivity study to the surface orography (comparing the results produced with consortium and DTM data-sets).

2. The choice of the optical parameters for the dust will be made after an extensive review of the existing and often contradictory literature.

3. The simple scheme to be develop for CO_2-ice clouds will, of course, depend on a number of parameters, some of which will be tuned in order to fit the Viking IRTM fluxes which were analyzed in detail by Forget and Pollack (1994).

4. The scheme developed for gravity waves will also require tuning and validation (Joshi et al., 1994) .

5. Finally, we propose to take advantage of the strong sensitivity of the mass budget of the polar regions to the albedo and emissivity of the polar caps to fit the annual

surface pressure variations observed by the Viking landers, following a procedure described by Hourdin et al. (1994).

Test-plan and model validation

A first test which must be performed with the GCM is its ability to run over a long period. Generally speaking this is not a problem for GCMs. Long period simulations will be performed with the resolution chosen for the atmospheric data-base. A series of shorter term simulations will also be performed with a 150 km horizontal resolution at different seasons.

In addition to the tuning of parameters presented above, we intend to perform a series of comparisons of the model with existing data. The variability of the surface pressure will be compared to the Viking pressure measurements. Results of simulations will be compared with the temperatures retrieved from the available orbiter infrared measurements, especially from Mariner 9 as representing the only ones to have a significant vertical resolution in the atmosphere, and to the Viking IRTM flux measurements (which contain information on the surface temperature and will be used in particular to validate the model in term of its diurnal cycle).

Version of the model to be delivered to ESA

The model to be delivered to ESA will be extracted from the ensemble of codes presented above. It will mainly consist of the LMD grid-point dynamics and physical package with the improvements presented above.

The ITT requires initial states at four different seasons. First we propose to increase the seasonal sampling by delivering initial states for about 12 different dates of the year. In addition, we propose to deliver for each of those dates not only one initial state but a series (~ 10) of initial states taken from the multi-annual simulations. This will allow the potential user of the GCM at ESA to perform a series of simulations at a given date and estimate the variability of the results.

The initial states will be provided at the model resolution retained for the data-base. A tool will be provided allowing for an automatic initialization of the run for any (coarser or finer) resolution. The model is also designed in such a way that the grid can be automatically refined on a selected area ('zoom') which may be of particular interest for the preparation of *in-situ* missions. The 'zoom' facility is presently under validation at LMD for terrestrial applications. It allows the user to stretch the grid by a factor of up to about three in each direction, which would enable the model to easily resolve horizontal scales of order 100 km on Mars. If present validation tests show that the zoom facility works satisfactorily, it will be included in a user-friendly manner in the GCM which will be delivered to ESA.

The model is entirely managed under classical UNIX tools (shell scripts, make ...) and it already runs on SUN and HP workstations as well as on CRAY-2 and CRAY-98. The standard input-output include instantaneous and time averaged pressure, temperature and wind components (to which density, which is a combination of pressure and temperature, could be added if required by ESA), and a number of physical diagnostics such as radiative fluxes. All the input and output use the Data-Retrieval-System

(DRS) developed by the Lawrence Livermore Laboratory for the Atmospheric Model Intercomparison Program (AMIP).

2.2.3 The Martian Climate Database

The project requires the production of a database intended to represent (a) the time-mean state of the Mars atmosphere and environment and its geographical variations, (b) its seasonal variations and estimates of intraseasonal variability on space and time cales ranging from the meteorological 'synoptic' (near-planetary) scale to the small scales typical of boundary layer turbulence. An extension, which we consider as necessary for the reliability of the database, is to include estimates of the interannual variability of the atmosphere. The database is primarily required within the present project to provide information useful for the planning of future spacecraft missions to Mars, which may entail the deployment of instrumentation on or near the Martian surface as well as remote-sensing from Mars orbit.

In order to enable the production of meaningful statistics, it is proposed to carry out a series of full climate simulations of the Martian atmosphere using relatively high resolution versions of the GCM model suite developed by our groups in Paris and Oxford. Because of the differing, but equally valid, behaviour of the two dynamical schemes available to us (gridpoint and spectral representations), we consider it highly desirable in estimating dynamical variability to carry out two parallel simulations for each case, both of which use the same physical parametrizations but with gridpoint or spectral computation of model dynamics. The gridpoint model will comprise the baseline model at roughly 250 km horizontal resolution with approximately 20-25 vertical levels, and the physical parametrizations produced for WPII. The spectral version will use the same physical parametrizations but the Oxford spectral dynamical solver (at comparable spatial resolution to the gridpoint code).

Note that the resolution proposed here for the database is somewhat less than specified in the ITT. This is proposed in order to keep the computational demands (in terms not only of computer time, but also of data storage and manipulation requirements) to within reasonable bounds, given the time and resources available for the project. It should be noted that a resolution of 250 km is comparable with the highest resolution typically used for climate simulation experiments using GCMs in the Earth's atmosphere, as represented e.g. in the AMIP project.

We propose that the simulations to form the basis of the database should comprise the following cases or scenarios:

(i) A simulation of several Mars years duration using both model versions, in which the full diurnal and seasonal cycle of insolation will be represented, and in which the atmospheric dust loading remains relatively small (though varies with season in a manner suggested from observations?) as typical of 'clear atmospheric conditions'.

(ii) A similar pair of simulations of several Mars years duration, but for conditions typical of relatively dusty conditions (though again varying with season).

(iii) A series of 10-15 simulations of a single season, each with differing initial conditions from scenario (ii), in which the atmospheric dust loading is maintained as typical of a global dust storm. The season chosen will correspond to that at which global dust storms are most prevalent in observations (i.e. Southern Hemisphere summer).

The data generated from each simulation consists of a "history file", which typically comprises a series of instantaneous "snapshots" of all main meteorological variables (3 wind components, temperature, geopotential height and surface pressure) recorded on the 3D model grid at least 6 times per Martian day (perhaps more frequently over shorter intervals, e.g. to capture the diurnal cycle), and certain variables relevant to the physical parametrizations (CO_2 ice mass and extent etc.), recorded at more infrequent intervals, compatible with their intrinsic variability. This is expected to result in history files of $\sim$ 5-10 Gbyte per 1 year simulation at the proposed resolution which, for a 5-10 year run, is close to the limits of present workstation technology for convenient storage and access. Further increases in resolution to below 200 km would increase this data storage and manipulation requirement by a factor of at least 1.5, which is considered here to be impractical without making undesirable compromises on the duration of each simulation.

What we propose to deliver to ESA is a set of statistics, computed from the history-files, which summarise the mean and seasonally-varying states of the simulated Mars atmosphere and surface environment in a more manageable and accessible form. Although the detailed design of the database is to be the subject of a study within the present project, we outline below a baseline concept which may be taken as a starting point for the proposed study.

For each dust scenario (i) and (ii), we propose to divide the Mars year into 8-12 distinct 'seasons', as represented by equal intervals of L_s [2]. For each season (including the dust storm scenario (iii)), mean maps (in the form of grid-point arrays in latitude, longitude and height at the model resolution) will be obtained by averaging respectively over the entire season and over the 10 year ensembles of simulated seasons. Variables to be recorded will include atmospheric pressure, temperature, density and wind velocity, together with the assumed dust distribution and simulated cloud cover. Horizontal maps of surface properties (temperature, CO_2 ice cover.....) will also be included.

For the estimates of variability, maps on a similar grid as above will be obtained which represent at least the variance of each of the above mean statistics (and perhaps other measures of variability to be determined) for each season. Such variances may be computed for several ranges of time-filtered timescales, including diurnal timescales (tides etc.), synoptic (meteorological or 'weather') timescales (1–50 days?), dust storm periods ($\sim$ 60 days) and interannual timescales (i.e. between seasonal means in different years). The requirement to evaluate small-scale variability on scales not explicitly resolved by the model will be addressed by computing maps of suitable variances inferred from the physical parametrization schemes used in the model itself, including boundary layer variability and topographically-induced gravity wave activity.

It is proposed to provide the above data (a) in machine-readable form (using the Data Restrieval System of the AMIP programme), for display using simple graphics packages, and (b) in document form, including both summary numerical tables and graphical contour maps (e.g. of means and variances in latitude-longitude or latitude-height sections) in a form similar to that produced for the climate of the Earth (e.g. see Hoskins et al. 1989). The document may take the form of a technical note, and would include a description of the simulations, a general commentary on the database and a critical comparison of the derived statistics with the MARS-Gram model and

[2] L_S is the longitude of the sun in Mars centered coordinates (areocentric longitudes). It is used as seasonal index with $L_S = 0$ at northern vernal equinox.

other existing engineering models of the Mars environment.

2.3 Study plan

The study plan is illustrated in Fig. 2.1 and commented in the present section.

Specifications

In addition to the review, the study must begin with specifications for the GCM (including test-plans) and for the climate database.

Development

After that, three kind of software packages must be developed:

1. new parametrizations for the GCM (clouds, gravity waves scheme, boundary layer)

2. tools for the validation and tuning of the GCM.

3. tools for computing appropriate statistics and building the database from the history files produced with the GCM.

The validation and tuning of the GCM will be concomitant with the implementation of model improvements (new developments can be added or even removed depending on the improvement in term of comparisons with existing data). This validation-tuning phase requires a series of simulations ("Test simulations"), including a few simulations with a full seasonal cycle in order to tune the annual cycle of the surface pressure (Hourdin et al., 1994) . Those simulations will be used at the same time for the development and test of the diagnostic tools intended for the database production.

Production

For the production of the database itself, we must perform a series of multi-annual simulations with various dust-scenarios. Those simulations will be very expensive in term of CPU and storage (for the history files). Part of the diagnostics will be run immediately after the simulations.

The final part of the project will also include the development of the software package necessary for an easy use by ESA of the model and the production of the ensemble of initial states.

2.4 Compliance statement

The contractors undertake to follow all the requirements of the ESA Work Statement of ITT A0/1-2798/94/NL/JG with the reservation that the horizontal spatial resolution for the database is proposed to be not less than 250 km at the equator.

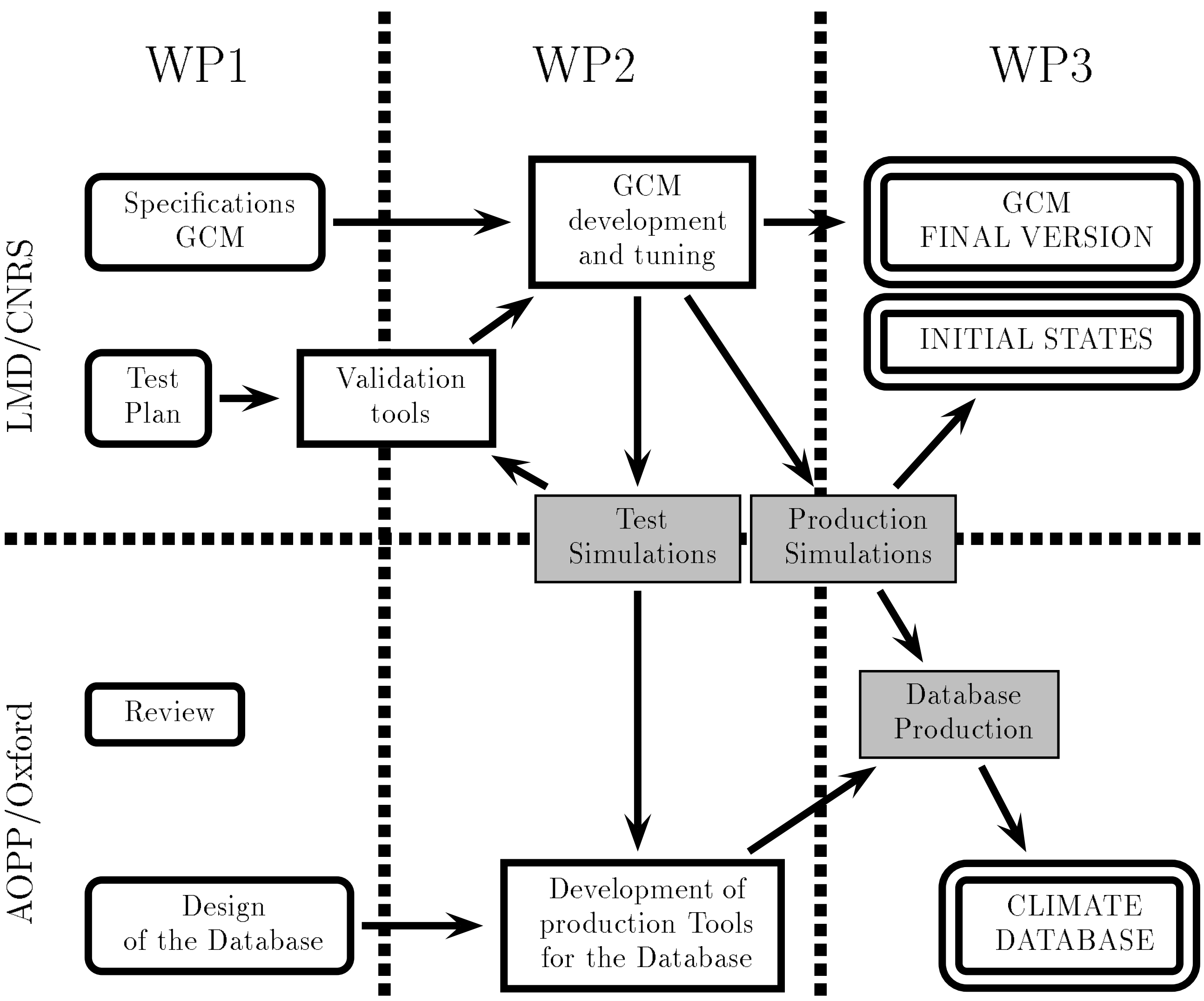

Figure 2.1: Flow chart for the study plan.

