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ATMOSPHERIC PREDICTABILITY OF THE MARTIAN ATMOSPHERE: FROM LOW-DIMENSIONAL DYNAMICS TO OPERATIONAL FORECASTING?.

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Introduction

Since the work of Barnes (1980, 1981), it has been evident that Martian mid-latitude meteorology is commonly dominated by large-scale baroclinically unstable transient waves. Viking Lander data showed that such waves are strongly modulated by the seasonal cycle, apparently disappearing altogether during northern summer. During seasons around northern winter, however, they are typically very active and dominated by relatively low wavenumbers (m = 1-3). Unlike their terrestrial counterparts, however, Barnes (1980, 1981) found that Martian baroclinic transients were typically highly regular in their behaviour in time, with near-periodic signals at the VIking Lander sites persisting for months and with temporal frequency spectra (see Fig. 1) exhibiting strong peaks at periods of 2-8 days. The impression was therefore that Mars's atmosphere is typically more coherent, and therefore perhaps intrinsically more predictable, than that of the Earth.

Subsequent modelling and observations have largely confirmed this impression. In particular, Collins et al. (1996) showed in simple model experiments that, in the absence of thermal tidal forcing, baroclinic waves in an otherwise reasonably realistic circulation would develop into extremely regular, spatially monochromatic wave patterns progressively moving around the winter pole, with occasional jumps in wavenumber as the seasonal cycle advanced. Comparison of successive years of such simulations even gave the impression of hysteretic behaviour in wavenumber transitions, much as found in the regular regime of laboratory experiments on baroclinic waves in rotating, cylindrical containers (e.g. Hide and Mason (1975)). Such extremely regular behaviour in the non-diurnal Mars general circulation model (GCM) simulations was significantly more coherent than the observations of Barnes (1980, 1981), although more realistic episodic variability was restored when simulations were re-run with the diurnal cycle included. Such results suggest that much of Mars' synoptic variability may owe much to an interaction between a relatively small number of freely evolving, global, baroclinically unstable atmospheric modes and the periodically-forced diurnal tide.

The simple spatial structures associated with such a simple spectrum of near-normal modes of the atmosphere with a periodic forcing would strongly suggest that synoptic-scale meteorology on Mars may be governed by a relatively low-dimensional attractor. This is in significant contrast to the Earth, for which the likely attractor dimension is probably quite high. The consequences for atmospheric predictability in a regime dominated by a low-dimensional attractor (chaotic or not) could be profound, with correspondingly important implications for the practical ability of atmospheric models to forecast Martian meteorology from a given initial state. In this presentation, we will review various studies exploring the possible nature of the low-dimensional Martian meteorological 'attractor' in simplified models, and recent attempts to characterize more realistic atmospheric circulation systems in Mars GCMs and assimilated data (see Lewis et al., this volume). Most recently, attempts have been made by Newman et al. (2004) to determine quantitatively the growth of perturbations in realistic Martian circulation patterns, based on the 'breeding vector' method (Kalnay, 2004). This leads on naturally to the possibility of ensemble forecasting experiments, and the presentation will conclude by giving an overview of recent results and future prospects of making detailed synoptic forecasts of Martian meteorology.

1 Low-order POD models

Given a system whose behaviour is governed by the nonlinear interaction of a limited number of discrete, orthogonal modes, various approaches have been developed to formulate simplified nonlinear models of such systems directly from timeseries of realisations from the full system. A statistical analysis of suitable timeseries can be used to decompose the spatio-temporal 'signal' as the superposition of time-varying amplitudes of a set of distinct, orthogonal patterns. Depending upon the norm used, such modes may represent distinct contributions e.g. to the variance of the timeseries, or its kinetic or total energy. The approach uses singular value decomposition of covariance or energy matrices, and is often referred to as 'Proper Orthogonal Decomposition' (Holmes et al., 1996) or POD.

Subsets of such POD modes can be used as the basis for a low-dimensional dynamical system, by substitution into the original (or approximated) equations of motion, together with suitable projections of physical forcing and dissipative processes. The resulting model, in the form of a closed set of nonlinear ordinary differential equations, is referred to as a 'POD-Galerkin' model.

