RECENT ADVANCES IN THE DEVELOPMENT OF A EUROPEAN MARS CLIMATE MODEL AT OXFORD.

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Introduction:

Since the early 1990s, efforts have been under way in Oxford to develop a range of numerical weather and climate prediction models for various studies of the Martian atmosphere and near-surface environment. Early versions of the Oxford model were more in the way of 'process models', aimed at relatively idealised studies e.g. of baroclinic instability[1] and low-level western boundary currents in the cross-equatorial solsticial Hadley circulation[2]. Since the mid-1990s, however, the group in Oxford have worked closely with the modelling group at LMD in Paris to develop a joint suite of more sophisticated and comprehensive numerical models of Mars' atmosphere. This collaboration, partly sponsored in recent years by the European Space Agency in connection with the associated development of a climate database for Mars[3], culminated in a suite of global circulation models[4], in which both groups share a library of parametrisation schemes, but in which the Oxford team use a spectral representation of horizontal fields (in the form of spherical harmonics) and the LMD group use a grid-point finite difference representation.

These models were described in some detail by Forget et al.[4], and their preliminary validation and use in the construction of first versions of the European Mars Climate Database by Lewis et al.[3]. In the present report, we will review further developments which have taken place since the latter papers were published. Aspects of these developments which are common to both the LMD and Oxford groups will also be covered in the companion contribution by Forget et al. in this meeting, and so will only be touched on briefly here. Instead, we will concentrate on those advances which are more specific to the Oxford version of the model. In the following sections, we outline the main new developments to the model formulation since 1999. Subsequent sections then describe some recent examples where the new model is being utilised to advance a diverse range of studies of Mars atmospheric science.

Extensions to the model:

One of the main objectives of recent joint developments to the LMD/Oxford model has been to extend its capabilities of representing the full altitude range of atmospheric circulation systems, whilst retaining moderate resolution in the horizontal (up to T31 in spectral space, corresponding to a grid-point resolution of 96 x 48 in longitude and latitude respectively). To date this has resulted in an extension of the vertical extent of the model domain from an altitude of around 100 km in 1999 to around 125km (15 pressure scale heights), and increasing the number of model levels from 25 to 32 (though further extensions into the thermosphere itself are currently under way at LMD). A weak ∇^2 diffusion is implemented in the top few model levels to act as a 'sponge layer' to eliminate spurious reflections from the top boundary. This has enabled the model to provide physically plausible simulations to be obtained up to altitudes in excess of 100 km, corresponding roughly to the base of the Martian thermosphere and ionosphere.

In association with this extension, it has been necessary to adapt the near infrared heating and far infrared cooling schemes in the model to take account of significant departures from LTE in CO_2, which become important at altitudes above about 70-80 km[5]. This has entailed the development and implementation of novel parametrization schemes to represent such effects economically, which have been achieved in collaboration with Dr Miguel Lopez-Valverde at IAA in Granada, Spain.

Both the LMD and Oxford versions of the GCM now use the MOLA dataset to define the surface topography. In the latest work, the 0.25° resolution MOLA data are smoothed to the model resolution to represent the effects of resolved topography, and the full resolution information is used in the Lott & Miller[6] scheme to represent the effects of subgridscale orographic and gravity wave drag. Use of this new dataset has required a recalibration of the gravity wave drag scheme.

In connection with efforts to study the transport cycles of dust and water in the Martian atmosphere, both groups have developed and implemented tracer transport schemes to represent the advection of material tracers in parallel with the dynamical model, using winds calculated during the evolution of the simulated flow. In the Oxford version of the model, a fully three-dimensional semi-Lagrangian material transport scheme has been implemented[7] on a regular latitude-longitude grid, equivalent to the grid used to compute the 'physics' terms in the main model. Cubic Lagrange interpolation is used in the implentation of semi-Lagrangian advection, and the approach of Priestley[8] is used to ensure global conservation of transported tracers.