3 Content of the financial, management and administrative proposal

3.1 Background experience

3.1.1 LMD/CNRS

Laboratoire de Météorologie Dynamique has acquired a very broad experience in all domains of atmospheric dynamics, particularly as concerns numerical modelling of atmospheric circulation, assimilation of observations, and planning and preparation of spacecraft missions, which are all topics of primary importance for the present proposal.

Numerical modelling of the atmospheric circulation is organized at LMD around a General Circulation Model developed under the scientific direction of R. Sadourny (Sadourny and Laval, 1984) . At present, the research group devoted to that activity comprises about thirty persons, among which nine are permanent scientists and about ten are visitors or (doctoral or post-doctoral) students. The model, described in more detail in Appendix A, has been used for many years for a large number of diverse studies of the climate of the Earth and of its past and possible future variations. Among the more recent of these studies, one can mention particularly the impact of moisture and clouds on climate, and the representation in GCM's of the corresponding processes (Li and Le Treut, 1992) , the greenhouse effect, both in its natural and possible anthropogenic aspects (Bony et al., 1992; Le Treut et al., 1994) , the physics of the planetary boundary layer and the interaction with surface processes (Polcher and Laval, 1994; Chalita and Le Treut, 1994) , and the impact on climate of the past fluctuations of solar irradiance (Nesme-Ribes et al., 1993) . A "zoom" facility, through which the resolution of the model can be increased at will over a prespecified region of the Earth, and similar to what is required in the Invitation to Tender, has been developed, in cooperation with the Centre for Atmospheric Sciences (IIT, Delhi, India), in order to study the Indian monsoon (Sharma et al., 1987) . Harzallah and Sadourny (1994) have performed a nineteen-year integration of the model, intended as a detailed study of the interannual variability of the terrestrial atmospheric circulation, also in a way very similar to what is required for Mars in the Invitation to Tender.

The LMD GCM is used for cooperative projects with a number of other groups, in France and abroad. In addition to the aforementioned Centre for Atmospheric Sciences in Delhi, the LMD model is used, for different purposes, by Electricité de France (Chatou, France), Laboratoire de Modélisation du Climat et de l'Environnemment (Saclay, France), Laboratoire de Glaciologie et Géophysique de l'Environnement (Grenoble, France), Institut d'Astronomie et de Géophysique Georges Lemaitre (Louvain-la- Neuve, Belgium) and Centro de Investigaciones del Mar y la Atmosfera (Buenos-Aires, Argentina). The "physical package" of the Martian version of the model has been introduced, as explained in 2.2.2, in the Martian model of the Atmospheric, Oceanic and Planetary Physics group of Oxford University, cocontractor to the present proposal. Close continuous cooperation is maintained with Laboratoire d'Océanographie Dynamique et de Climatologie (Paris), as well as with other research groups in oceanography, on the fundamental questions of the interactions between the atmosphere and the ocean, and of the development of coupled GCM's. Finally, the LMD GCM is one of the 29 models whose performances have been submitted to systematic comparison within the Atmospheric Model Intercomparison Program.

Concerning the atmospheres of the other planets, our first study was carried out with the LMD GCM by Tourte (1984) on the superrotation of the Venusian atmosphere. That work showed the basic role played by the Hadley circulation in the maintenance of the superrotation. More recently, and mostly as part of the doctoral thesis of Hourdin (1992a), the model has been adapted to Mars and Titan, while a "parameterized" version of the model, in which the atmosphere to be studied is defined by the specification of 19 parameters, was simultaneously developed. The Martian model required the development of an appropriate radiative code (Hourdin, 1992b) . Being built, as the terrestrial model, upon fundamental physical principles, it contains no *ad hoc* processes intended, for instance, to avoid long term drift from observations. It is the first GCM to have simulated a complete Martian annual cycle, and shows excellent agreement with the available observations. Among the conclusions that have been obtained from studies performed with the LMD Martian model, one can mention the fact that the observed large amplitude seasonal variations of the surface pressure are not only due to condensation and sublimation of the atmospheric gas into the polar caps, but are also modulated by latitudinal redistribution of mass, associated with purely dynamical and thermal orographic effects (Hourdin et al., 1993) . As for the Titan version and the parameterized version of the LMD GCM, they have been applied to the study of the phenomenon of superrotation, for which a consistent interpretation, which confirms and completes an explanation first suggested by Gierasch (1975), has been obtained. The parameterized model is capable to produce a superrotation, starting from a state of rest and without ad hoc forcing. The development and the use of the various planetary versions of the LMD GCM, in addition to their intrinsic scientific interest, have provided the opportunity for a number of improvements which have been incorporated in the terrestrial version of the model (concerning particularly the conservation of angular momentum and the representation of thermal soil processes), as well as for major programming reorganization and for development of numerous tools for diagnostic and visualization.

Assimilation of observations is also an active field of research at LMD, under the direction of O. Talagrand, who is a leading specialist in that domain. The work done at LMD on assimilation has so far been centred on the study of theoretical methods for assimilation. LMD in particular has played a major role in the definition and study of variational assimilation, based on the use of the adjoint equations of the assimilating model, and which allows one to take into account exactly the dynamics of the atmosphere, as described by the assimilating model (Courtier and Talagrand, 1990, Talagrand, 1993). Variational assimilation is now being developed for operational purposes in several major meteorological centres, in particular Météo-France and the European Centre for Medium Range Weather Forecasts (Reading, England). The expertise acquired at LMD on assimilation of observations puts it in a very favorable position for developing assimilation procedures appropriate for observations of the Martian atmosphere.

LMD has long been associated with the preparation of spatial missions and with the exploitation of the data they have produced. It is one of the about 10 french "spatial laboratories" which receive special support from Centre National d'Etudes Spatiales. In recent years, LMD (R. Kandel) has had the scientific responsability for the Franco-Russian ScaRaB project, intended at accurately measuring the global energy balance of the Earth. The ScaRaB instrument, built at LMD, was launched in January 1994, and LMD has now begun exploitation of the data. A series of ScaRaB instruments will follow, some of which are planned for the ESA ENVISAT and METOP missions.

F. Hourdin and F. Forget, coauthors to the present proposal, are both associated with the preparation of future space missions. F. Hourdin is involved in the preparation of the joint ESA/NASA Cassini-Huygens mission and, in particular, he has been invited several times to the meetings of the "Huygens Science Working Team" and to the "Atmospheric Working Group" of the Cassini mission. F. Forget has been closely associated with the studies performed by Centre National d'Etudes Spatiales on the definition of a balloon flight in the atmosphere of Mars, and with preliminary studies for the NASA Pathfinder project (Forget et al., 1994) .

3.1.2 AOPP/Oxford

The Atmospheric, Oceanic & Planetary Physics sub-Department within the Department of Physics at the University of Oxford is engaged in an extensive research programme which includes the design and operation of space instrumentation for the measurement of the structure and composition of planetary atmospheres, a wide range of theoretical and numerical atmospheric and oceanic modelling and fundamental studies of nonlinear processes in geophysical fluid dynamics and other areas of physics.

AOPP has been the leading university research group in the UK for more than 20 years in the development of space instruments for the infrared remote sensing of atmospheric structure, especially of the Earth's stratosphere and mesosphere. These instruments are typically built in collaboration with a number of international partners, and flown as part of much larger missions mounted by NASA and ESA. Ten of these instruments are already in space: seven in Earth orbit, one orbiting Venus and others have been launched to Jupiter and Mars. The instrument group pioneered the 'pressure modulation radiometry' technique in the 1970s, which has been successfully employed in a number of advanced instruments including the 'Improved Stratospheric And Mesosphere Sounder' (ISAMS) which flew on the NASA Upper Atmosphere Research Satellite (UARS) in 1991. The group also took a leading role in the design and calibration of the Along Track Scanning Radiometer (ATSR) which flew on ESA's ERS1 mission in 1991. The group is also involved in the development of new space experiments to form components of future missions, including Earth-orbiting remote sensors to form part of the NASA Earth Observing System, and the Composite InfraRed Spectrometer (CIRS) on board the ESA/NASA Cassini-Huygens mission to Saturn and Titan (for which Prof. F. W. Taylor and Dr P. L. Read are Co-Investigators). The group had a leading role in the development of the Pressure Modulator Infrared Radiometer (PMIRR) experiment on board the NASA Mars Observer mission (with Prof. Taylor as Co-Investigator and Dr Read as Participating Scientist), with the aim of measuring temperature, humidity and dust in the atmosphere of Mars. Since the failure of the Mars Observer spacecraft in 1993, a new version of PMIRR is under development for reflight at a future date.

AOPP is also involved in a wide range of numerical modelling activities, largely aimed at interpreting the types of satellite measurement obtained from the spacecraft instruments developed in-house. Three distinct sub-groups are currently active in this area.

(1) The ocean modelling group has developed a variety of models, in collaboration with scientists at the Hadley Centre for Climate Prediction and Research at the UK Meteorological Office, for studying the interaction between the Earth's atmosphere and oceans. Emphasis is currently placed on studying such interactions in the tropical regions, particularly over the Pacific ocean, where they give rise to "El Niño" conditions which lead to climate variability on timescales of a few months to a few years. The models used range from fully-comprehensive models of the atmosphere and oceans to models of intermediate complexity that retain only the essential physics, and the objectives of this work are directed towards investigating the predictability of the tropical ocean-atmosphere system.

(2) The middle atmosphere modelling group works with a range of large-scale numerical models of the Earth's stratosphere and mesosphere, in collaboration with the UK Universities' Global Atmospheric Modelling Programme (a national research programme involving several university groups within the UK, coordinated and funded through the UK Natural Environment Research Council) and the Meteorological Office. The models used include both simple fluid dynamical systems with simplified physics and fully comprehensive GCMs which represent the dynamics, radiative processes and chemical transport of the observed middle atmosphere in considerable detail. The main aim of this programme is to elucidate the dynamics and physics of the middle atmosphere, including studies of ozone depletion and the greenhouse effect, particularly with reference to observations obtained from space instruments such as ISAMS. In this context, the group is also involved in efforts to assimilate such observations into GCMs through collaboration with the UK Meteorological Office, who have implemented a version of their operational Analysis Correction scheme (as used for routine weather prediction in the troposphere) for use in the stratosphere and mesosphere.

(3) AOPP has also been involved in theoretical and modelling studies of the atmospheres of planets other than the Earth for more than 10 years. Early studies of this type were typically aimed at developing an understanding of particular processes (radiative, dynamical etc.) in the atmospheres of Venus, Mars, Jupiter, Saturn and Neptune. The first dynamical studies were carried out in the early-mid 1980s by Dr S. R. Lewis and Dr P. L. Read (then working at the UK Met. Office), and made use of a range of simple numerical models to study large-scale coherent oval eddies in the atmospheres of Jupiter, Saturn and Neptune. This work led to the formulation of new hypotheses concerning the role of thermodynamical processes in the maintenance of long-lived eddies such as Jupiter's Great Red Spot. Later, X. Li (1993) investigated the possible role of equatorially-trapped planetary waves in driving cyclic oscillations of wind and temperature in the upper atmospheres of Jupiter and Venus, again using highly simplified models. This study demonstrated the feasibility of this process in accounting for an observed oscillation with a period of 4 years (the so-called Quasi-

Quadrennial Oscillation, Leovy et al. 1991) in the atmosphere of Jupiter.

