Planetary Eddies in the Martian Atmosphere: FFSM Analysis of TES Data

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Introduction:

Planetary scale eddies of various types play very important roles in the general circulation of the Martian atmosphere and in the climate system of Mars. In particular, transient baroclinic eddies (midlatitude weather systems) and quasi-stationary eddies are prominent. Both types of eddies are fundamentally analogous to their counterparts in the terrestrial atmosphere, opening up excellent opportunities for comparative studies. Transient baroclinic eddies were predicted to be present in middle and high latitudes in the fall, winter, and spring on Mars on the basis of theory and GCM simulations (1). The Viking Lander Meteorology data allowed their existence to be verified, and some of their most basic properties to be determined (2,3). Quasi-stationary eddies were also predicted by theory and modeling to be present in all seasons, in both the tropics and the extratropics. Viking IRTM data appeared to evidence these eddies, and MGS TES and RS data have recently allowed their existence to be confirmed (4).

The MGS TES data allow the determination of the basic properties and dynamics of the transient baroclinic and quasi-stationary eddies. This can be done in different ways. We have utilized a technique referred to as Fast Fourier Synoptic Mapping (FFSM), in order to do this with the TES nadir temperature data. To date we have analyzed in detail a sub-set of all of the data, focusing upon seven time intervals averaging about 40-50 sols in length.

Data Analysis:

The FFSM technique was originally developed some time ago (5,6), but it has not been used very much with terrestrial data. It offers some very considerable benefits, however. In particular, it allows the production of twice-daily synoptic maps from the highly asynoptic TES data. These maps reflect the full space-time resolution of the data, which extends to zonal wavenumber 6 and to periods slightly shorter than 1 sol (for eastward traveling waves). Relatively higher frequency (1-3 sols) features are not distorted or smoothed by the FFSM analysis, something that is often a major problem with other methods. An intermediate product of the FFSM analysis is a set of spectra for the interval being examined. These spectra allow the identification of the dominant wave modes which are present in the data, and the characterization of their amplitude and phase structures. The volume of the TES data allows the spectra to have very high statistical significances, which allows even quite weak eddies to be found. The synoptic maps allow the full time evolution of the disturbances to be seen, and they provide a starting point for the computation of various higher-order quantities (winds, heat and momentum fluxes, EP fluxes, etc.).

The FFSM analyses require considerable preprocessing of the data. First the data must be sorted into ascending and descending orbit observations for each latitude bin and TES pressure level. We have chosen to "oversample" in the vertical (using ~ 15 levels), and to employ one degree latitude bins spaced at 5 degree intervals. The small bin size greatly helps to avoid aliasing due to very sharp meridional gradients in the data. All gaps in the data then have to be filled in using interpolation schemes – either interpolating along an orbit or interpolating between orbits for longer gaps. After close examination of the resulting time series of data, the basic FFSM analysis can be carried out for each latitude bin and vertical level. This analysis yields the twice-daily maps as well as the spectra – one for each zonal wavenumber, and for each latitude and vertical level (typically, a very large number of spectra). The maps can be produced in various ways, depending on how one selects the spectral coefficients to be used in the mapping. We have produced maps of the full temperature fields as well as maps of the transient eddy part of the temperature fields as standard products; other maps can be very useful in various circumstances. The maps can be produced at much higher time resolutions (as well as much higher longitudinal resolutions – we have used 5 degrees as a standard) than twice-daily in order to facilitate the detailed study of transient features via movies, but the true resolution of the data is equivalent to two maps per sol.

The spectra are examined closely in order to identify the dominant spectral peaks. These then lead to the selection of multiple frequency-band modes, at each zonal wavenumber. The amplitudes and phases of the wave modes are then calculated from the spectral coefficient values.

