REGULAR AND IRREGULAR BAROCLINIC WAVES IN A MARTIAN GENERAL CIRCULATION MODEL: A ROLE FOR DIURNAL FORCING?

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ABSTRACT

The development and evolution of baroclinic transient waves are simulated in a high resolution, general circulation model (GCM) of the Martian atmosphere, including simulations both with and without a representation of the diurnal cycle of solar heating. Simulations with diurnally-averaged insolation are found to develop highly regular baroclinic transients during northern hemisphere autumn, winter and spring seasons, characterized by zonal wavenumber 1 or 2 and periods of 2-6 sols (a sol being a Martian day). With a diurnal cycle, however, transients are found to be significantly more irregular throughout the winter season, sporadically changing their dominant wavenumber and frequency, and resemble more closely data from the Viking Lander time series. These results are discussed with reference to some simple conceptual models in nonlinear dynamics, in terms either of a periodically-perturbed, self-exciting oscillator, or of attractor-merging near a crisis in a periodically perturbed bistable system.

INTRODUCTION

Baroclinic waves are a prominent, though seasonally-varying, component of the transient large-scale atmospheric circulation of Mars, and are widely believed to contribute strongly (as on Earth) to the transport of heat, momentum and other tracers at middle and high latitudes in the Martian atmosphere. Such waves are well known to occur in the terrestrial atmosphere, and arise from a baroclinic (potential energy-releasing) instability of the zonal flow state produced primarily as a result of differential solar heating between equator and poles. Unlike the Earth, however, such waves have been observed at northern mid-latitudes on Mars to show strong regularities and apparently enhanced predictability compared with their terrestrial counterparts. Detailed *in situ* observations in the northern hemisphere of surface meteorological variables were obtained by the Viking landers, and revealed coherent oscillations in pressure, wind and temperature with periods around 2-10 sols (often peaking around 2.5 sols, see /1/) during the autumn, winter and spring seasons. These oscillations were identified as being due to a partially coherent train of baroclinic waves centred at high latitudes, with zonal wavenumbers typically ≤ 5, and which persisted for periods $\sim$ 10-50 sols. The spatial and temporal regularity of these wave systems has led to comparisons being drawn with the regular wave regime of the thermally-driven rotating annulus experiments in the laboratory (cf /2/, /3/), which exhibit a range of regular and oscillatory flows, multiple equilibria, etc. Recently a simplified GCM of the Martian atmosphere has been used /4/ to simulate baroclinic waves with a high degree of spatial and temporal regularity.

We present here results from simulations of the full seasonal cycle of the Martian atmospheric circulation using a new, high resolution general circulation model of the Martian atmosphere, focussing primarily on the development and evolution of transient baroclinic wave activity. The model includes a comprehensive representation of most relevant physical processes on Mars, including a realistic representation of radiative heating and cooling. Experiments have been carried out either with diurnally-averaged insolation, or with a full representation of diurnal variations. We present below results from these simulations, which show that remarkably (and unrealistically) regular flows occur with diurnally-averaged insolation, but with realistic diurnal variations the waves are somewhat less regular and resemble more closely the behaviour found by the Viking landers. This apparent transition from highly regular to partially disordered behaviour by the addition of a periodic perturbation is reminiscent of phenomena observed in a range of much simpler nonlinear dynamical systems.

MODEL DESCRIPTION

The Oxford-LMD Martian General Circulation model (hereafter MGCM) is formulated using a pseudo spectral representation of model dynamics in the horizontal /5/, here used with a resolution corresponding to a triangular truncation in wavenumber space at total wavenumber 21 (hereafter T21; roughly equivalent to a regular grid spaced at $5^o \times 5^o$ in latitude and longitude). A finite difference formulation is used in the vertical in terrain following σ-coordinates (defined as $\sigma = p/p_s$, where p_s is surface pressure), with 10 levels equispaced in pressure spanning the approximate altitude range 500m - 30km.