AOPP's involvement in the large-scale modelling of the Martian atmosphere began in 1990, when a joint project, lead in Oxford by Dr P. L. Read, was started in collaboration with Dr I. N. James at the Dept. of Meteorology at the University of Reading with the aim of developing a range of simple GCMs aimed at studying dynamical processes (baroclinic waves, topographic effects and gravity wave drag) in the atmosphere of Mars. The models used were based on the spectral dynamical code for solving the primitive equations of dynamical meteorology in a spherical atmosphere, originally developed at Reading University by Hoskins & Simmons (1975) and used by I. N. James (James & Gray 1986; James 1994) for idealized studies of the circulation of planetary atmospheres. This code was adapted for Mars by including the full USGS DTM topography in the lower boundary condition, and using simple parametrizations of diabatic and other physical processes to relax the flow towards a realistic Martian 'climatology', and was run at resolutions up to T42 in the horizontal (see above). Studies using this model by M. M. Joshi (AOPP) and M. Collins (Reading, now at AOPP) resulted (a) in the identification of equator-crossing low-level jets, located on the western flanks of major topographic features on the Martian surface, as a form of western boundary current (and hence akin to certain major coastal currents in the oceans; Joshi et al. 1994), (b) in the discovery and elucidation of a highly regular and predictable regime of baroclinic planetary waves, bearing on interpretations of the near-periodic behaviour observed in time series from the Viking Landers (Collins 1993), (c) in elucidating the propagation and structure of topographically-forced planetary waves (Collins 1993; Joshi 1994), and (d) in the development of a prototype topographic gravity wave drag scheme for Martian models (Joshi 1994).

Most recently, under the leadership of Dr P. L. Read, the group has been involved in the development of facilities (i) to realistically simulate the atmospheric circulation of Mars, by enhancing the aforementioned spectral model with a comprehensive package of physical parametrizations (obtained as part of our collaboration with LMD), and (ii) to assimilate past and future observational data from Mars into our Mars GCM. With the successful implementation of the LMD package into our spectral model, completed at the end of 1993 with the assistance of Dr Hourdin of LMD, a number of new studies have now begun, including an investigation of the role of diurnal effects in decreasing the intrinsic predictability of baroclinic transient planetary waves (Collins et al. 1994).

The assimilation scheme under development is based on the Analysis Correction scheme used operationally by the UK Meteorological Office (Lorenc et al. 1991), which was provided through collaboration with Dr A. Lorenc of the Meteorological Office. This scheme has been in successful operational use at UKMO for several years, and represents a more pragmatic and traditional approach than the variational schemes currently under development at LMD, neatly complementing Dr Talagrand's efforts in this area. To date, the scheme has been implemented and tested by Dr S. R. Lewis in Oxford using simple versions of our spectral GCM, and successful assimilations of test data obtained from runs of other versions of our model have been achieved (Lewis & Read, 1994). By adapting an operational weather prediction scheme already in use for the Earth, the scheme retains the ability to assimilate any kind of data obtained from both satellite instruments and *in situ* measurements. The aim of the present work is to evaluate the assimilation scheme and model by attempting to assimilate data obtained from past missions to Mars (notably the IRIS temperature measurements from Mariner 9), and to make preparations to participate in the data analysis effort for future missions to Mars such as the NASA Mars Surveyor orbiter.

3.2 Organisation and management

The project will be organised as two parallel contracts between ESA and both CNRS and Oxford University.

3.2.1 Structure of organizations

LMD/CNRS organisation

LMD is a laboratory of the Centre National de la Recherche Scientifique (CNRS). Its staff of about 140 persons is located in two sites: 60 persons in Paris (ENS/Jussieu) and 80 in Palaiseau in the suburbs of Paris (Ecole Polytechnique). The present project would be done entirely at ENS in Paris. The main activity of LMD/ENS is centered on the development and use of a climate GCM for terrestrial and planetary applications.

The structure of LMD with the position of the key personnel for the present proposal is illustrated in Fig 3.1.

AOPP/Oxford organisation

The Atmospheric, Oceanic & Planetary Physics group is one of six semi-autonomous Sub-Departments within the Department of Physics at the University of Oxford. In addition to its contribution to the teaching of physics in the University, AOPP is engaged in an extensive research programme which includes the design and operation of space instrumentation for the measurement of the structure and composition of planetary atmospheres, a wide range of theoretical and numerical atmospheric and oceanic modelling and fundamental studies of nonlinear processes in geophysical fluid dynamics and other areas of physics. AOPP currently consists of about 90 members, including 11 permanent academic or research staff, some 20 post-doctoral researchers and senior visitors, over 30 graduate students (engaged in doctoral research) and about 20 technicians and support staff.

The structure of AOPP within Oxford University, and the positions of the key personnel named in this proposal, are shown in Fig. 3.2.

3.2.2 Management plans

Dr. O. Talagrand will be responsible for the management of the whole project, and for the management of the LMD/CNRS group. Dr. Peter Read will be responsible for the management of the AOPP/Oxford University group.

Managerial decisions, including in particular detailed assignment of tasks between the two contracting groups and detailed definition of the time schedule, will be taken on the occasion of the regular technical progress meetings required by Appendix 1 to the ITT. The scope of these meetings will therefore be larger than strictly required by the ITT. All relevant clauses of Appendix 1 to the ITT, and in particular clause 3.2.1 relative to the preparation and distribution of minutes, will apply to these meetings.

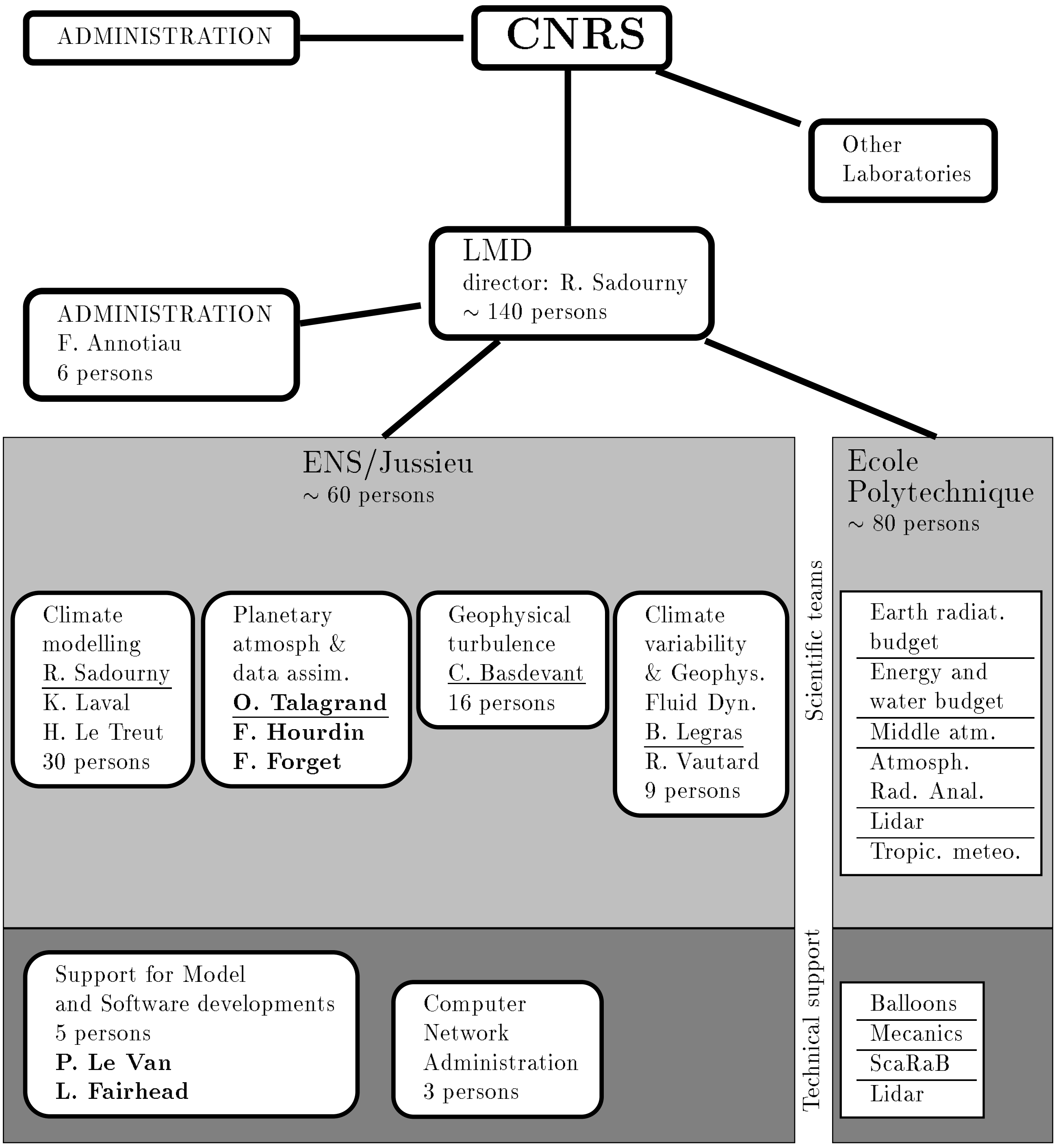

Figure 3.1: LMD structure. Names of the key personnel for the present proposal are printed as bold-face characters.

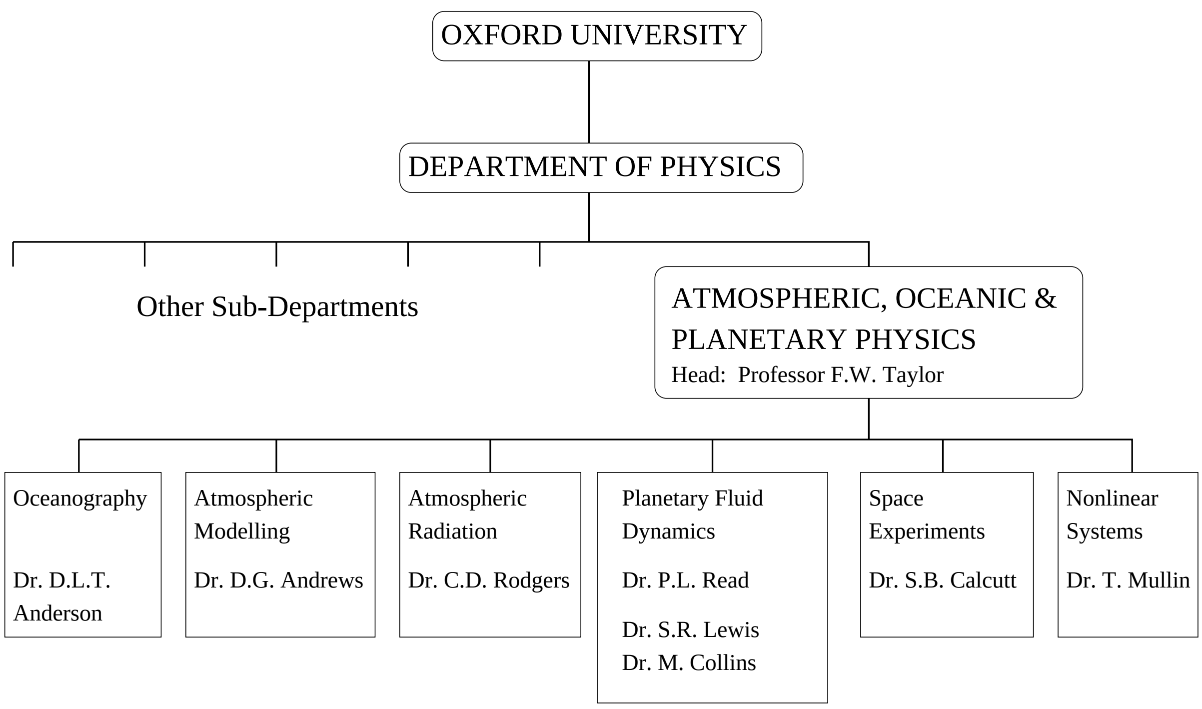

Figure 3.2: Structure of AOPP within Oxford University, and positions of the key personnel named in this proposal.

A tentative schedule for the progress meetings is included with the general time schedule of the project (Fig. 3.3). The meetings, which will be attended by one representative at least of each of the two contracting groups, will normally be held alternatively in Oxford and Paris. Third parties may be invited to the progress meetings by mutual agreement between the two contracting groups, with due notice to ESA.

Ordinary communication between the two contracting groups will normally be conducted through electronic mail, for which a common mailing list has been established. The preparation of the monthly progress reports required by the ITT, and the communication of these reports to ESA, will be under the responsability of the LMD group. The AOPP group will send its contribution to the reports to LMD, through electronic mail, at the latest on the Thursday preceding the day the report is due.

M. François Forget will be in charge of the preparation of the progress meetings and progress reports, as well as of all associated tasks, such as for instance the preparation and distribution of minutes of the progress meetings.

3.3 Facilities

3.3.1 LMD/CNRS

The planetary group of LMD is hosted, together with the climate modelling group, by Ecole Normale Supérieure. Ecole Normale Supérieure is located in the University area of Paris (Quartier Latin). It hosts about fifteen other laboratories, where research is done in domains such as theoretical physics, radioastronomy, geophysics and biology.

LMD is one of the major components of the newly created Institut Pierre Simon Laplace pour les Sciences de l'Environnement, which can be described as a "federation" of laboratories, and consists of seven laboratories located in the Paris area, specializing in various aspects of environmental science.