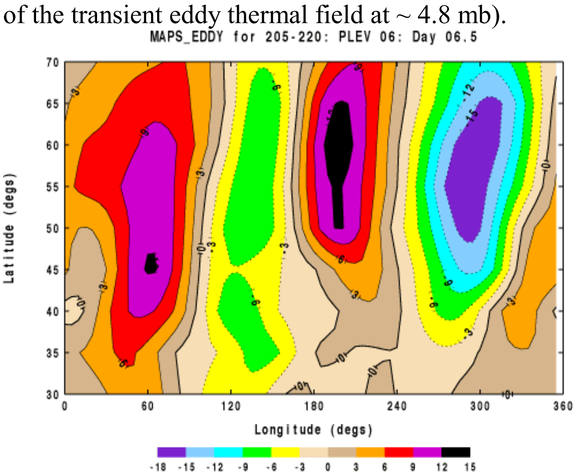
The seven data intervals which we have chosen for analysis to date include two that surround northern winter solstice during the first mapping year, one earlier in the winter (prior to the major dust storm event) of that first year, one surrounding northern spring equinox during the first mapping year, two intervals surrounding southern winter solstice in the second mapping year, and one interval during the middle of southern winter during the first mapping year. These intervals allow an excellent comparison of the eddies in the north and south, as well as an initial look at the variation of the eddies with season in each hemisphere.

Results:

We summarize some of the basic results of the analyses below, separately for each seasonal interval.

Early northern winter This interval covers the range of L_s ~ 205-220 in the first mapping year, a period in early winter before the occurrence of a major regional dust storm - the Noachis Terra storm. Fairly strong eddy activity is present in northern middle/high latitudes during this period – one in which the mean thermal gradients are not as sharp as they are later on in the winter - as eddy temperature variance values are ~ 40-60 K^2 at both lower and upper levels.

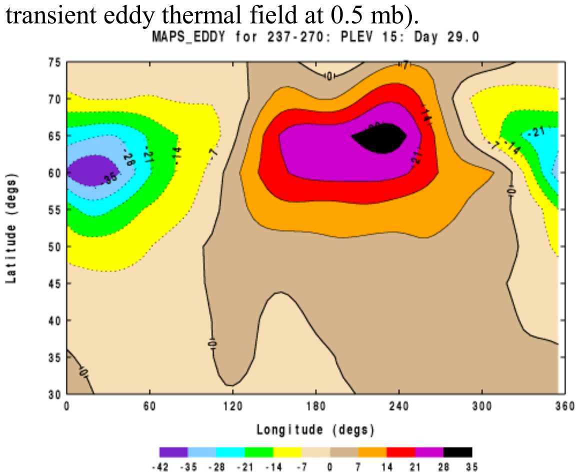
The largest amplitude transient eddy mode in this seasonal interval has a period of ~ 5-10 sols. Zonal wavenumber one has the largest amplitude, but wave 2 also has substantial amplitude. The wave 1 mode exhibits larger amplitudes at upper levels than at low ones; the wave 2 amplitudes are similar at lower and upper levels. The second dominant mode has a period of ~ 2-4 sols, and sizeable amplitudes at both wavenumbers 2 and 3. At wavenumber 2 there is significant amplitude at upper levels, though the largest amplitudes are at the lowest levels, while wave 3 is shallower. There is also a shorter period mode, with a period of ~ 1.4-1.7 sols, which has sizeable amplitudes at both wavenumbers 2 and 3. At times during the interval the eddy thermal field at low levels has a very regular and coherent structure around the planet (Fig. 1 below, showing an example of the transient eddy thermal field at ~ 4.8 mb).



Stationary eddies are present, with substantial amplitude at both wavenumbers 1 and 2; wave 2 is the more dominant. The eddy activity is enhanced in storm zones, maximizing in the vicinity of Acidalia and Arcada.

Northern winter solstice I This interval covers the range of L_s ~ 237-270 in the first year, a period just following the Noachis Terra dust storm event. Eddy temperature variances are as large as ~ 45 K^2 at lower levels and ~ 225 K^2 at upper levels in northern middle and high latitudes. Thus, the eddies have a very strong upper-level character in this period.

Most prominent during this interval is an eastward-traveling, very large amplitude, zonal wavenumber one disturbance having a period of 15-25 sols (Fig. 2 below, showing an example of the transient eddy thermal field at 0.5 mb).



This disturbance has only small temperature amplitudes at low levels, so it is clearly not a typical baroclinically unstable mode. It appears to have a phase structure consistent with barotropic energy conversions, as well as baroclinic coversions. Such a slowly moving wave one mode has been found in GCM simulations. The large amplitudes of this mode during the period just after the dust storm event certainly suggest that it is favored by a more intense zonal-mean circulation. There have been recent speculations that it could be associated with inertial instabilities in low latitudes (7).

