

POD/EOF MODELS OF MARS' ATMOSPHERIC CIRCULATION: IS MARTIAN METEOROLOGY CHAOTIC?. P. L. Read¹, S. R. Lewis¹, S. G. Whitehouse² and I. M. Moroz², ¹Atmospheric, Oceanic and Planetary Physics, University of Oxford (Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, UK. email: p.read1@physics.ox.ac.uk, ²Mathematical Institute, University of Oxford (26-29 St Giles, Oxford, OX1 3LG, UK. email: moroz@maths.ox.ac.uk).

Introduction: Since the early analyses of the Viking lander observations of pressure, wind and temperature variations on the surface of Mars [1],[2], it has been apparent that certain components of Mars' meteorology exhibit a much stronger degree of periodicity and coherence than the corresponding phenomena on Earth. This was particularly clear for the baroclinic transients during Northern Hemisphere fall, winter and spring, during which signals from travelling wave disturbances could be detected which corresponded to relatively low planetary wavenumbers ($m = 1-3$) with periods of $\sim 2-8$ sols and which persisted for intervals of 10-50 sols. Together with the presence of strong, periodic diurnal tides, such observations suggest that Mars' climate and meteorology may operate in a dynamical regime which is more ordered and less chaotic than that of the Earth, and hence may be more predictable in the sense of meteorological weather forecasting.

GCM simulations & chaotic attractors?: Such coherent behaviour in baroclinic transients has also been qualitatively reproduced in GCM model simulations of Martian meteorology [3],[4]. Where such simulations were carried out without a full representation of the diurnal variation of insolation (i.e. using diurnally-averaged insolation), not only was the diurnal tide absent, but the baroclinic transients in the model became almost perfectly periodic and spatially monochromatic [4]. Abrupt changes of spatial wavenumber took place during the seasonal cycle, but which were not reproduced precisely in subsequent years of the simulation, indicating hysteretic transitions between almost intransitive, multiple equilibria, much as observed in a variety of theoretical and experimental nonlinear systems (such as the well known thermally-driven rotating annulus experiments [5]) in regular or quasi-periodic (non-chaotic) regimes.

Erratic and apparently chaotic transitions between such regimes were apparent when the diurnal cycle was included in the model, much as found in the original Viking observations, indicating that the diurnal tide could stimulate transitions between otherwise intransitive equilibria dominated by regular baroclinic waves of differing spatial wavenumber. Such an interpretation would imply that Mars' mid-latitude winter meteorology typically comprises the interaction of a small number of free and forced spatial eigenmodes of the global atmospheric circulation, and is therefore, in contrast to the Earth, consistent with a low-dimensional ($d \sim 3-5$?) chaotic attractor.

POD/EOF analyses and models: The hypothetical existence of the role of such an attractor, as put for-

ward by Collins et al.[4], and the elucidation of the main factors (e.g. static stability, surface topography, thermal structure and forcing etc.) determining whether the basic dynamical regime is regular or chaotic, are difficult to establish from GCM simulations alone. In the present study, therefore, we have made use of techniques based on Proper Orthogonal Decomposition (POD)[6] (a) to analyse the results of both comprehensive and simplified GCM simulations of the Martian atmospheric circulation in terms of 3D empirical orthogonal functions (EOFs), and (b) to use truncated sub-sets of such EOFs as Galerkin bases for the formulation of low-order, nonlinear quasi-geostrophic models of baroclinic wave dynamics under conditions appropriate for Mars.

An EOF decomposition was carried out on a SH winter simulation of the atmospheric circulation of Mars, obtained using the Oxford/LMD comprehensive Mars GCM[7]. Some 95-98% of the variance or total energy of the flow was explained with just 10 wave components, indicating that the flow might be consistent with relatively low-dimensional dynamics. The leading 3-4 EOFs represented respectively the diurnal and semi-diurnal tides, whilst subsequent EOFs represented the main baroclinic wave disturbances centred at mid-latitudes and with periods of 2-5 sols.

In preparation for the formulation of low-order models, a further analysis was carried out on a simulation using a simplified GCM[9]. in which diurnally-averaged heating and cooling was represented by a Newtonian relaxation, surface drag was represented by a Rayleigh friction, and topographic and other surface variations were absent. In the simulations carried out by Collins & James[9], the mid-latitude flow was dominated by a single, regular $m=3$ baroclinic wave, travelling at a constant speed around the north pole. This was reflected in the EOF decomposition, which indicated that $\sim 90\%$ of the variance or $\sim 80\%$ of total energy was captured by just 4 wave components, consistent with a very simple, quasi-periodic regime with just a single travelling baroclinic wave.

Analysis of low-order models: By using a truncated set of EOFs as a basis for a low-order quasi-geostrophic model, the original GCM could be reduced to a simple set of coupled, nonlinear ODEs. A detailed mathematical analysis of these self-consistent, low-order quasi-geostrophic models with 6, 12 or 21 components demonstrated that, in parameter regimes appropriate to Mars, two dominant baroclinic wave modes, corresponding to either an $m = 3$ or an $m = 2$ flow, are close to marginal stability. Depending upon

the precise conditions, the fully-developed flow may equilibrate either to a steady travelling wave of either wavenumber, or a more complex mixed wavenumber state. The frequencies, amplitudes and propagation speeds of the fully-developed waves in the POD/Galerkin model are remarkably close to those in the original (primitive equation) SGCM, indicating that the quasi-geostrophic models form an accurate representation of the main dynamical processes in the SGCM. The resulting bifurcation analysis of the low-order models accounts for most of the main features of the empirical regime diagram for the SGCM obtained by Collins & James[9], indicating that this simplified model is governed by low-dimensional dynamics under conditions analogous to Mars.

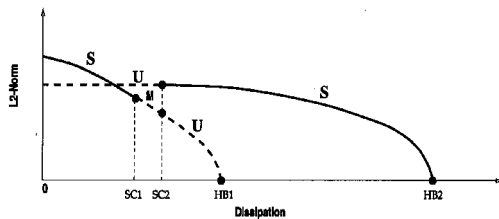


Figure 1: Bifurcation diagram for a POD/Galerkin model of baroclinic flow on Mars in the absence of topography and thermal tides, showing wave amplitude (L2-norm) versus dissipation (surface drag). Solid lines denote a stable wave solution and dashed lines unstable.

Future work: Having established the success of the POD/Galerkin approach to the formulation of low-order QG models of baroclinic dynamics in the SGCM under conditions appropriate to Mars, future work will attempt to apply the same kind of analysis to comprehensive simulations using the full Oxford/LMD Mars GCM. Such a simplified formulation will enable the earlier study to be extended to allow a systematic investigation of the possible roles of mechanical and thermal surface topography, and of the diurnal thermal tide, on the dynamics of the flow.

Having also established the degree of success by which QG dynamics can represent the quantitative behaviour of baroclinic waves in a Mars GCM, this suggests that a QG model can be used to facilitate other kinds of study of the predictability of the Martian atmosphere. In future work, therefore, we plan to make use of a QG model[10] to derive dynamically consistent perturbations for use in ensemble prediction experiments. In the latter, an initial state for a full GCM (derived either from free-standing simulations or data assimilation from spacecraft observations) is perturbed and simulations run from each initial condition. The predictability of the system can then be determined from the subsequent divergence of simulations and the corresponding sensitivity to initial conditions. Such a study is expected to provide a valuable source of insight into the factors determining intrinsic predictabil-

ity of terrestrial planetary atmospheres, including that of the Earth itself.

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