Whitehouse et al. (2005a,b) conducted a study in

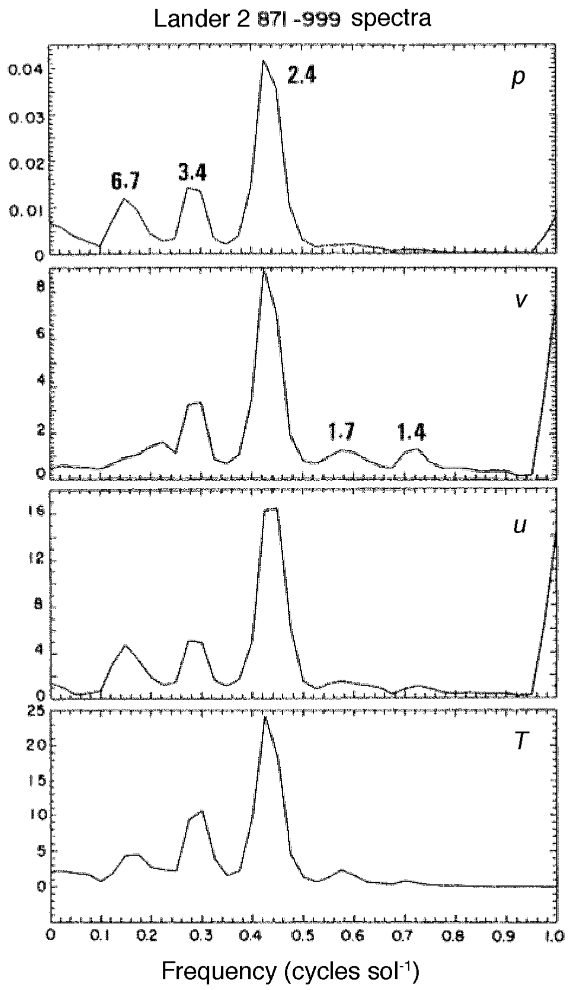

Figure 1: Temporal spectra of baroclinic transients found by Viking Lander 2 (after Barnes 1980; 1981).

the context of Mars, in which a POD analysis was performed on data from a series of simple GCM simulations based on the work of Collins and James (1995). The latter model comprised a low-resolution (T21) simulation of a Mars-like circulation forced by thermal relaxation towards a reasonably realistic background temperature distribution, but without topography or diurnal or seasonal cycles. The resulting dominant POD modes were found to take the form of latitudinally-confined wave trains with sinusoidal variation in longitude of relatively low wavenumber. An example of such a dominant mode, projected onto four separate vertical eigenmodes, is shown in Fig. 2.

Subsequent POD-Galerkin models based on relatively small subsets of such modes (Whitehouse et al., 2005b), in conjuction with the quasi-geostrophic equations of motion in a spherical atmosphere, were found to be remarkably successful in reproducing the behaviour of the dominant wavenumbers in the original (primitive equation) model flow. Moreover, by varying the forcing and dissipation parameters, a bifurcation analysis of the POD-Galerkin model could be carried out which predicted the existence of various wave regimes, including a mixed-wavenumber state characterized by coexistence of two distinct wavenumbers (e.g. see Fig. 3).

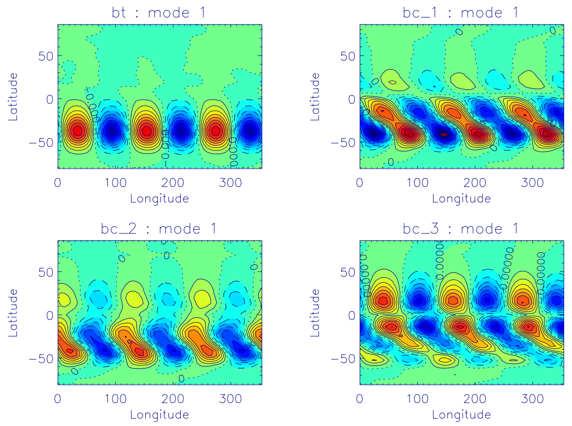

Figure 2: First POD mode in an analysis of a wavenumber m= 3, southern hemisphere winter flow regime of Collins & James (1995) on a Mars-like planet with flat topography, obtained by Whitehouse et al. (2005a). Fields are shown projected onto each of the four principal vertical eigenmodes of the vertical structure equation (see Whitehouse et al. (2005a) for further details).