The parametrizations of physical processes are essentially the same as those used in the LMD Martian GCM, as described in /6/ and provided by Dr F. Hourdin (LMD), though with some differences outlined below, and includes: (i) the radiative transfer scheme of /7/ which represents absorption and emission by CO_2 in the infrared, and absorption and scattering by dust in the visible; (ii) a formulation for vertical turbulent mixing; (iii) an energy-conserving vertical convective adjustment scheme (mixing heat and momentum); (iv) an 11-level diffusive model of heat transport in the surface soil; (v) a representation of the condensation and sublimation of CO_2 at the surface, using an energy-balance scheme which conserves total energy and total mass of the combined atmosphere and ice-caps; and (vi) a planetary boundary layer scheme, representing surface drag and heat exchanges through turbulent mixing near the ground. In the case of (i) and (vi), full seasonal and diurnal variations in solar insolation and surface exchanges can be represented, computing the radiative forcing up to 20 times per day.

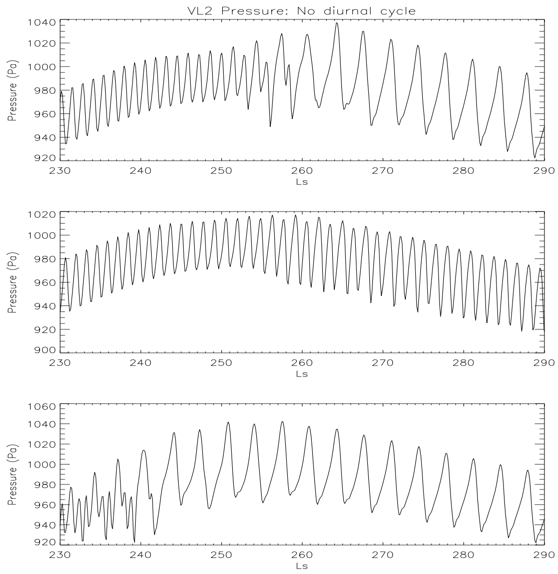
Our schemes differ from those of /6/, in using (a) a modified version of the boundary layer scheme, (b) a form of horizontal diffusion of temperature which acts on pressure surfaces (rather than on σ surfaces), (c) a modified form of the CO_2 mass budget in (v), and (d) in the fields of surface topography, albedo and thermal inertia. In the case of the latter, we use the current version of the USGS Digital Terrain Model, and forms of the 'Consortium datasets' for albedo and thermal inertia, extended towards the poles (provided courtesy of Prof. D. A. Paige of UCLA).

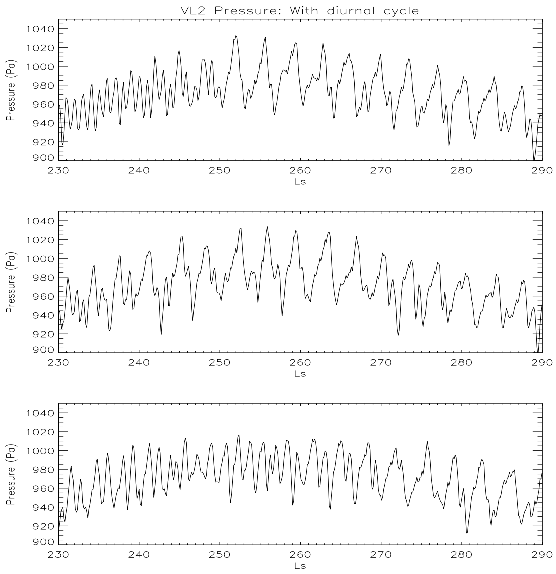
MGCM BAROCLINIC WAVE PHENOMENOLOGY

Simulations of several years of the Martian global circulation have been performed with the MGCM. All the simulations were performed with a horizontal resolution of T21 and with 10 equally spaced σ levels in the vertical with an altitude range of 500m - 30km. The dust optical depth was fixed at 0.2 as in /6/. The simulations fall into two distinct categories, in the first of which the incoming solar radiation was averaged over a Martian day in order to eliminate the diurnal cycle and the second in which the insolation was allowed to vary diurnally.

