A diagnosis of low-order dynamics in the atmosphere of Mars

Conference or Workshop Item

A DIAGNOSIS OF LOW-ORDER DYNAMICS IN THE ATMOSPHERE OF MARS.

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Introduction

There is considerable evidence that shows that the Martian atmosphere behaves in a more regular fashion than its terrestrial counterpart [1, 2, 3, 4]. This evidence leads to the hypothesis of the Martian climate attractor being of a relatively low dimension, which, in turn, would imply the possibility of describing the state of the atmosphere by means of a relatively few degrees of freedom. We explore this hypothesis by assuming that the atmospheric total energy (TE), i.e. the sum of kinetic energy and total potential energy (gravitational potential energy plus internal energy), is confined in a few coherent structures which dynamically interact nonlinearly with each other.

Methodology

Our approach consists of a composite technique aimed at the identification of coherent structures in the atmosphere and the dynamical relations between them.

First we used the technique of proper orthogonal decomposition (POD). This is a method for extracting coherent structures from an ensemble of data [5]. The coherent structures, commonly called empirical orthogonal functions (EOFs), are optimised with respect to an energy-like quantity such as variance (statistical dispersion of the data) or kinetic energy. In the present case, the EOFs were optimised with respect to TE. The set of EOFs is orthogonal and can serve as a basis for the function space where the climate attractor exists. The original dataset can be reconstructed as a linear combination of EOFs. The EOFs' coefficients are known as principal components (PCs) and contain information on the evolution of the corresponding EOFs.

In contrast with previous work by Whitehouse *et al.* [6], who also used POD in their analyses, we used the primitive equations (PEs) of dynamic meteorology in sigma-coordinates as underlying equations of motion as opposed to the quasi-geostrophic (QG) approach taken in [6]. The need of using PEs arose from the use of a more realistic general circulation model (GCM), which includes a comprehensive package of parameterised physical processes and topography, than the simplified Mars GCM used in [6]. Given these conditions, we performed a fully three-dimensional POD, simultaneously decomposing three atmospheric fields, namely the two horizontal velocity components and a thermal variable.

The second technique was Fourier analysis, which we used to study the evolution of PCs and then, to extract specific atmospheric wave components given their zonal wavenumber and frequency (including direction of zonal displacement) [7, 8]. For the latter procedure, we employed a spatio-temporal short-time Fourier transform with a 4-sol window with a sampling interval of 12 samples per sol. This settings enabled us to look into a frequency range from 0 to 6 sol^{-1} with a resolution of 0.25 sol^{-1}. Since baroclinic waves on Mars are known to have periods between 2 and 8 days, this frequency range and resolution is appropriate for our purposes. We focused our study on tides, including the diurnal, semidiurnal and diurnal Kelvin wave, and transient baroclinic waves (defined for this purpose as the remainder after subtracting tidal motions), as well as stationary waves modulating the atmospheric basic state. Once these components were separated, they were projected onto the EOFs. This procedure allowed us to determine the tidal and transient TE content that was explained by every EOF.

These methods were applied to a dataset produced by the UK-MGCM [9] in free-running mode under conditions corresponding to the transition from autumn to winter. This period is characterised by strong baroclinic activity in the northern hemisphere. The dataset had a duration of 90 sol sampled every 2 Martian hours (i.e. 1/12 sol).

Results from POD

The results from POD reveal that the distribution of TE is strongly concentrated within the first few EOFs with 80% of TE concentrated in as few as 7 EOFs and 90% in just 20 EOFs.

The spatial structure of the EOFs bears immediate identification with important atmospheric motions on Mars. For example, EOF3 exhibits an aspect similar to the diurnal tide (figure 1) and EOF5 has a structure that resembles the structure of a transient baroclinic wave train (figure 2).

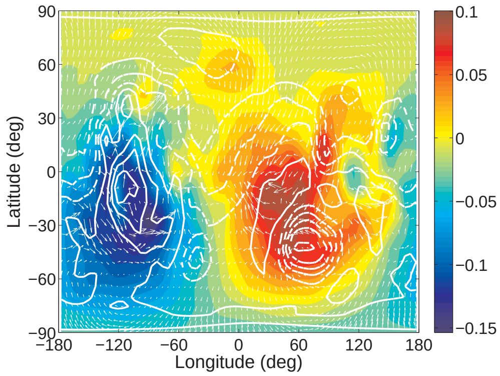


Figure 1: Horizontal velocity (arrows) and thermal field (colours) in EOF3: horizontal structure approximately 5 km above the planetary surface. White contours represent topography. The fields are non-dimensional and the units, arbitrary.