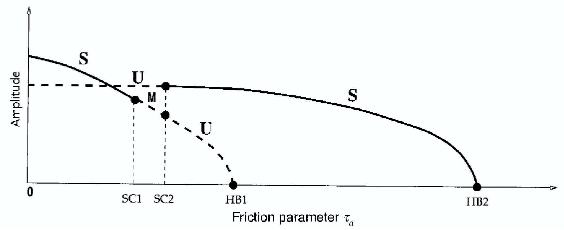

Figure 3: Bifurcation diagram obtained in a POD-Galerkin model based on the POD analysis of the simple Mars-like circulations of Collins & James (1995) by Whitehouse et al. (2005b). The figure plots normalized wave amplitude for each of two dominant zonal wavenumber components as a function of the Rayleigh friction dissipation parameter. Stable solutions are labelled S and unstable U.

More recently, Martinez-Alvarado et al. (2005) has begun a comparable study using more realistic data derived from a data assimilation of the Mars Global Surveyor Thermal Emission Spectrometer (MGS TES) dataset (Smith et al. (2001); see also Lewis et al., this volume). In this case, the derived POD modes include strong contributions from large-scale modes representative of the diurnal tide in addition to those from baroclinic transients (see Fig. 4).

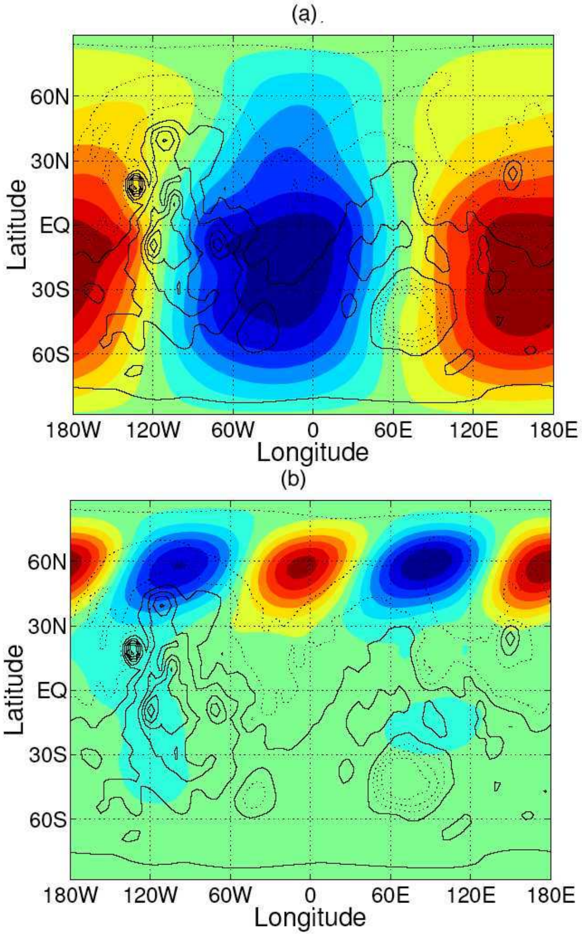

Figure 4: First and third POD mode derived from a northern winter assimilation of Martian atmospheric data from the MGS TES instrument (Martinez-Alvarado et al. 2005), plotted as a map of temperature at a nominal altitude of 20 km.

In work currently in progress, POD-Galerkin models will be derived using these modes as a basis within the full meteorological primitive equations. The latter are necessary because the very large topography on Mars, and the strong non-geostrophic thermal tides, renders the quasi-geostrophic approximation inapplicable to this problem.