Computing facilities

The team which would be in charge of the project at LMD is part of a $\sim$40 person team sharing a common computer installation including work-stations, hard-disks, tape monitors and X–terminals connected through ethernet. About 30 persons are in fact directly working in connection with the LMD GCM (for terrestrial or planetary applications) and are jointly developing programs, diagnostics and graphical software. This team is supported by 6 computer specialists.

The current local LMD network includes:

- 13 workstations (HP, Sun, Mips and Next). Among these, three HP workstations (HP-720, HP-730 and HP-735) are currently used for Climate simulations (Earth, Mars, Titan ...) using the LMD GCM.
- 28 X–terminals.
- shared hard disks (about 10 Gbytes).
- Magnetic Optical Disk, Data Audio Tape and Exabyte storage facilities.

- access to the international "internet" network (possibility of sending/recieving messages and data) through "REseau NATional de l'Education et de la Recherche" (RENATER).
- access to the CRAY–98 of IDRIS (the computing centre of CNRS).

Further developments

The HP workstations are used currently for Martian simulations at rather low spatial resolutions or for short high-resolution test-simulations and will be used for the model development and validation. However, those workstations are not powerful enough to perform the long period simulations required for the production of the Martian Climate Database. Upgrade of the current LMD facilities is thus planned for the present project possibly including an upgrade of the current storage facilities for the production of the GCM "history–files" which will be used for the production of the Martian Climate Database. This upgrade of computer facilities would be in a large part, charged directly to the contract.

Graphics

Numerous diagnostic/graphical tools have been developed at LMD based on the use of commercial or public domain graphical packages. The following packages are available at LMD:
Drawplot and Contour (public domain)
gnuplot (public domain)
ximage, xdataslice (public domain)
GMT (public domain)
Khoros (public domain)
Spyglass
IDL
AVS
UNIRAS
Matlab
Mathematica

DRS (AMIP)

LMD has adopted the Data Retrieval System developed for the Atmospheric Model Intercomparison Program as format for the history files created by the GCM. All the available DRS facilities developed by the Lawrence Livermore Laboratory (FORTRAN routine libraries, tools for visualisation, interface with standard graphical packages) are already implemented on the LMD local network.

Other Facilities

LMD/CNRS has its own library that contains most of the relevant atmospheric and planetary journals and important text books, and has access to all the relevant international litterature through agreements between CNRS and University libraries.

3.3.2 AOPP Facilities

Buildings

AOPP is mostly accommodated in a single 3-storey building situated in the main Science Area of Oxford University. This comprises a mixed area of offices and laboratories, and also includes a number of smaller units in nearby buildings. The Mars modelling group is located in one of the adjacent buildings to AOPP in a compact suite of offices for the group head, post-doctoral scientists, students and support programmer.

Several other rooms are available for small (up to 5 persons) or large (tens of persons) meetings. A lecture theatre that can hold up to 100 persons and that contains up-to-date visual display systems is also available.

Computing facilities

The Mars modelling group makes extensive use of powerful desktop workstations for most of its computing work. At present, these comprise the following:

DEC AXP 3000/400 Alpha,

DECStation 5000/200,

DEC Station 5000/33.

In addition the group has 3 Apple Macintosh PCs, Laser and colour inkjet printers. The DEC AXP 3000/400 Alpha is currently the machine on which the Oxford GCM is typically run, while the smaller Decstations are used for model development and diagnostic computations. The group also has access to some computer facilities e.g. similar workstations and printers, with the rest of the department, and AOPP as a whole shares computer support staff for system management. Oxford University Computer Services (the University central computing facility) can also be accessed by the group, making available specialised printing and data processing facilities. All the computers are connected to the internet so that messages/data can be sent internationally using electronic mail, xmosaic etc. AOPP is licenced for many software items of relevance to this project, including graphics packages (e.g. IDL, Uniras), mathematical routines (e.g. NAG, Numerical Recipes), word processing (e.g. LaTeX, Word) etc.

These facilities are already working close to their capacity for ongoing projects, though are certainly adequate for development and small-scale trial computations. For production of the main database, however, it will be necessary to purchase significant upgrades to our facilities in order to complete the climate integrations required for WPIII. An allowance for this additional expenditure is therefore included in our cost analysis.

Other Facilities

AOPP has its own library that contains many of the relevant atmospheric and planetary journals and important text books. Access to other Departmental Libraries and the Bodlean Library is readily available, providing full access to the scientific literature.

3.3.3 Access to the Mars-Gram/Cospar models

We confirm that we will have acquired the Mars-Gram/Cospar models before the start of the activities from C. G. Justus and B. F. James.

3.3.4 The GCM to be reused

The GCM is extensively described in Appendix A.

The GCM will be delivered to ESA with a free of charge license for internal use. ESA will have the right to modify the code for the sole purpose of experiments intended for studying the behaviour of spacecraft under Martian conditions.

In order to obtain the radiative code included in the GCM, which has been developed in part at the European Centre for Medium Range Weather Forecasts, ESA will have to send an appropriate request to ECMWF. LMD will assist ESA in this respect.

The delivering by ESA of the whole, or parts, of the GCM to third parties will be submitted to prior authorization from CNRS and the University of Oxford.

3.4 Key personnel and their roles

3.4.1 LMD/CNRS

Name and time allocation on the project	Grade	Relevant expertise & participation to the project
Olivier Talagrand (30%)	Directeur de Recherche CNRS (1ere classe)	Expertise in atmospheric dynamics, planetary atmospheres and numerical techniques. Leading specialist in meteorological data assimilation (manager of a summer-school and "Groupement de Recherche" on this subject). Manager for the entire Project and for the CNRS team.
Frédéric Hourdin (30%)	Chargé de Recherche CNRS (2eme classe)	Expertise in numerical modelling of atmospheric dynamics and physics. Author of the LMD Martian physical package. Responsible for model development, validation and tuning. Contribution to the review (modelling efforts) and the design of the database.
François Forget (75%)	Allocataire de recherche du Ministère de l'Enseignement Supérieur et de la Recherche	Expertise in analysis of Martian data, physics of ice and clouds and numerical modelling of the Martian atmosperic circulation. Contribution to the review (data). Development and validation of new parametrizations (clouds,boundary layer), and contribution to the design and production of the database.
Le Van Phu (20%)	Ingénieur de Recherche CNRS	Computer specialist. Has coded the LMD grid-point GCM. Contribution to development of models and diagnostics.
Laurent Fairhead (10%)	Ingénieur de Recherche CNRS	Computer specialist. Has implemented the DRS software in the LMD GCM. Contribution to development of diagnostics softwares for the GCM and database

The personnel listed above will be available for working on the project at the beginning of the contract. In addition, one person payed directly on the contract money will work on the project for model development and tuning and for the production of the Martian database. This person could be Ali Harzallah presently at LMD on a two-year post-doctoral position. A. Harzallah has in particular performed a series of 19-year simulations with the LMD terrestrial climate GCM (Harzallah and Sadourny, 1994) and contributed to the AMIP program.

CURRICULUM VITAE

(mise à jour : Septembre 1994)

Olivier TALAGRAND

Né le 8 Mars 1946 au Mans (Sarthe)
Diplôme d'Ingénieur de l'Ecole Polytechnique (1966)
Diplôme d'Etudes Approfondies (Météorologie), Faculté des Sciences de l'Université de Paris (1967)
Doctorat d'Etat ès-Sciences, Université Pierre-et-Marie-Curie, Paris (1977)

Positions actuelles

Directeur de Recherche (première classe), Centre National de la Recherche Scientifique (1992-)
Maître de Conférences à l'Ecole Polytechnique (Département de Mécanique) (1985-)

Positions antérieures

Directeur de Recherche (deuxième classe), Centre National de la Recherche Scientifique (1986-1992)
Chargé de Recherche, Centre National de la Recherche Scientifique (1977-1986)
Attaché de Recherche, Centre National de la Recherche Scientifique (1970-1977)
Boursier, Centre National d'Etudes Spatiales (1967-1970)

Affectations

Laboratoire de Météorologie Dynamique, CNRS (1981-)
Centre Européen pour les Prévisions Météorologiques à Moyen Terme, Reading, Grande-Bretagne (1979-1980)
Laboratoire de Météorologie Dynamique, CNRS (1970-1978)
Geophysical Fluid Dynamics Laboratory, Princeton, Etats-Unis (1969-1970)
Service d'Aéronomie, CNRS (1966-1968)

Thèmes de recherche

Assimilation des observations météorologiques et océanographiques dans ses différents aspects. En particulier, assimilation variationnelle et liens entre l'assimilation et la théorie des systèmes dynamiques.
Application des techniques d'optimisation et de contrôle à l'étude de la prévisibilité et de l'instabilité de l'écoulement atmosphérique, et à l'étude de la sensibilité de modèles numériques aux paramètres.
Dynamique des atmosphères planétaires.
Etude expérimentale des ondes de gravité stratosphériques.

Publications récentes

(l'astérisque (*) désigne les publications soumises à un comité de lecture avant parution)

(*)Hourdin, F., F. Forget, et O. Talagrand, 1994, The sensitivity of the Martian surface pressure and atmospheric mass budget to various parameters: a comparison between numerical observations and Viking observations, soumis à publication dans J. Geophys. Res..

Hoang H. S. et O. Talagrand, 1994, Theorem on Approximate Non-Gaussian Estimation in Linear Model with Dependent State and Noise Vectors, Systems and Networks: Mathematical Theory and Applications (Comptes-rendus du 10ème Symposium International, Mathematical Theory of Networks and Systems, Ratisbonne, République Fédérale d'Allemagne, Août 1993), Akademie Verlag, 225-226.

H. C. Upadhyaya, Sangeeta Agrawal et O. Talagrand, 1994, Variational Data Assimilation with an Adiabatic Version of the LMD GCM using Adjoint Method, Proc. Indian Nation. Sci. Acad., 60, 193-204.

(*)Hoang Hong S. et O. Talagrand, 1993, On regularization approach to parameter estimation and its application to design of stable filters, soumis à publication dans Control Engineering Practice.

(*)Hourdin, F., et O. Talagrand, 1993, Superrotation of Planetary Atmospheres: a Numerical Study, soumis à publication dans J. Atmos. Sci..

(*)F. Hourdin, Le Van P., F. Forget et O. Talagrand, 1993. Meteorological variability and the annual surface pressure cycle on Mars, J. Atmos. Sci., 21, 3625-3640.

(*)F. Rabier, P. Courtier, J. Pailleux, O. Talagrand et D. Vasiljevic, 1993, A comparison between four-dimensional variational assimilation and simplified sequential assimilation relying on three-dimensional analysis, Q. J. R. Meteorol. Soc., 119, 845-880.

(*)F. Rabier, P. Courtier et O. Talagrand, 1992. An Application of Adjoint Models to Sensitivity Analysis, Beitr. Phys. Atmosph., 65, 177-192.

(*)O. Talagrand, 1991. The Use of Adjoint Equations in Numerical Modeling of the Atmospheric Circulation, dans Automatic Differentiation of Algorithms : Theory, Implementation, and Application, publié sous la direction de A. Griewank et G. F. Corliss, Society for Industrial and Applied Mathematics, Philadelphie, Etats-Unis, 169-180.

(*)P. Courtier et O. Talagrand, 1990. Variational assimilation of meteorological observations with the direct and adjoint shallow-water equations. Tellus, 42A, 531-549.

O. Talagrand, 1988. La dynamique des atmosphères planétaires. La Recherche, 19, 1010-1021.

(*)J.-F. Lacarra et O. Talagrand, 1988. Short-range evolution of small perturbations in a barotropic model. Tellus, 40A, 81-95.

(*) P. Courtier et O. Talagrand, 1987. Variational assimilation of meteorological observations with the adjoint vorticity equation. II: Numerical results. Q. J. R. Meteorol. Soc., 113, 1329-1347.

(*) O. Talagrand et P. Courtier, 1987. Variational assimilation of meteorological observations with the adjoint vorticity equation. I: Theory. Q. J. R. Meteorol. Soc., 113, 1311-1328.

(*) F.-X. Le Dimet et O. Talagrand, 1986. Variational algorithms for analysis and assimilation of meteorological observations : theoretical aspects. Tellus, 38A, 97-110.

Communications récentes invitées dans des congrès

O. Talagrand, Assimilation of observations, an introduction, Colloque International sur l'Assimilation des Observations en Météorologie et Océanographie, Organisation Météorologique Mondiale, Tokyo, Japon, Mars 1995 (invitation).

O. Talagrand, P. De Mey, Hoang Hong S., C. Pires et R. Vautard, Data Assimilation with Strongly Nonlinear Systems. Model Errors and Adaptive Filtering, Sixth Bureau of Meteorology Research Center Modelling Workshop, Bureau of Meteorology Research Center, Melbourne, Australie, Octobre 1994 (invitation).

O. Talagrand,Variational Data Assimilation. A Few Recent Developments, Sixth Bureau of Meteorology Research Center Modelling Workshop, Bureau of Meteorology Research Center, Melbourne, Australie, Octobre 1994 (invitation).