Recent studies of the dust transport cycle by Newman et al.[7] have also entailed the development of new parametrization schemes to model the spontaneous lifting and deposition of dust. Gravitational sedimentation is the main mechanism included for dust deposition from the atmosphere, though ongoing work is investigating methods of representing scavenging processes due to condensation of water ice onto suspended dust particles. Lifting of dust from the surface is obtained by two distinct processes represented in the model: (a) direct injection of dust by the action of local wind stress and consequent saltation, and (b) indirect injection through the action of convective vortices (dust devils). The latter are represented by use of a thermodynamic model of dust devils due to Renno[9], whose strength is governed strongly by the magnitude of the temperature difference between the ground and near-surface atmosphere. Relatively high lifting thresholds were found to be necessary to obtain spatial and temporal intermittency of dust lifting similar to that observed on Mars, but the resulting simulations have enabled for the first time a GCM to simulate the complete life cycles of realistic regional dust storms. An example is illustrated below.

Further studies are under way to make use of the same semi-Lagrangian transport scheme as used for the dust cycle to represent the hydrological cycle on Mars. In this case, schemes are under development to represent sources and sinks of water vapour in the Martian atmosphere, including direct condensation and evaporation/sublimation at the surface, a simple ice cloud scheme and a more complex representation of water storage and adsorption in the Martian regolith. This work will be discussed in more detail in a companion presentation at this meeting by Böttger et al.

Model validation:

Earlier studies[3],[4] made use of Mariner 9, Viking and Pathfinder measurements to validate various aspects of the model and its simulated circulation. In more recent studies, extensive use has been made of the detailed measurements obtained during the MGS mission, including TES retrievals of temperature and dust in the Martian atmosphere, and high resolution temperature profiles from MGS radio science occultations.

The latter measurements in particular show generally very good agreement with model simulations, except perhaps in the polar regions where agreement is less satisfactory.

Dust transport simulations:

As mentioned above, the dust-transporting version of the model takes account of both direct lifting of dust by near-surface wind stress (NSWS) and by dust devils (DD). The strength of NSWS lifting is parametrised by a flux proportional to the saltating sand flux, H, defined according to White[9] as

$$H = \max[0,\ 2.61\rho/g\ (u_{drag})^3(1 - u_{drag}^t/\ u_{drag})(1 - u_{drag}^t/\ u_{drag})^2] \qquad (1)$$

where u_{drag} is the near-surface drag velocity in the boundary layer and u_{drag}^t the threshold value, computed to take into account atmospheric density and interparticle cohesion effects. This parametrisation is therefore threshold-sensitive, although a relatively threshold-insensitive version has also been explored, which attempts to take account of short-term gustiness in surface winds. This can enable dust lifting to occur even if the mean wind near the surface is well below the computed lifting threshold.

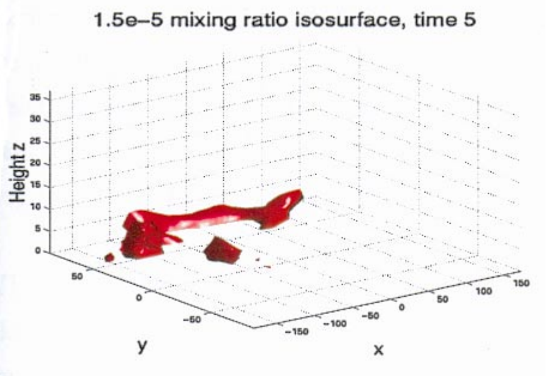
DD lifting parametrisations are based on the model of Renno et al.. The first is threshold-insensitive, and sets the lifted dust flux proportional to the 'dust devil activity' proposed by Renno et al. (thermodynamic efficiency x sensible heat flux). The second parametrisation uses the model to estimate the tangential velocity around a dust devil, then predicts the threshold value of this for dust lifting (using semi-empirical equations which resulted from laboratory dust devil experiments, as reported by Greeley and Iversen). Dust is then only lifted when the tangential velocity exceeds the predicted threshold.