2 Predictability and ‘breeding vectors’

The existence of a low-dimensional attractor governing the meteorology of Mars might be expected to have some influence on the predictability of the atmosphere. The intrinsic predictability of an instantaneous atmospheric state is commonly quantified by use of a variety of perturbation techniques in which the growth of a small perturbation is monitored, either in linearized (as ‘singular vectors’) or fully developed form (as ’bred vectors’; see Kalnay (2004)). Newman et al. (2004) computed bred vectors within a set of numerical simulations of Mars climate using the Oxford MGCM under various seasonal conditions. Depending upon the amplitude of the initial perturbation, Newman et al. (2004) found that, for a number of seasons, the typical exponential growth rate of perturbations was actually negative (i.e. perturbations actually decayed slowly with time over a 30 sol interval; see Fig. 5). This would imply a near-absence of chaotic behaviour during this season, implying a highly forecastable flow. Only during seasons around NH winter was the mean growth rate significantly greater than zero, implying an actively chaotic atmosphere. The peak growth rate corresponds to a mean perturbation doubling period of around 2.1 sols, comparable to the Earth’s tropospheric meteorology (Kalnay, 2004).

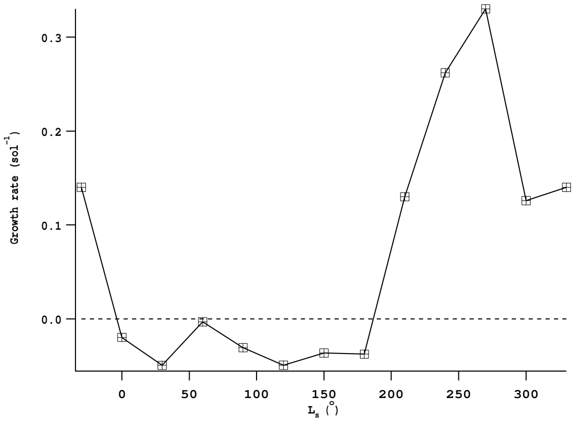

Figure 5: Growth rate (in sol^{-1} of the dominant breeding vector in the Viking (relatively dusty) scenario Mars GCM simulations of Newman et al. (2004), averaged over sols 3-30 of each of 12 seasons throughout the Martian year.

The bred vector method also enables the structure of the most rapidly growing perturbation. During NH winter, Newman et al. (2004) found that, after 30 sols, the mode exhibiting the most rapid sustained mean growth resembled the dominant large-scale baroclinic mode of instability. Fig.6 shows some examples of horizontal streamfunction maps at two vertical levels in the lower atmosphere for seasons 11 and 12 ($L_s = 300 - 360°$), which clearly show modes dominated by $m = 1 - 2$ at high northern latitudes.

Newman et al. (2004) found some sensitivity in the structure and behaviour of the bred vectors to the amplitude of the initial (random) perturbations, with some very small amplitude perturbations initially growing rapidly but then saturating before reaching the amplitudes obtained in the computations shown in Figs 5 and 6.

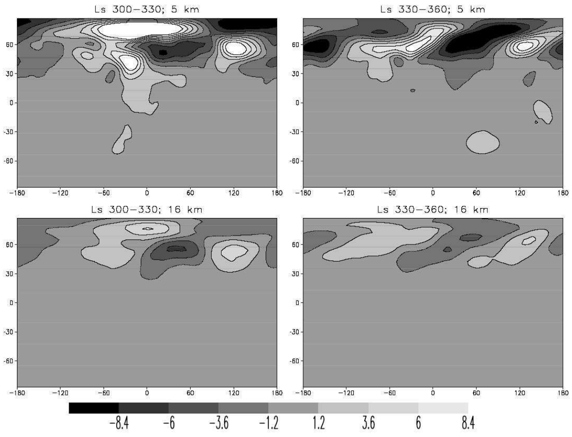

Figure 6: Normalized streamfunction perturbation at the end of a 30 sol breeding run in the Viking (relatively dusty) scenario Mars GCM simulations of Newman et al. (2004). Maps are shown for seasons 11 and 12 (NH winter) at altitudes of 5km and 16km.

3 Future work

In ongoing research, the subsequent evolution of atmospheric circulation patterns emerging from finite amplitude perturbations based on bred vectors is being investigated (a) from stand-alone GCM simulations, and (b) from GCM forecasts initialized from atmospheric states initialized using MGS TES observations during the period 1999-2004 (see Lewis et al., this volume). This presentation will conclude with a report on preliminary ensemble predictions from this study.

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