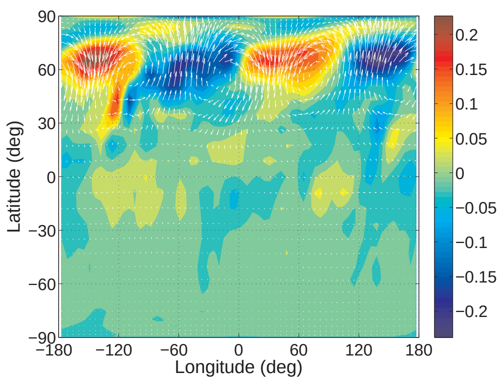
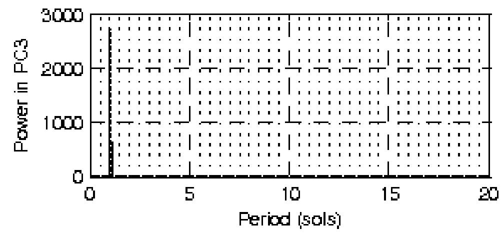


Figure 2: Horizontal velocity (arrows) and sigma-velocity ($\dot{\sigma} = d\sigma/dt$, color) in EOF5: horizontal structure approximately 32 km above the planetary surface. White contours represent topography. The fields are non-dimensional and the units, arbitrary.

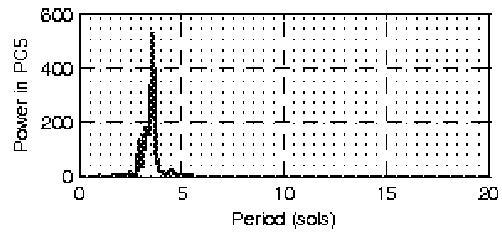
These observations are supported by the Fourier analysis of the time series of the corresponding PCs which display strong peaks at 1 sol, in the case of EOF3 (figure 3(a)), and 3.5 sol, in the case of EOF5 (figure 3(b)).

Results from short-time Fourier analysis

The short-term Fourier analysis shows that the most energetic EOFs are identified with important components of motion in the Martian atmosphere such as the diurnal and semidiurnal tides, the diurnal Kelvin wave and transient baroclinic waves. As an example, figure 4 shows the EOF-decomposition of the diurnal tide and transient



(a) PC3



(b) PC5

Figure 3: Power spectra vs period.

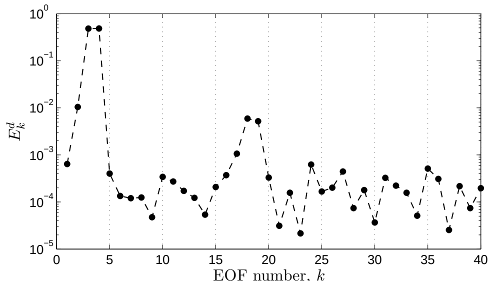
waves over 40 EOFs. The diurnal tide mostly corresponds to EOF3–4 and EOF18–19 (figure 4(a)). Transient waves are more evenly distributed but mostly correspond to EOF5–8 (figure 4(b)).

These results confirm that indeed EOFs and atmospheric wave motions correspond to each other to a large extent. However, the fact that the atmospheric motions here considered spread over a range of EOFs rather than being completely explained by just one or a single coupled pair of EOFs indicates that their evolution is intrinsically linked to one another. This supports the hypothesis of nonlinear interaction between EOFs. However, it does not rule out the possibility of higher-order EOFs having a decisive influence in the evolution of the atmosphere.

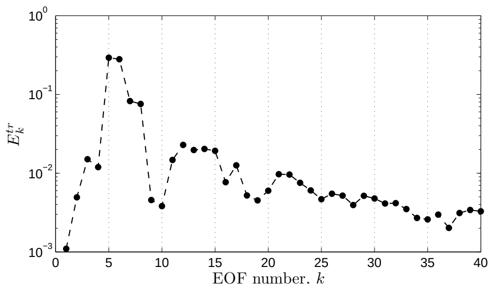
Conclusion

The main conclusion that can be withdrawn from the combined results of the POD and the Fourier analysis is that those motions known to have a predominant role in the development of the characteristic features of the Martian atmosphere are also the most energetic coherent structures.

Given the hypothesis of a low-dimensional Martian climate attractor, we can conjecture that the nonlinear interaction of the most energetic EOFs determine the evolution of the atmosphere on synoptic scales. If this was true, then the corresponding PCs would be the fundamental degrees of freedom of the atmosphere (at synoptic scales). The formulation of dynamical systems based on



(a) Diurnal tide



(b) Transient waves

Figure 4: (a) Diurnal tide and (b) transient wave decomposition over 40 EOFs averaged over 90 sols.

these assumption seems to support this idea to a certain extent [10]. However, the need of parameterising the influence of higher-order EOFs suggests that these modes exert a non-negligible action on the evolution of the general circulation as well.

Future work

We expect to apply these techniques to datasets under different conditions and for different times of the year. In particular, we are interested in the analysis of simulations including data assimilation. For example, we could analyse the transition autumn-winter to obtain a comparison between the results presented here and those including data assimilation.

Another possible variant could be the analysis of simulations under extreme conditions such as those posed by planet-encircling dust storms, for which the global character of our approach seems suitable. This could lead to new insights into the interaction between Kelvin waves and radiative heating anomalies and the mechanisms leading to teleconnections in the Martian atmosphere, as described by Montabone *et al.* [8].

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