Dust lifted by these processes is allowed to interact directly with the radiation scheme, so that solar heating of the atmosphere may be strongly affected by a large injection of dust in a simulated storm. This also allows the model to include some representation of realistic feedbacks in the dust cycle.

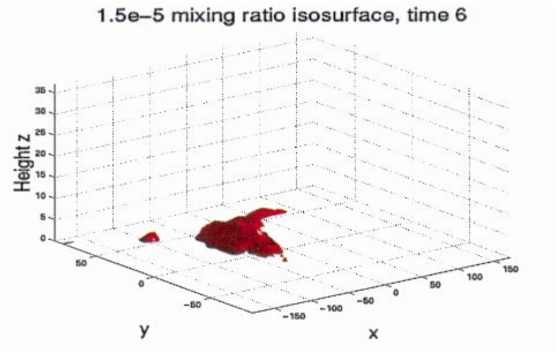
A range of numerical experiments have been carried out to evaluate the influence of such feedbacks. These clearly show that the strength of lifting by NSWS processes are enhanced as the dust content of the atmosphere increases, consistent with the positive feedbacks necessary to sustain the growth of local and regional dust storms. DD lifting, on the other hand, tends to be inhibited by increased atmospheric dust content, since this reduces the temperature contrast between atmosphere and surface. Thus, dust devils are predicted to occur under quiet and clear conditions, and not during major dust events.

Dust storm events are found to occur sporadically in the model, and favour many similar regions on Mars to those observed to be sites of dust storm initiation. The resulting regional dust storms can follow remarkably realistic life cycles. An example is shown in Fig. 1, which shows a visualisation of a dust cloud raised from a local storm in the Chryse region during southern summer. The resulting cloud is advected southward before being caught up in the main seasonal Hadley circulation. This enables the cloud to spread in longitude and to be carried northwards, back across the equator.

The fully interactive dust-transporting model is also sufficiently stable to be run over several Mars years, allowing experiments to study possible interannual variability due to variations in dust movement from one year to another. Fig. 2 shows a time-series of longitude-averaged dust optical depths from one such run, roughly equal amounts of threshold-sensitive NSWS and DD lifting. The results show some interannual variability from one year to another, with a clear peak in dust content in southern summer. In some years of this simulation, the onset of dust storm activity during southern summer can show similarities with the Viking storms of 1977, in exhibiting two distinct peaks in dust activity early and late in the season.



(a)



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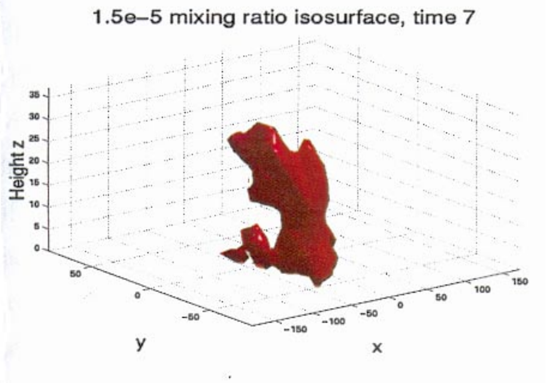

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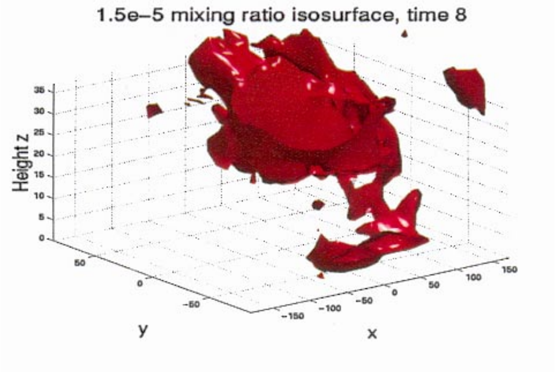

(d)

Fig. 1: Four stages during the growth of a simulated dust storm in the Chryse region. Shown are the 1.5 x 10^{-5} kg/kg mixing ratio isosurfaces