F. Hourdin et O. Talagrand, The Martian General Circulation, Session "The Atmospheres of Venus and Mars", 30ème Congrès du COSPAR, Hambourg, Allemagne, Juillet 1994.

O. Talagrand, Calcul Scientifique et Météorologie, Minisymposium "Quelques problèmes de Météorologie", 26ème Congrès National d'Analyse Numérique, Les Karellis, Mai 1994.

O. Talagrand, Variational data assimilation. Atelier "Numerical Weather Prediction in Tropics", New-Delhi, Inde, Janvier 1994.

Participation à des groupes de travaux et d'administration de la recherche, organisation de colloques, etc (activités récentes)

Membre du Comité International de Programme du Colloque International sur l'Assimilation des Observations en Météorologie et Océanographie, Organisation Météorologique Mondiale, Tokyo, Japon, Mars 1995.

Directeur de l'Ecole Assimilation des Observations Météorologiques et Océanographiques. Théorie, Méthodes et Problèmes Asssociés, La Garde, France, Août 1993.

Membre du Comité National de la Recherche Scientifique (Section 13, Physique et Chimie de la Terre, membre du bureau) (1991-).

Créateur et Directeur du Groupement de Recherche CNRS Méthodes Variationnelles en Météorologie et Océanographie (1989-)

Membre du Comité Scientifique Consultatif du Centre Européen pour les Prévisions Météorologiques à Moyen Terme (1988-) (vice-président, 1989-92, président, 1992-) (président du sous-comité chargé de la définition de la stratégie à long terme, 1990-91)

Enseignement dans des écoles de spécialité, séminaires, etc.

NATO Advanced Study Institute, Mesoscala Data Assimilation and Forecasting, Pologne, Eté 1996 (invitation).

European Research Course on Atmospheres, Physics and Chemistry of the Atmospheres of the Earth and of Other Solar System Objects, Grenoble, Janvier 1994.

Ecole d'Eté Internationale Assimilation des Observations Météorologiques et Océanographiques. Théorie, Méthodes et Problèmes Asssociés, La Garde, France, Août 1993.

European Research Course on Atmospheres, Physics and Chemistry of the Earth's Atmosphere and of the Other Planetary Atmospheres, Grenoble, Février 1993.

CURRICULUM VITAE

Frédéric HOURDIN
Date of birth : 21/02/66, Paris, FRANCE

Higher education:

1983-1985: "classe préparatoire"

1985-1988: Ecole Polytechnique

1988-1989: DEA (Master) in Astrophysics (University)

1989-1992: Thesis University Paris VII.
subject: "Study and numerical simulation of the general circulation of planetary atmospheres" (Defended 04/12/92, adviser: Olivier Talagrand).

Scientific experience. Numerical simulation of the general circulation of planetary atmospheres. Application to the study of Mars, Titan (in connection with the preparation of the Cassini-Huygens mission) and for the more general study of the phenomenon of atmospheric "superrotation". Numerical simulation of the Earth climate. Expertise and development of algorithms in the field of radiative transfer, parametrization of the planetary boundary-layer and atmospheric hydrodynamics. Numerical analysis as applied to geophysical fluid dynamics.

Positions:

1992-1994: Post-doctoral research at Laboratoire de Météorologie Dynamique

1994 : Permanent position (CNRS) at Laboratoire de Météorologie Dynamique

Major publications:

– Hourdin, F., 1992, A new representation of the CO_2 15μm band for a Martian general circulation model, *J. Geophys. Res.*, *97*, (E11), 18,319–18,335, 1992.
– Hourdin, F., P. Le Van, F. Forget, and O. Talagrand, 1993, Meteorological variability and the annual surface pressure cycle on Mars, *J. Atmos. Sci.*, *50*, 3625–3640, 1993.
– Hourdin, F., and O. Talagrand, Superrotation of planetary atmospheres: a numerical study, submitted to J. Atmosph. Sci., 1994.
– Hourdin, F., F. Forget, and O. Talagrand, The sensitivity of the Martian surface pressure to various parameters: a comparison between numerical simulations and Viking observations, submitted to J. Geophys. Res., 1994.

CURRICULUM VITAE

François FORGET
Date of birth : 23/09/67, Lille, FRANCE

Education

- **Currently :** Graduate Studient at LMD. Adviser : Olivier Talagrand.

- **1991 :** Graduated from the *Ecole Nationale Supérieure de Techniques Avancées* in Paris.
  Graduated from the *University of Paris VI* : "D.E.A." in Oceanography, Meteorology and Environment.

- **1988-1991 :** The *Ecole Nationale Supérieure de Techniques Avancées*, in Paris.

- **1985-1988 :** "Classes préparatoires" in Paris.

Scientific Experience

- **Since July 1993 :** At LMD : Study and modelisation of the Martian atmosphere with the LMD GCM : parametrisation of the polar clouds and simulation of the dust cycle.

- **April 1992 - June 1993 :** National service as a Research Associate at *NASA Ames Research Center, Space Science Division* (California), supported by CNES.
  - Analysis of Viking and Mariner 9 thermal infrared observations in the polar region. Study of the Martian CO_2 and H_2O clouds
  - Preparation of the CNES Mars Balloon project : Study of the deployment and flight environment, trajectories simulations with the Ames Martian GCM and Planetary Boundary Layer model.

- **March - June 1991 :** DEA Thesis at LMD : Simulation of the CO_2 cycle in the Martian GCM. Analysis of the pressure cycle.

- **October 1991 - March 1992 :** Engineer at *Bureau Veritas* (Consulting in offshore engineering). Study and modelisation of underwater pipe-lines.

Publications and Reports

- Forget F. and Pollack, J.B. (1993) Impact of the CO_2 and H_2O Clouds of the Martian Polar Hood on the Polar Energy Balance, *Bull. Amer. Astron. Soc.*, 25, p1070, 1993.

- Forget F. and Pollack, J.B. (1994) Climatology and Impact of the CO_2 and H_2O Clouds from Thermal Infrared Observations, submitted to *J.Atmos.Sci*, 1994.

- Forget F., Hourdin F., and Talagrand O. (1994) Mars Pathfinder Meteorological Observations on the Basis of Results of an Atmospheric General Circulation Model, in *Mars Pathfinder Landing Site Workshop*, LPI Technical Report 94-04, 1994.

CURRICULUM VITAE

Phu LE VAN
Nationalité: Française
date et lieu de naissance: 14/06/43, Hanoï, Vietnam

Formation

Baccalauréat Mathématiques (Paris)

Maitrise de Physique (Faculté des Sciences de Paris)

C4 d'Informatique Appliquée (Faculté des Sciences de Paris)

Fonction: Ingénieur de recherche CNRS, classe 2.

Expérience professionnelle:

Plus d'une vingtaine d'années d'expérience dans le domaine de la modélisation de la circulation générale atmosphérique et de la simulation numérique de la terre .

En particulier, auteur de l'écriture du premier modèle de circulation générale atmosphérique du L.M.D, vers l'année 1974.

Auteur également de l'écriture du modèle actuel de circulation générale, surtout dans sa partie 'dynamique', lequel modèle sert aussi pour les expériences de simulation des atmosphères autres que terrestres, comme celles de Mars et de Titan .

CURRICULUM VITAE

Laurent FAIRHEAD
Né le 13/03/63 à Ramsgate, Kent, Grande-Bretagne
Nationalités: Française et britannique

Etudes Supérieures

1980: Baccalaureat C, Lycée Francais de New-York

1983: Bachelor of Science (B.Sc.), Maths, Physique, Astrophysique, Queen Elizabeth College, London

1984: Master of Science (M.Sc), Maths, University of London

1985: DEA "Astronomie Statistique et Dynamique", Observatoire de Paris, Paris

1989: Thèse (Nouveau regime), "Chronométrage du pulsar rapide PSR1937+214: observations et analyse", Obervatoire de Paris / Bureau des Longitudes

Expérience scientifique

1985: Stage de DEA au Bureau des Longitudes, "traitement et analyse d'anciennes obervations d'occultations des satellites galiléens de Jupiter"

1996 à 1989: Participation dans le cadre de ma thèse à la conception et la réalisation du dispositif de chronométrage de pulsar rapide à l'observatoire de Nancay. Réalisation des logiciels de prédiction et de contrôle necessaire à ce dispositif. Développement d'un programme d'analyse de données de chronométrage de pulsars.

1989 à 1990: Séjour post-doctoral à Berkeley dans l'équipe de D.C. Backer. Comparaison des logiciels d'analyse de données de chronométrage. Campagne d'observations multifréquence de pulsars. Observations interferométriques de pulsars au VLA à des vues astrométriques

Situation professionnelle

1990: Recrutement au LMD/CNRS en tant qu'ingénieur de recherche en informatique et calcul scientifique au sein du groupe modelisation. Occupations: gestion du modele actuel du LMD, passage à la haute résolution du modèle, couplage du modèle du LMD avec le modèle d'océan du LODYC, gestion des entrées/sorties de lmdz, moyens graphiques, gestion des serveurs d'informations (Web, gopher) du laboratoire

3.4.2 AOPP/Oxford

Name and time allocation on the project	Grade	Relevant expertise & Participation to the project
Dr P. L. Read (10%)	University Lecturer, Dept of Physics (AOPP), University of Oxford.	Expertise in atmospheric dynamics, planetary atmospheres and modelling. Proposed contributor to reviews and design of database. Project Manager for Oxford team.
Prof. F. W. Taylor (5%)	Head of Atmospheric, Oceanic & Planetary Physics, University of Oxford	Expertise in spacecraft instrument design and mission operations, and in the physics and structure of the Earth and planetary atmospheres. Proposed consultant, editor and contributor to reviews and database design.
Dr S. R. Lewis (30%)	Research Scientist, Dept. of Physics (AOPP), University of Oxford	Expertise in planetary atmospheres dynamics, atmospheric modelling and data assimilation for Mars. Proposed contributor to reviews, design and implementation of parametrization schemes, and in production and review of database.
Dr M. Collins (40%)	Research Scientist, Dept. of Physics (AOPP), University of Oxford	Expertise in planetary atmospheres atmospheric modelling and data analysis for Mars. Proposed contributor to reviews, design and implementation of parametrization schemes, and in production and review of database.

The personnel listed above will be available for working on the project at the beginning of the contract.

The main science personnel named on this proposal (P.L. Read, F.W. Taylor, S.R. Lewis and M. Collins), who have formidable experience in research on the atmosphere of Mars, will contribute to this project according to the manpower schedule detailed above. In addition, a programer support scientist will be funded to assist in model and database development and production. Note that the time allocations for Dr Read and Prof. Taylor represent basic contractual obligations specific to this project. They are also involved in other related activities during the proposed duration of this project, however, which will also result in additional contributions to the work. AOPP also includes several other groups with relevant complementary expertise, who may be consulted during the course of the project. These include (i) the planetary experiments group, headed by S.B. Calcutt, who have expertise in instrumentation radiative transfer and remote sounding, and mission operations, (ii) the middle atmosphere group, headed by D.G. Andrews, who have expertise in large-scale GCM modelling and, in particular, gravity wave parametrization schemes, as applied to the Earth's stratosphere and mesosphere, and (iii) the atmosphere/oceans modelling group, headed by Dr D.L.T. Anderson, also has expertise in GCM modelling and data assimilation and analysis. Normal administrative support will be provided by departmental and university administrators, technicians and secretarial staff.

PETER LEONARD READ

PERSONAL DETAILS

Date of Birth: 18 October 1953 Nationality: British

Work Address: Atmospheric, Oceanic and Planetary Physics, Department of Physics,
Clarendon Laboratory, Parks Road, Oxford OX1 3PU United Kingdom

Telephone: +44 865 272082 Fax: +44 865 272923 e-mail: *read@atm.ox.ac.uk*

HIGHER EDUCATION

1972 – 1975 *B.Sc.* (Physics)
University of Birmingham.

1975 – 1979 *Ph.D.* (Radio Astronomy) Peterhouse, University of Cambridge.
Thesis title: "λ21 cm Observations of Atomic Hydrogen in Galactic HII Regions."

CURRENT & PREVIOUS POSITIONS

1979 – 1980	Higher Scientific Officer, High Atmosphere Branch, Meteorological Office, Bracknell.
1980 – 1983	Senior Scientific Officer, Geophysical Fluid Dynamics Laboratory, Meteorological Office, Bracknell.
1983 – 1988	Principal Scientific Officer, Geophysical Fluid Dynamics Laboratory, Meteorological Office, Bracknell.
1988 – 1991	Principal Scientific Officer & Head of Met. Office Unit, Robert Hooke Institute, Oxford.
1991 – present	University Lecturer & Tutor in Physics (Trinity College), University of Oxford.