Figure 1 (a) shows the surface pressure at the approximate location of Viking Lander 2 (VL2) for seasonal dates $L_s = 230$ to $L_s = 290$ in the first year of a simulation, in which the insolation was averaged over each day. The oscillations of pressure have an extremely periodic nature, much more periodic than the observations taken by VL2 itself, with the successive appearance of two distinct frequencies. The higher frequency oscillation has a period of approximately 2.01 Martian days (sols), whilst the lower frequency oscillation has a period of approximately 5.56 sols. Also shown in Figure 1 are two winters from simulations with the same boundary conditions as in Figure 1(a) but with a white noise surface pressure perturbation of order 10^{-2} Pa added to the initial conditions at $L_s = 0$. In Figure 1(b) only the higher frequency oscillation is present whilst in Figure 1(c) the higher frequency oscillation is somewhat modulated in amplitude and the lower frequency oscillation emerges at an earlier seasonal date. The model thus exhibits a form of interannual variability which is sensitive to the initial conditions.

The spatial characteristics of the two modes of pressure oscillation are illustrated in Figure 2, which shows longitude-time maps of surface pressure anomaly at 75^oN. The time-averaged surface





Left Fig 1. Three model winters of Viking Lander 2 pressure from simulations with diurnally averaged insolation. (a) Control, (b) with a white noise surface pressure perturbation of magnitude 10^{-2} Pa added to the simulation at $L_s = 0^o$ and (c) as in (b) but with a different white noise pressure perturbation.
Right Fig 3. Three model winters of Viking Lander 2 pressure from from simulations with diurnally varying insolation.

pressure has been subtracted to remove the effects of the mountains. The higher frequency wave is mainly composed of zonal wavenumber 2 with a phase speed of 90^o longitude per day or 43 m s^{-1} at 45^oN. The lower frequency wave is mainly composed of zonal wavenumber 1 with a phase speed of 65^o longitude per day or 31 m s^{-1} and 45^oN. Note that the wave amplitudes (as measured by the magnitude of surface pressure anomaly) are not constant with longitude, but are modulated by orographic features at the surface.

Figure 3 shows three model VL2 pressure traces for simulations in which the diurnal cycle in insolation was retained. Such a periodic forcing can excite thermal tides, slope winds and also the equatorial Kelvin wave, though such phenomena have their largest amplitudes in the equatorial and summer hemisphere regions of Mars. Although the diurnal cycle in pressure is small at the VL2 site ($O(\pm 1) Pa$), the pressure oscillations due to the passage of baroclinic waves have the appearance of being much more noisy than those seen in the simulations with daily-averaged insolation. Simply comparing the pressure oscillations by eye, it would appear that including the diurnal cycle in the simulations causes the baroclinic wave activity to be more aperiodic than in the case with diurnally averaged insolation. A simple linear addition of frequencies is not evident. Spectral analysis of the pressures again show bimodality with two characteristic higher and lower frequency oscillations, but with much more background noise. Longitude time plots of surface pressure anomaly (Figure 4) show that the higher frequency oscillations have a zonal wavenumber 2 character whilst the lower frequency oscillations have a zonal wavenumber 1 character. However, the waves are less spatially coherent than in the case with daily averaged insolation.

SIMPLE NONLINEAR ANALOGUES?

The transformation from periodic to aperiodic and/or noisy periodic behaviour upon application of a periodic perturbation is highly reminiscent of at least two kinds of phenomenon observed in simple nonlinear dynamical systems, as reported in the literature of nonlinear dynamics and chaos. A comparison with such analogues may suggest particular mechanisms for generating chaotic behaviour in our models which could account for the observations reported above.

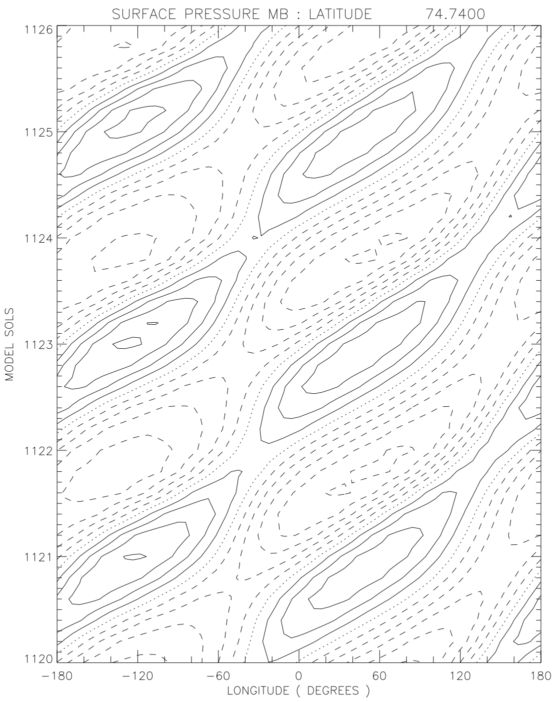


Fig 2. Two longitude time plots of surface pressure anomaly, in mb, at 75^{o}N from the northern winter of a simulation with diurnally averaged insolation. (a) A higher frequency zonal wavenumber 2 wave, (b) A lower frequency zonal wavenumber 1 wave. Solid contours are positive and dashed contours are negative. The contour interval is 0.1 mb.