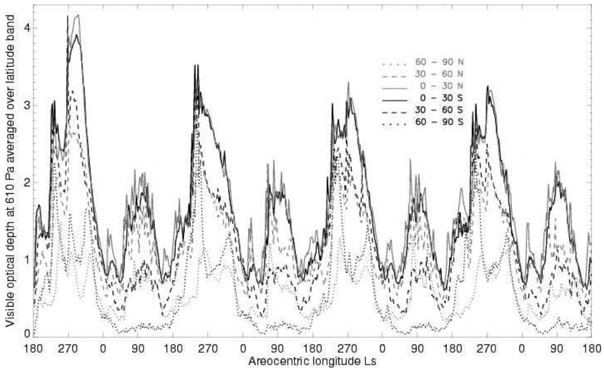

Figure 2: Four Mars years of zonally-averaged visible optical depths, adjusted to the 610 Pa surface, for a multi-annual simulation of the fully-interactive dust cycle in the Oxford MGCM. This simulation uses a combination of both NSWS and DD lifting parametrisations, and corresponds to case NOGDTH1 of Newman et al. (2002)[7].

Other ongoing studies:

In addition to the studies mentioned above, the Oxford version of the European Mars GCM is being utilised in a variety of other ongoing studies of Mars' present and past meteorology and climate.

Super-rotation in a dusty atmosphere: In some recent work involving the dynamics of the Martian atmosphere under dusty conditions, the diurnal tide has been identified as playing an important role in the low-level angular momentum budget at low latitudes. In particular, nonlinear interactions associated with the enhanced wave of diurnal heating produced by increased dust in the low-level atmosphere were found to lead to a strong westerly jet of up to 50 m s^{-1} at an altitude of around 15-25 km (see Fig. 3). This appears to have little to do with the well known topographic resonance with the diurnal tide, even though that can lead to the excitation of a strong prograde Kelvin wave response. This was confirmed in further experiments in which the topography was replaced by a smooth underlying surface. These results are further discussed in a forthcoming paper in *J. Geophys. Res.*[10].

Data assimilation: Since before the launch of the *Mars Observer* spacecraft, preparations have been under way in Oxford to apply meteorological data assimilation methods to analyse mapping observations of Mars from orbiting spacecraft. These methods are now operational in conjunction with the new version of the Mars GCM, and being used to analyse mapping observations from the MGS TES instrument, both from the pre-mapping science phasing period and, most recently, from the current mapping phase. Results from this study will be presented elsewhere in this meeting by Lewis et al.

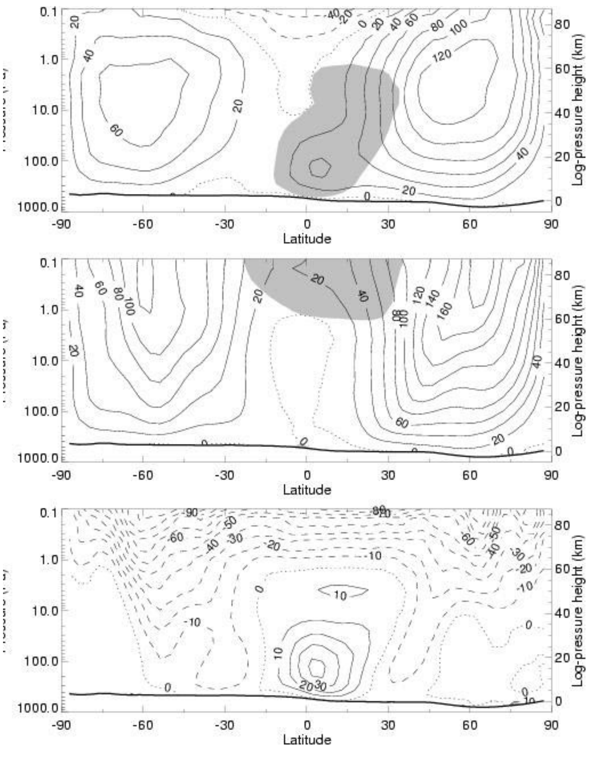

Figure 3: Comparison of the zonal mean zonal wind in a run of the Oxford MGCM (a) with the normal diurnal cycle, (b) with diurnally-averaged insolation, and (c) the difference between them. Regions in which the atmosphere is locally super-rotating are shaded, and both runs use the specified Viking dust scenario of [3] with dust amounts increased by a factor of 5. The fields correspond to a time average over the period following northern autumn equinox ($L_S = 180^o – 210^o$) – after Lewis & Read[11].