RELEVANT EXPERIENCE

After completing my doctorate at the University of Cambridge in observational radioastronomy, I joined the UK Meteorological Office (UKMO) as a research scientist. I was initially based in the High Atmosphere Branch, and worked on novel retrieval methods for ground-based remote-sensing of ozone and NO_2. I then joined the Geophysical Fluid Dynamics Laboratory of the UKMO under Prof. R. Hide, to work on a range of problems in fundamental fluid dynamics, stimulated by issues in planetary atmospheric dynamics. This led to laboratory, theoretical and numerical modelling studies on coherent eddies in rotating stratified flows (applied to Jupiter, Saturn and Neptune), baroclinic instability, 'free modes' and super-rotation (also in the context of the atmospheres of Venus and Titan). More recently, my research has been concerned with investigating nonlinear wave interactions and 'chaos' in baroclinic flows, both in laboratory experiments and in atmospheric models, and in the evaluation of numerical advection schemes in CFD using laboratory methods.

In 1991, I was appointed University Lecturer at Oxford University. This enabled me to become more closely involved in research related to planetary missions. In this context, I have served on the Instrument Definition Science Team for the facility imaging instrument on board the NASA/ESA Cassini orbiter (1988-1990), and was appointed Participating Scientist on the NASA Mars Observer mission in 1992. I am currently a Co-Investigator on the CIRS instrument team for Cassini. At present, I lead two related research programmes (a) in fundamental geophysical fluid dynamics (involving laboratory studies of nonlinear baroclinic and barotropic instabilities) and (b) in the development and application of large-scale numerical models and GCMs (in collaboration with LMD, Paris) and data assimilation methods (in collaboration with UKMO) to the Martian atmosphere.

CURRICULUM VITAE

Fredric William TAYLOR
Born Amble, Northumberland, 24 September 1944.

Education

Duke of Northumberland's School, Alnwick, 1957-63.

University of Liverpool, 1963-66. B.Sc. (First Class honours in Physics)

University of Oxford, 1966-70. D. Phil. (Atmospheric Physics)

Professional Experience

1970 - 1979. Planetary Atmospheres Section, Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

1979 - present. Oxford University.
Professor of Atmospheric Physics.
Head of Atmospheric, Oceanic and Planetary Physics in the
Department of Physics.
Professorial Fellow, Jesus College.

Professional Activities (Space Experiments).

Principal Investigator for the Orbiter Infrared Radiometer experiment on the Pioneer Venus mission (launched 1978), the Stratospheric and Mesospheric Sounder experiment on Nimbus 7 (launched 1978), and the Improved Stratospheric and Mesospheric Sounder experiment on the Upper Atmosphere Research Satellite (launched 1991).

Co-investigator for the Pressure Modulator Radiometer experiment on Nimbus 6 (launched 1976),the Dual Frequency Temperature Sounder aircraft programme for the US Office of Naval Research, the Atmospheric Trace Molecular Spectroscopy experiment on Spacelab 3 (launched 1985), the Near Infrared Mapping Spectrometer experiment on the Galileo Jupiter orbiter mission (launch 1989), the Along- Track Scanning Radiometer on the European Remote Sensing satellite ERS-1 (launch 1990), the Pressure Modulator Infrared Radiometer on the NASA Mars Observer mission (launched 1992), the Composite Infrared Spectrometer on the NASA/ESA Cassini/Huyghens mission to Titan, and the High-resolution Infra-Red Dynamics Limb Sounder and the Tropospheric Emission Spectrometer on the NASA Earth Observing System (launch 2003).

Publications

Over 130 books and publications in refereed journals.

STEPHEN RICHARD LEWIS

PERSONAL DETAILS

Date of Birth: 19 June 1963 Nationality: British

Work Address: Atmospheric, Oceanic and Planetary Physics, Department of Physics, Clarendon Laboratory, Parks Road, Oxford OX1 3PU United Kingdom

Telephone: +44 865 272086 Fax: +44 865 272923 e-mail: *lewis@atm.ox.ac.uk*

HIGHER EDUCATION

1981 – 1984 *M.A.* Natural Sciences Tripos (Part II: Theoretical Physics) Gonville & Caius College, Cambridge University.

1984 – 1988 *D.Phil.* (Atmospheric Physics) Jesus College, Oxford University. Thesis title: "Long-lived eddies in the atmosphere of Jupiter."

1989 – 1991 Junior Research Fellow, Worcester College, Oxford University.

CURRENT POSITION

1988 – 1994 Post-doctoral research assistant in Atmospheric, Oceanic and Planetary Physics, Oxford University.

RELEVANT EXPERIENCE

My research since 1984 has concerned the application of mathematical models and numerical methods to the study of dynamical processes in planetary atmospheres. This has involved a range of numerical models of varying complexity, from a relatively simple model of flow in a channel, through more complete models of fluid flow on a rotating sphere, to a complex general circulation model of the atmosphere of Mars. For my thesis research I worked on idealized models of coherent vortices and their possible relation to the variety of long-lived spots observed in the atmospheres of the major planets. After completing my thesis I worked with extensions of the idealized model, including one using spherical geometry, and also gained some experience with a complete Navier-Stokes equations simulation of flow in a laboratory rotating annulus experiment.

Since 1990 I have been primarily responsible for the development of techniques and computer programs for a combined observational and modelling study of the structure of the atmosphere of Mars, and of particular phenomena which govern the martian climate. I have modified a basic semi-spectral global circulation model so that it will run on various workstations, and have collaborated with colleagues at Oxford, Reading and Paris in the introduction of new physical parametrization schemes appropriate to Mars. In addition to independent modelling studies, one aim of this project was to assist in the analysis of the atmospheric data which was expected from the Mars Observer spacecraft. To meet this goal I have adapted a data assimilation scheme (based on techniques in current operational use at the UK Meteorological Office) to work with various versions of the martian model. I am now conducting a programme of experiments involving validation using artificially-generated data and model-intercomparisons, and plan to use the scheme for re-analysis of earlier martian atmospheric observations as well as preparing it for the analysis of observations from any future spacecraft missions.

CURRICULUM VITÆ

MATTHEW COLLINS

PERSONAL DETAILS

Date of Birth:	27 April 1969	Nationality:	British

Work Address: Atmospheric, Oceanic and
Planetary Physics,
Clarendon Lab, Parks Rd.,
Oxford. OX1 3PU.
United Kingdom.

Telephone: +44 865 272913
Fax: +44 865 272923

CURRENT POSITION

Research assistant in Atmospheric, Oceanic and Planetary Physics, Oxford University. Current work includes research into the dynamics and physics of the Martian atmosphere using the current version of the LMD/Oxford Mars GCM. One particular field of interest is the question of the highly periodic nature of planetary scale baroclinic waves in the Martian atmosphere. My Ph.D. work involved a study of such waves using a simplified GCM and I am now extending that work using the LMD/Oxford Mars GCM. I am also invoved in the development of the GCM.

EDUCATION

Postgraduate	1990 – 1993	*University of Reading*
Higher degree	Ph.D. in the Department of Meteorology. Thesis title: "The Meteorology of Mars"	
Undergraduate	1987 – 1990	*University of Swansea*
Degree	1990	First Class B.Sc. (Hons.) in Pure and Applied Mathematics.

ADDITIONAL EDUCATION and EXPERIENCE

Courses	Sep. 1990-April 1991	Attended Meteorology M.Sc. courses during first 8 months of Ph.D.
	Sep. 1991	Geophysical and Environmental Fluid Dynamics Summer School, Department Applied Mathematics and Theoretical Physics, University of Cambridge
Conferences	April 1992	European Geophysical Society 17th Assembly
	June 1993	Mars Atmospheric Transport Through Time
	April 1994	European Geophysical Society 19th Assembly
	July 1994	30th COSPAR Meeting

RELATED PUBLICATIONS (AOPP)

Read, P. L. (1986) "Stable baroclinic eddies on Jupiter & Saturn: a laboratory analogue and some observational tests" *Icarus* ***65,*** 304-334.

Read, P. L. (1986) "Super-rotation and diffusion of axial angular momentum" *Quart. J. R. Met. Soc.* ***112,*** 231-272.

Read, P. L. (1988) "On the scale of baroclinic instability in deep, compressible atmospheres" *Quart. J. R. Met. Soc.* ***114,*** 421-437.

Lewis, S.R. (1989) "Long-lived eddies in the atmosphere of Jupiter," in *The Effect of Background Rotation on Fluid Motions,* Hopfinger, E.J. and Linden, P.F., eds., European Mechanics Colloquium **245,** 60pp..

Lewis, S.R. (1990) "The Voyager encounter with Neptune," *Weather* ***45,*** 14–19.

Joshi, M.M., Lewis, S.R. and Read, P.L. (1992) "The steady-state response of the martian atmosphere to orographic forcing," *Annales Geophysicae* ***10,*** C491.

Lewis, S.R. and Read, P.L. (1992) "Data assimilation for the martian atmosphere," *Annales Geophysicae* ***10,*** C495.

Lewis, S.R. (1992) "A quasi-geostrophic numerical model of a rotating internally heated fluid," *Geophysical and Astrophysical Fluid Dynamics* ***65,*** 31–55.

Read, P. L. (1992) "Applications of Singular Systems Analysis to "baroclinic chaos"", *Physica D,* ***58,*** 455-468.

Read, P. L., Bell, M. J., Johnson, D. W. & Small, R. M. (1992) "Quasi-periodic and chaotic flow regimes in a thermally-driven, rotating fluid annulus", *J. Fluid Mech.,* ***238,*** 599-632.

Read, P. L. (1993) "Applications of chaos to meteorology and climate" in *The Nature of Chaos (ed. T. Mullin)*, Oxford University Press, pp222-260.

Read, P. L. (1993) "Phase portrait reconstruction using multivariate singular systems analysis", *Physica D,* ***69,*** 353-365.

Joshi, M.M., Lewis, S.R. and Read, P.L. (1993) "Orographic influences in the martian atmosphere," *Annales Geophysicae* ***11,*** C461.

Lewis, S.R. and Read, P.L. (1993) "Modelling and data assimilation for Mars Observer/PMIRR," *Annales Geophysicae* ***11,*** C462.

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3.5 List of deliverables

The contractors undertake to deliver all items as indicated in the Work Statement of ITT A0/1-2798/94/NL/JG (with the reservation made above in Section 2.4 about the horizontal resolution for the Martian Climate Database).

3.6 Work breakdown structure

The work will be distributed between CNRS and Oxford University according to the following guidelines.

CNRS will be mainly in charge of the model development and of all that concerns "physical environment" (dust, clouds, boundary layer).

Oxford University will be mainly in charge of the production of the Martian climate database and of all that concerns atmospheric variability.

The distribution of the responsibilities for the major tasks between the LMD and AOPP teams is illustrated in Fig. 2.1. A more detailed description is given in the following forms.

PLANED DATE: t_0
PLANED DATE: t_0+5 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP1
W.P. TITLE: Review of Martian Data and existing modelling efforts CONTRACTOR: CNRS (LMD) MAJOR CONSTITUENT: Specifications for the GCM (e.g. Subsystem) START EVENT: END EVENT: URD for the GCM W.P. MANAGEMENT: O. Talagrand	SHEET 1 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- the GCM to be reused

MAJOR TASKS:

- Specifications for the GCM development
- Design of the acceptance test-plan

DELIVERABLES:

- Listing and copy on tape of the existing GCM
- Existing documentation of the GCM
- User Requirement Document for the GCM
- Software Requirement Document for the GCM
- Architectural Design Document for the GCM
- Description of the acceptance test-plan

PLANED DATE: t_0
PLANED DATE: t_0+5 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP1
W.P. TITLE: Review of Martian Data and existing modelling efforts CONTRACTOR: Oxford University (subcontractor) MAJOR CONSTITUENT: Specifications for the database (e.g. Subsystem) START EVENT: Review END EVENT: URD for the database W.P. MANAGEMENT: P. Read	SHEET 2 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- Data Retrieval System (AMIP) software and documentation

MAJOR TASKS:

- Design of the diagnostic and software packages for the creation of the database
- Review on the Martian environment and past modelling effort

DELIVERABLES:

- Review
- User Requirement Document for the database
- Software Requirement Document for the database

PLANED DATE: t_0+2 months

PLANED DATE: t_0+9 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP2
W.P. TITLE: Development and testing of relevant models CONTRACTOR: CNRS (LMD) MAJOR CONSTITUENT: Model improvement and validation (e.g. Subsystem) START EVENT: END EVENT: documentation W.P. MANAGEMENT: O. Talagrand	SHEET 3 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- the GCM to be reused

LIST OF TASKS:

- Improvements and validation of the GCM
  1. parametrizations for the CO_2-ice clouds
  2. boundary layer and subgrid-scale variability

- Execution of the test-plan for the GCM
  1. Tuning
  2. Test of the ability to run over long periods
  3. Validation (Comparison to observed temperatures and infrared fluxes)

DELIVERABLES:

- Up-to-date version of the GCM

- Draft User's manual for the Martian GCM

- Technical note on GCM testing

- GCM DDD

PLANED DATE: t_0+2 months
PLANED DATE: t_0+9 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP2
W.P. TITLE: Development and testing of relevant models CONTRACTOR: Oxford University (subcontractor) MAJOR CONSTITUENT: Model of the breaking of gravity waves (e.g. Subsystem) START EVENT: END EVENT: ADD for the database W.P. MANAGEMENT: P. Read	SHEET 4 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- The GCM to be reused

LIST OF TASKS:

- Improvements and validation of a gravity waves scheme for the GCM
- Tuning of the gravity waves scheme
- Execution of the test plan:
  1. Tuning of the gravity waves scheme
  2. Choice of an appropriate vertical resolution
  3. Validation (comparison to Viking pressure data in term of planetary waves and interannual variability; impact of horizontal resolution changes)

DELIVERABLES:

- Architectural Design Document for the database.
- Draft User's manual for the Martian GCM
- Technical note on GCM testing

PLANED DATE: t_0+7 months

PLANED DATE: t_0+18 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP3
W.P. TITLE: Generation of the Martian climate database CONTRACTOR: CNRS (LMD) MAJOR CONSTITUENT: Long term simulations (e.g. Subsystem) START EVENT: climate simulations END EVENT: GCM delivery W.P. MANAGEMENT: O. Talagrand	SHEET 5 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- The up-to date Martian GCM
- Planning documentation for the GCM (approved by ESA)

LIST OF TASKS:

- Long term simulations for the database
- Production of initial states for the ESA GCM
- Development of the final GCM version

DELIVERABLES:

- Copy of the martian GCM on a tape
- Restart files on a tape
- Final form of the user manual for the GCM
- Final report

PLANED DATE: t_0+7 months

PLANED DATE: t_0+9 months

WORK PACKAGE DESCRIPTION

PROJECT: Martian Environment Models PHASE:	W.P. REF: WP3
W.P. TITLE: Generation of the Martian climate database CONTRACTOR: Oxford University (subcontractor) MAJOR CONSTITUENT: Climate database (e.g. Subsystem) START EVENT: Climate simulations END EVENT: ADD for the database W.P. MANAGEMENT: P. Read	SHEET 6 OF 6 ISSUE REF.: 1 ISSUE DATE.: September 22, 1994

AVAILABLE TO START THE WP:

- The up-to date Martian GCM
- Planning documentation for the GCM (approved by ESA)

LIST OF TASKS:

- Long term simulations
- Generation of the database

DELIVERABLES:

- A tape containing the climate database
- DDD for the database
- User manual for the climate database
- Technical note on the critical review of the climate database

3.7 Planning

The planning is summarized as a bar-chart in Fig. 3.3. The project entails carrying out three main types of task in order to achieve the objectives required by the ITT. These may be classified as follows:

(a) Mars Environment Review. This comprises the main component of WPI, to review current knowledge of the Mars environment and previous attempts to model the Martian atmospheric circulation. This entails a systematic survey of the scientific literature, and the writing of a report. Given the breadth of expertise at both LMD and AOPP, this task will be carried out jointly by both contracting groups, with AOPP coordinating the final form of the report. This task is expected to be completed within 4 months of the start of the project, and the main deliverable (the report) will be available for approval by ESA in time for the progress meeting scheduled in Month 5.

(b) Development of a comprehensive numerical model of the Mars atmosphere. This comprises the main deliverable for WPII, and will take as a starting point the existing models in current use at LMD and AOPP. Proposed work will entail reviewing and extending the documentation for this model, extraction of a subset of the code for eventual delivery to ESA, development of new physical parametrization schemes for gravity wave drag and CO_2 clouds, and final validation of all aspects of the model. This task will be primarily carried out by LMD, with contributions from AOPP to the development of the gravity wave drag scheme and to the design of the final acceptance plan. The main development of this model is expected to require approximately 6 months, with the validation requiring a total of 5 months (though much of this validation can be carried out in parallel with the development itself). Results of the development and validation are to be presented for review by ESA in time for the progress meeting in Month 7, which is time-critical with respect to the start of the climate simulations necessary for part (c). A first delivery of the code, including acceptance tests, is to be completed for the meeting in Month 9. Finally, a user-friendly version of the GCM must be delivered to ESA with a user manual at the end of the contract.

(c) Production of Database. This comprises the main deliverable for WPIII, and the task will entail carrying out a series of long term (multi-annual) simulations of Mars' atmospheric circulation at moderate-high resolution, an extensive statistical analysis of the simulated results, and production of a database which summarises information on mean environmental conditions and variability. A report on the database will also be produced. Logical tasks respectively require the production of a plan for the format and content of the database, performance of the main simulations, statistical analyses, production of the database and writing of documentation. This component of the project will be carried out jointly, with AOPP taking primary responsibility for the design and production of the database.

Design of database format and development of statistical (diagnostic) tools needed for database production will be started in AOPP at the earliest opportunity. We propose to carry out the basic climate simulations jointly at both LMD and Oxford, using both grid-point and spectral versions of the model and the joint physical parametrization package developed for (b). Based on experience with our existing models, these simulations are expected to require approximately 8 months to complete, and a total of 9 months to carry out the statistical analysis (though this may overlap with running the simulations themselves). Because these tasks are rather time-consuming, they rep-

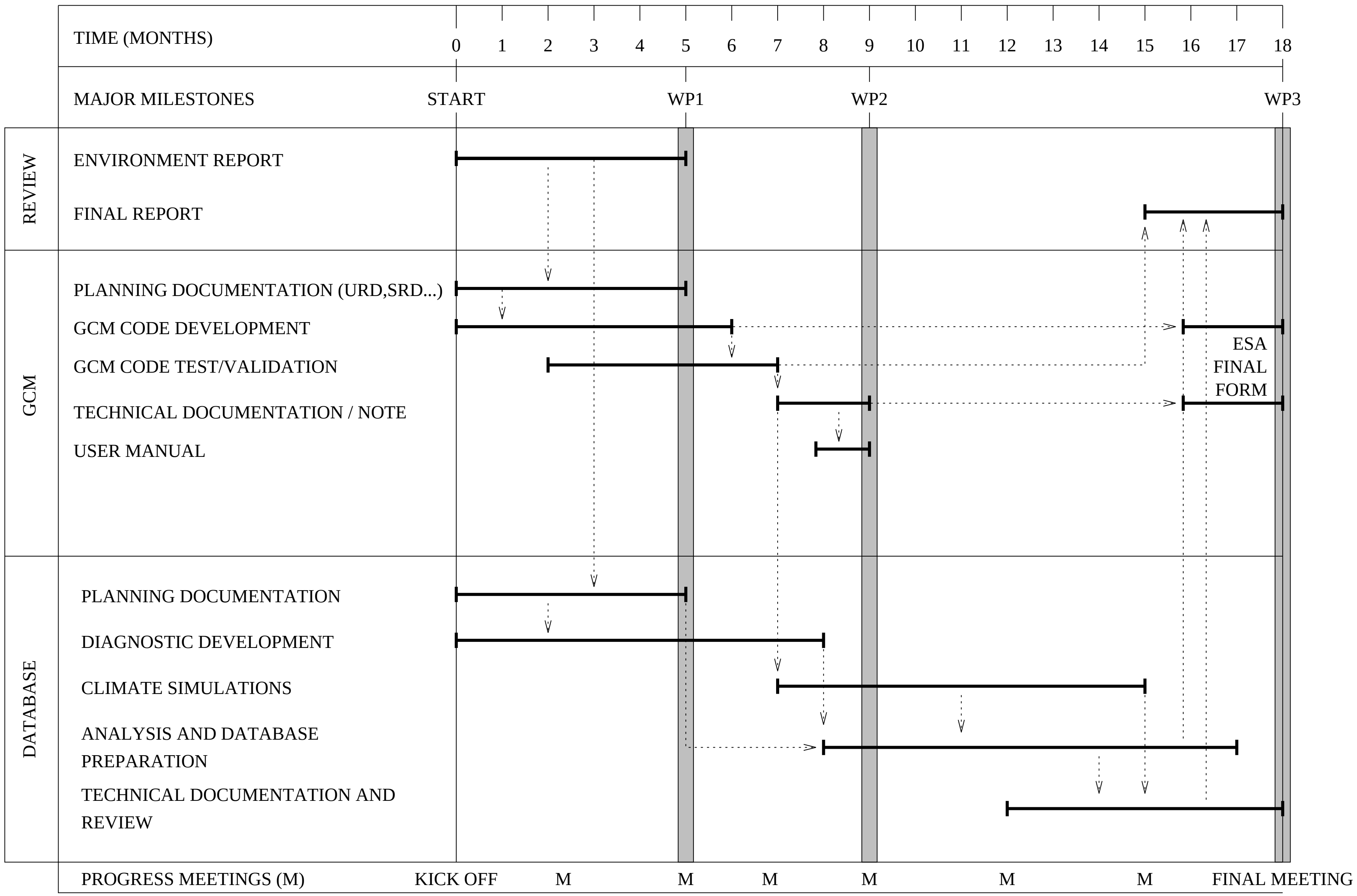

Figure 3.3: Planning.

resent a highly time-critical component of the project, and must be started by Month 7 of the project if an over-run is to be avoided. In addition, ESA approval of the basic model and physics package developed for (b) will be necessary before starting the climate simulations. Technical documentation and review of the database may require up to 6 months to complete, and will be started by Month 12 of the project (once the climate simulations and analyses are under way). Progress in the climate simulations and analyses will be reviewed at the meetings in Months 9-16, and first iterations of the database and documentation presented for review by ESA in Month 16. Final delivery of the completed database and documentation will be completed in time for ESA approval in Month 18.

3.8 Cost price data

3.9 Profit

No profit will be made by either of the two groups on the present proposal.

3.10 Conversion rates

See 3.12 below.

3.11 Type of price

See 3.12 below.

3.12 Milestone payments plans

The total sum requested in the present proposal amounts to 250,000 (two hundred and fifty thousand) Accounting Units, firm fixed prices. This sum is to be divided into 132,000 (one hundred and thirty-two thousand) Accounting Units for LMD/CNRS and 118,000 (one hundred and eighteen thousand) Accounting Units for AOPP/Oxford University. The corresponding amounts in national currencies are respectively, in agreement with the conversion rates attached to the Invitation to Tender, 869,285 (eight hundred and sixty-nine thousand two hundred and eighty-five) French Francs and 92,499 (ninety-two thousand four hundred and ninety-nine) Pounds Sterling.

Following clauses 20, 21 and 22 of the draft contract, 20% of the total amount is asked by both CNRS and Oxford University at both the beginning (advance payment) and the end of the 18 months (WPIII).

Additional payments are asked at completion of WPI and WPII. The corresponding amounts and percentages are given below.

3.12.1 LMD/CNRS

Payment	Start	WP1	WP2	WP3	total
KAU	26.4	65	14.2	26.4	132
%	20	49.25	10.75	20	

A substantial part of the payment will be asked at the end of WP 1, a large part of the money being used for improving the CPU capacities of the LMD network for the production of the Martian Climate Database.

3.12.2 AOPP/Oxford

Payment	Start	WP1	WP2	WP3	total
KAU	23.6	35.4	35.4	23.6	118
%	20	30	30	20	

3.13 Travel & Subsistence Plan

As a project entailing international collaboration between groups in France and the United Kingdom, coordinated through ESTEC in the Netherlands, it is anticipated that a number of visits to participating institutions will be required. These visits are expected to be of three main types: (a) attendance of initial and final project meetings at ESTEC, (b) regular progress meetings between the contractors at approximately 2-3 month intervals during the project, alternating in location between Oxford and Paris, and (c) a small number of more extended technical visits of individual scientists in Oxford or Paris to visit their complementary group in Paris or Oxford, in order to enable the completion of certain critical tasks, such as installation of newly-developed software. The provisional plan for the regular visits is outlined in the matrix below, though this scheme may be varied in practice if deemed appropriate.

MEETING	PLACE	TIME (T0+..)	LMD	AOPP
Project start (a)	ESTEC	0	3 persons	3 persons
Progress (b)	LMD	2		1 person
Progress (b)	AOPP	5	1 person	
Progress (b)	LMD	7		1 person
Progress (b)	AOPP	9	1 person	
Progress (b)	LMD	12		1 person
Progress (b)	AOPP	15	1 person	
Project completion (a)	ESTEC	18	3 persons	3 persons

We anticipate that visits under category (c) totalling up to 3 man-weeks from each participating contractor will be necessary, to be scheduled as required during the project.

Costs for these visits have been calculated assuming attendance levels as outlined above, standard economy class air travel, and accommodation in medium price hotels. On this basis, we estimate a requirement for a total cost of 7.5 KAU for each participating contractor (grand total of 15 KAU), comprising approx. 5KAU for the regular meetings (a) and (b), and 2.5 KAU for technical visits.

Appendix A The GCM to be reused

As already explained in the technical report, the GCM we intend to use as a basis for this ESA proposal is a suite of models developed as a joined effort of LMD and Oxford laboratories and includes two dynamical codes and one physical package.