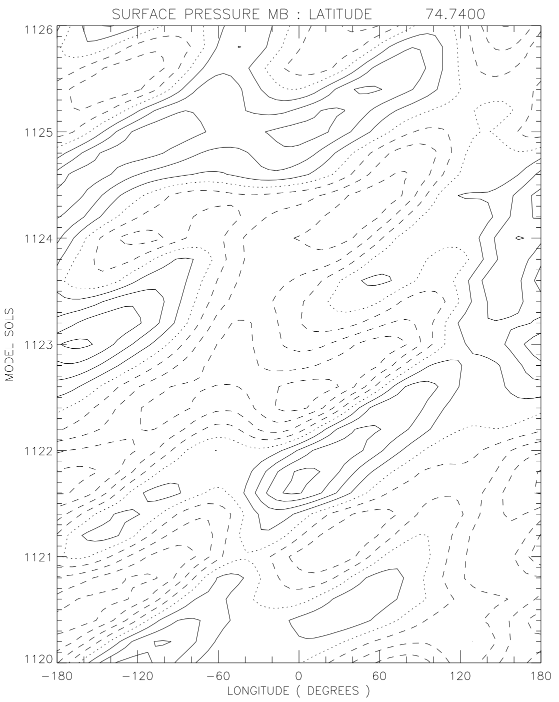


Fig 4. Two longitude time plots of surface pressure anomaly at 75^{o}N from the northern winter of a simulation with diurnally varying insolation. Solid contours are positive and dashed contours are negative. The contour interval is 0.1 mb.

Several self-exciting nonlinear oscillators, for example, the van de Pol and 'Brusselator' systems /8/, exhibit well-defined periodic oscillations in the absence of perturbations, which are then modified in the presence of a periodic perturbation in a manner which is a strong function of the amplitude and frequency of that perturbation ('scenario A'). If the perturbing frequency ω_p is incommensurate with that of the self-oscillation ω_s, weak forcing results in a simple additive response, but with stronger forcing a sequence of transitions occur, typically involving frequency entrainment and locking between ω_s and ω_p, a period doubling cascade and ultimately chaotic behaviour as forcing amplitude is increased.

An alternative 'scenario B' is found in certain systems which may have two or more distinct stable states which may coexist at a given point in parameter space /8/. The state observed may then depend upon the initial conditions. If such attractors are sufficiently close together in phase space (close to a 'crisis' in the terminology of nonlinear dynamics, /9/), a small perturbation (either periodic or noisy) of sufficient amplitude may cause the system to begin to flip erratically between the two initially distinct attracting states, resulting in a form of 'attractor merging' which may result in chaotic behaviour. The development of such chaotic behaviour as perturbation amplitude is increased is not, however, necessarily accompanied by a well-defined sequence of lockings and period-doublings as above.

TESTING HYPOTHESES USING A SIMPLE GCM

This distinction may offer the possibility of testing the relevance of either analogue to the interpretation of our MGCM results discussed above. Experiments are currently under way using a highly simplified version of our MGCM in which physical parametrizations are replaced by simple Newtonian relaxation and Rayleigh friction (as in /4/) both with and without surface topography, and with the addition of a simple representation of diurnal heating whose amplitude can be varied. Preliminary results without topography show no evidence for frequency entrainment or period-doubling as the diurnal perturbation amplitude is increased. Such a result would initially tend to favour 'scenario B', although further work is certainly needed to confirm this. An analogy with the bistable form of the 'scenario B' system, however, is certainly suggested in the bimodal character of the diurnally-averaged MGCM simulations shown above. Time series from future *in situ* lander type measurements would help us to test this hypothesis, whilst remotely sensed orbiter data would help us to verify the MGCM used in this study.

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