Atmospheric predictability studies: The intrinsic predictability of the Martian atmosphere compared with that of the Earth is an intriguing topic for detailed study. In particular, it has been known since the Viking era that baroclinic wave activity on Mars may be much more regular and coherent than on Earth, though the intrinsic predictability has not so far been studied in detail.

In new work currently ongoing (see presentation by Newman et al.), the ‘breeding vector’ technique, well known in the operational numerical weather prediction community for terrestrial meteorology, is being applied to evaluate the sensitivity of the Martian atmospheric circulation to initial conditions. Preliminary results indicated that unstable (growing) perturbations are found only during certain seasons on Mars, and take the form of large-scale planetary wave structures, in contrast to their terrestrial equivalents.

Palaeoclimate studies: Given a validated model for Mars’ present climate, it is natural to consider extending its use to investigate alternative climate scenarios which might have prevailed in Mars’ geological past. In ongoing studies, the Oxford MGCM is being used in a systematic study of the climate of Mars at other phases of its obliquity and orbital cycles, such as may have prevailed during the past 10 Myrs or so.

References:

[1] Collins, M. and I. N. James, Regular and irregular baroclinic waves in a simplified model of the Martian atmosphere, *J. Geophys. Res., 100,* 14421-14432 (1995)

[2] Joshi, M. M., S. R. Lewis, P. L. Read and D. C. Catling, Western boundary currents in the Martian atmosphere: numerical simulations and observational evidence, *J. Geophys. Res., 100,* 5485-5500 (1995)

[3] Lewis, S. R., M. Collins, P. L. Read, F. Forget, F. Hourdin, F. Fournier, C. Hourdin, O. Talagrand and J.-P. Huot, A climate database for Mars, *J. Geophys. Res., 104,* 24177-24194 (1999)

[4] Forget, F., F. Hourdin, R. Fournier, C. Hourdin, O. Talagrand, M. Collins, S. R. Lewis, P. L. Read and J.-P. Huot, Improved general circulation models of the martian atmosphere from the surface to above 80 km, *J. Geophys. Res., 104,* 24155-24176 (1999)

[5] Lopez-Puertas, M. and M. Lopez-Valverde, Radiative energy balance of CO_2 non-LTE infrared emissions in the Martian atmosphere, *Icarus, 114,* 113-129 (1995)

[6] Lott, F. and M. Miller, A new sub-grid scale orographic drag parametrization: its formulation and testing, *Quart. J. R. Met. Soc., 123,* 101-128 (1997)

[7] Newman, C. E., S. R. Lewis, P. L. Read and F. Forget, Modeling the Martian dust cycle. 1: representations of dust transport processes, *J. Geophys. Res.,* in press (2002); and .. 2. Multi-annual radiatively active dust transport simulations, *ibid,* in press (2002)

[8] Priestley, A. A quasi-conservative version of the semi-Lagrangian advective scheme, *Mon. Wea. Rev., 121,* 621-629 (1993)

[9] Renno, N. O., M. L. Burkett and M. P. Larkin, A simple thermodynamic theory for Dust Devils, *J. Atmos. Sci., 55,* 3244-3252 (1998)

[10] Greeley, R. and Iversen, J. D., Wind as a Geological Process on Earth, Mars, Venus, and Titan, CUP, (1985)

[11] Lewis, S. R. and P. L. Read, Equatorial jets in the dusty Martian atmosphere, *J. Geophys. Res.,* in press (2002).