A.1 The LMD finite-difference dynamics

The dynamics of the LMD model are taken from the terrestrial general circulation model used at LMD for climate studies (Li and Le Treut, 1992; Le Treut et al., 1994; Polcher and Laval, 1994; Bony et al., 1992; Yu et al., 1991; Harzallah and Sadourny, 1994) . Classical *primitive equations* of meteorology (Navier Stokes equations for a perfect gas plus hydrostatic hypothesis and thin layer approximation, see *e. g.* Holton 1979) are integrated using finite differences in space and an explicit centered (or leapfrog) temporal scheme. The original formulation of this model is presented in details by Sadourny and Laval, 1984. We use in fact a more recent formulation by Sadourny, coded in FORTRAN 77 by Le Van, in which latitudes and longitudes of the grid can be chosen arbitrarily, which allows to zoom in a particular region on the sphere. The vertical discretization is based on σ coordinate (pressure normalized by its surface value $\sigma = p/p_s$). The vertical repartition of the $\sigma - levels$ can be arbitrarily fixed.

The discretization scheme conserves both potential enstrophy for barotropic divergent flows (Sadourny, 1975b; Sadourny, 1975a) and total angular momentum for stationary axi-symmetric flows. The latter property was not included in the original terrestrial version but was introduced in the Martian atmospheric circulation model (Hourdin et al., 1993) in which, because of the non numerical conservation of angular momentum, spurious prograde zonal winds were produced in equatorial regions. The new conservative formulation has since then been included in the terrestrial climate model and was found to strongly improve the simulation of the tropical trade-winds.

Non linear interactions between explicitly resolved scales and subgrid-scale processes are parametrized applying an horizontal dissipation operator on potential temperature and wind. This dissipation is based on an iterated Laplacian a technique commonly used in the modelling of two-dimensional turbulence and in many general circulation models (the iteration is introduced to be more selective in smaller scales, not acting directly on the explicitly resolved flow).

A.2 The Oxford Dynamical Code

The dynamical code used in the Oxford GCM is based on the work of Hoskins and Simmons (1975). It solves the primitive equations of meteorology in non-dimensional, inviscid, adiabatic form. The prognostic variables are the absolute vorticity ξ, the divergence D, the temperature anomaly from a prescribed vertical distribution T' and the surface pressure p_*.

Model variables are represented in terms of spherical harmonics, ${Y_n}^m$ i.e. a model variable, say X, is expanded as a series,

$$X = \sum {X_n}^m {Y_n}^m = \sum {X_n}^m {P_n}^m(\mu)\exp(im\lambda), \tag{A.1}$$

where ${X_n}^m$ are the spectral coefficients and ${P_n}^m$ are the normalised associated Legendre polynomials (Bourke et al. (1977)). The total wavenumber is n, the zonal wavenumber is m and $n-|m|$ is the number of zeros between the north and south poles. Spherical harmonics have the advantage that they are eigenfunctions of the Laplacian and the longitudinal derivative, so the taking of such derivatives involves the simple multiplication by eigenvalues or squares of eigenvalues. The latitudinal derivative also has a simple form.

The resolution of the model is determined by the chosen truncation of the series of spherical harmonics. The Oxford model uses "jagged triangular truncation" which can be thought of as the filter,

$${S_n}^m = \begin{cases} 1 & \forall n < m \leq M \text{ and } n = m \text{ when } n-|m| \text{ is odd} \\ 0 & \text{otherwise} \end{cases} \tag{A.2}$$

where

$$X = \sum {S_n}^m {X_n}^m {Y_n}^m \tag{A.3}$$

The terminology is TM where M is the truncation limit and T indicates the triangular form of the truncation in wavenumber space. This type of truncation provides near-isotropic coverage on the sphere.

The major problem with the specral technique is typically the calculation of the non-linear products. Early attempts involved the use of interaction coefficients and the multiplication of every coefficient with every other (see e.g. Bourke (1977)). This soon becomes computationally cumbersome, however, as the resolution increases. The Oxford model uses the so-called transform technique (Orszag (1970), Eliasen *et al.* (1970)) in which the model variabes are transformed from spectral space onto a longitude-latitude grid, the non-linear products computed and then transformed back to spectral space. The speed of the process is greatly enhanced by the use of fast Fourier transforms (Press *et al.* (1992) and Gaussian quadrature (Arfken (1985)). The grid on which the non-linear products are calculated must over-resolve the smallest wavelength in order to prevent aliasing. Hence the so-called 'dynamics grid' has $3M + 1$ points around a latitude circle.

One of the problems created by truncating the spectral series (A.1) involves the non-linear transfers of energy and enstrophy. During a simulation both these quantities may be conveyed past the truncation limit. This cannot actually occur, however, and energy and enstrophy will consequently build up at small scales (sometimes called spectral blocking). Bourke (1974) applied a $\kappa\nabla^2$ operator to the spectral fields to remove small-scale energy and enstrophy. Although this seems the most physically meaningful form of diffusion, it was found that the operator also affected the large scales significantly. These days it is fashionable to use the operator $\kappa\nabla^{2q}$ where q is an integer greater than 1. This so-called hyper-diffusion removes small-scale noise while not seriously affecting the larger scales. MacVean (1983) has suggested that q=3 or higher produces satisfactory results.

The model uses terrain-following σ coordinates, where $\sigma = p/p_*$, and σ varies from being 1 at ground level to 0 at the model top. This is particularly important for Mars which has large variations in surface height. The vertical differencing scheme employs a semi-implicit method in which the phase speeds of fast moving gravity waves are spuriously represented, but which allows relatively large timesteps to be taken.

A.3 The LMD physical package

A.3.1 Radiation

The radiative transfer code is adapted from the one developed in the context of terrestrial modelling by Fouquart and Bonnel (1980) for solar radiation and Morcrette et al. (1986) for thermal radiation. This code, originally developed for the climate LMD GCM, has since been included by Morcrette in the operational model of the European Centre for Medium-Range Weather Forecasts (ECMWF).

1. **For thermal radiation,** effects of both atmospheric carbon dioxide and dust are included. Particular attention has been given to the parametrization of absorption by the CO_2 15μ m band with inclusion of Doppler effect (Hourdin, 1992b) . Cooling rates computations have been carefully validated by comparison to line-by-line integrations. The model, in which Doppler effects are introduced, is very accurate up to 70 km. The thermal spectrum is divided into three parts, one for the core of the CO_2 15μ m band, one for the wings and the third one for the remaining part of the spectrum. For the three parts, the transmission by dust is computed using grey absorption approximation. For the two intervals of the CO_2 15μ m band, the total transmissivity is evaluated as the product between transmissivity of dust and that of carbon dioxide.

2. **For solar radiation,** absorption and scattering by dust are taken into account using the code developed by Fouquart and Bonel (1980), based on the computation of the upward and downward fluxs from the reflectance and transmittance of each layer. Transmittances and reflectances are computed using the Delta-approximation to account for the strong asymmetry of the aerosol phase function.

3. **The dust mixing ratio** in the atmosphere is pre-specified as a function of time and space since dust advection is not yet included in the GCM.

A.3.2 Vertical turbulent mixing

The effect of turbulent mixing on momentum and potential temperature $\theta = T\,(p_s/p)^{\kappa}$ is evaluated by the mean of a classical diffusion equation

$$\frac{\partial}{\partial t} = \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho K_z \frac{\partial}{\partial z}\right) \tag{A.4}$$

where the turbulent mixing coefficient K_z is computed as

$$K_z = l e^{1/2} \tag{A.5}$$

in term of mixing length l and a diagnostic estimate of the turbulent energy

$$e = Max\left\{ l^2 \left[\left(\frac{\partial \vec{V}}{\partial z}\right)^2 - 2.5\frac{g}{\theta}\frac{\partial \theta}{\partial z} \right], e_{min} \right\} \tag{A.6}$$

(the minimum value of the kinetic energy was set to $e_{min} = 1 \times 10^{-6}$ m^2 s^{-1}). In the case where $e > e_{min}$, the vertical mixing coefficient can be expressed as a function of the Richardson number

$$Ri = \frac{g\partial\theta/\partial z}{\theta\left(\partial\vec{V}/\partial z\right)^2} \tag{A.7}$$

as

$$K = l^2 \left\| \frac{\partial \vec{V}}{\partial z} \right\| \sqrt{1 - 2.5Ri} \tag{A.8}$$

A particular treatment is needed close to the surface (typically below few tens of meters) in the so-called surface planetary boundrary layer. The parametrization for the PBL layer is similar to that of ECMWF (Louis, 1979) . The drag coefficient is given by

$$C = \left(\frac{k}{\ln\frac{z}{z_0}}\right)^2 f\left(R_i, \frac{z}{z_0}\right) \tag{A.9}$$

where z_0 is the roughness length, z is the height of the middle of the first atmospheric layer, $k = 0.4$ is the von Karman constant and

$$R_i = \frac{gz(\theta - T_s)}{\theta||V||^2} \tag{A.10}$$

is the Richardson number where θ and $||V||$ are the potential temperature and wind velocity in the first atmospheric layer, and T_s the surface temperature. Two different functions f are used for momentum (f_m) and potential temperature (f_θ). In either case, a different formulation is used depending on whether the atmosphere is stable ($R_i > 0$)

$$f_m = \frac{1}{1 + 2bR_i/\sqrt{1 + dR_i}} \tag{A.11}$$

$$f_\theta = \frac{1}{1 + 3bR_i\sqrt{1 + dR_i}} \tag{A.12}$$

or unstable ($R_i < 0$)

$$f_m = 1 - \frac{3bR_i}{1 + 3bC\left[k/\ln\left(z/z_0\right)\right]^2 \sqrt{-R_i\left(1 + z/z_0\right)}} \tag{A.13}$$

$$f_\theta = 1 - \frac{3bR_i}{1 + 3bC\left[k/\ln\left(z/z_0\right)\right]^2 \sqrt{-R_i z/z_0}} \tag{A.14}$$

As in the original terrestrial version, we use $C = b = d = 5$.

A.3.3 Convective adjustment

If an unstable subadiabatic vertical temperature gradients

$$\frac{\partial \theta}{\partial z} < 0 \tag{A.15}$$

is produced by the model, an adiabatic profile is immediately restored with a simple energy conserving scheme. If the resulting temperature profile is unstable at its upper or lower limit this mechanism is instantaneously extended in such a way that the final profile is entirely stable.

Momentum is consequently mixed, the efficiency of the mixing depending on an estimate of the instability of the atmosphere computed from the relative enthalpy exchange necessary to restore the adiabatic profile $\bar{\theta}$ from the original profile θ

$$\alpha = \int \left|\theta - \bar{\theta}\right| \rho dz / \int \theta \rho dz \tag{A.16}$$

When $\alpha < 1$ (this condition is always verified in the simulations) the angular momentum is entirely mixed on a fraction α of the mesh.

A.3.4 Surface processes

The time evolution of the temperature under the surface is given by a classical conduction equation

$$\frac{\partial T}{\partial t} = -\frac{1}{C}\frac{\partial F_c}{\partial z} \tag{A.17}$$

where the conductive flux F_c is given by

$$F_c = -\lambda \frac{\partial T}{\partial z} \tag{A.18}$$

and where λ and C are the soil conductivity and specific heat per unit volume, respectively. In the simple case of a vertically homogeneous soil (which is assumed here), it can easily be shown that the model, as far as the time evolution of the surface temperature is concerned, is only dependent on the soil thermal inertia $I = \sqrt{\lambda C}$.

The time evolution of the surface temperature is deduced from the heat balance at the surface including thermal conduction in the soil, radiative and turbulent heat fluxes.

A.3.5 CO_2 condensation-sublimation

A vapor pressure curve is introduced based on the Clausius-Clapeyron relation for perfect gas:

$$\ln{(p/p_0)} = \frac{L}{R}\left(\frac{1}{T_0} - \frac{1}{T_{co2}}\right) \tag{A.19}$$

(where $L = 5.9 \times 10^5$ J kg^{-1} is the latent heat of sublimation, R is the gas constant and $T_0 = 136.3$ K is the condensation temperature corresponding to the pressure chosen as a reference, here $p_0 = 1$ mbar).

Both atmosphere and surface temperatures are prevented from falling below T_{co2} by precipitating atmospheric CO_2 onto the surface.

1. **In the atmosphere,** if the temperature of a given layer falls below T_{co2} (as an effect of dynamics or other physical processes), condensation occurs, in an amount appropriate to restore, by latent heat release, the condensation temperature corresponding to the local pressure. All condensed carbon dioxide instantly precipitates to the ground without sublimation. Surface pressure is modified in agreement with the total amount of precipitation.

2. **At the surface,** the temperature of the frost is kept at the condensation value either by condensing atmospheric CO_2 or by sublimating CO_2 ice.

The sublimation-condensation scheme exactly conserves both energy and mass.

A.3.6 Surface conditions

Three fields have to be specified at the surface: height of orography, thermal inertia and albedo of ice free surface.

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