A number of other transient eddy modes are also present in this interval. One mode is also primarily zonal wavenumber one, but its period is ~ 6-8 sols. It exhibits large amplitudes at upper levels, but also has (relatively) much larger amplitudes at low levels than the 15-25 sol mode. A wavenumber one mode with a period of ~ 6-8 sols is prominent in the Viking data, as well as in GCM simulations (1,2,3). The GCM studies indicate that this mode is a typical baroclinic one associated with the surface temperature gradient, whose low level temperature maximum cannot be seen by TES. The other prominent mode during this interval is a wavenumber two disturbance with a period of 3-4 sols. It has maximum temperature variance at the lowest levels, but also exhibits a secondary maximum at upper levels.

A very pronounced storm track structure characterizes the transient eddy activity in this period, with the largest variances (more than double the smallest values) occurring in the vicinities of Acidalia and Arcada. The storm tracks persist to the highest levels. Large amplitude stationary wavenumber one and two eddies are present in this period, with wave 2 dominating at lower levels.

Northern winter solstice II This interval covers the range of L_s ~ 270-293 during the first year; by this time the effects of the Noachis Terra storm had disappeared. Strong transient eddy activity is present, with variances as large as ~ 45 K^2 at low levels and ~ 125-150 K^2 at upper levels. The eddies thus do not have as much of an upper-level structure as those present before the solstice, and this is largely due to a considerable reduction in the amplitude of the long-period wave one mode. The sharpness of the mean thermal gradients is reduced in this interval, but not very greatly compared to the period prior to the solstice.

The variance due to the slow wave one mode is roughly a factor of three smaller than in the interval prior to the solstice. The relatively fast wave one mode (~ 6-8 sols) variance, however, is increased by a factor of about three. The 6-8 sol mode also has a strong wavenumber 2 component. The dominant wave 2 mode has a period of ~ 3.5 sols, with maximum amplitudes at the lowest levels. There is also a mode with a period of 2-2.5 sols, at both wavenumbers two and three, which is very shallow.

The transient eddy activity is characterized by pronounced storm zones as in the period before solstice, and the location of these is very similar. Large amplitude stationary wave one and two eddies are again present, with wzvenumber two being larger at both lower and upper levels.

Northern spring equinox This interval spans L_s ~ 350-10 in the first year, a period during which the VL-2 meteorology data show very strong transient eddy activity in midlatitudes (1). The examination of this interval has been hindered by relatively poor TES data coverage, as we have not been able to perform a full FFSM analysis poleward of 60 N. The temperature variance due to the transient eddies increases towards the pole, and there are values as large as ~30 K^2 at 60N at low levels, with the upper level values not exceeding ~ 25 K^2 at 60 N. The eddies are thus much shallower than they are earlier in the winter season.

The bulk of the transient eddy activity in this period is associated with a mode having a period of ~ 2.5-3.5 sols. This mode has sizeable amplitudes at both wavenumbers 2 and 3. At wavenumber 1 there is a mode with a period of 5-10 sols.

Enhanced eddy activity is found in the vicinity of Acidailia and Arcada, much as is the case near winter solstice. The amplitudes of the stationary eddies, waves 1 and 2, are much reduced compared to the two solstice periods, and these eddies have a shallower vertical structure than those present in the winter season.

Southern winter solstice I : This interval covers L_s ~ 75-90 in the second mapping year, a period for which GCM simulations exibit very weak transient eddy activity. The analysis of the TES data confirms that the transient eddy activity is indeed very weak near southern winter solstice. The eddy temperature variance does not exceed 15 K^2 and 25^2 at low and high levels, respectively - and typical values are substantially smaller than this.

A wavenumber one mode with a period of ~ 6-8 sols is present, having a very similar structure to the analogous mode in northern winter. There is also a westward propagating disturbance present with a period of roughly 2 sols, which has an upper-levelamplitude maximum.

The weak eddy activity is concentrated in a region roughly centered on Argyre. A very large amplitude wave one stationary eddy is present, as well as a weaker wave 2 eddy.

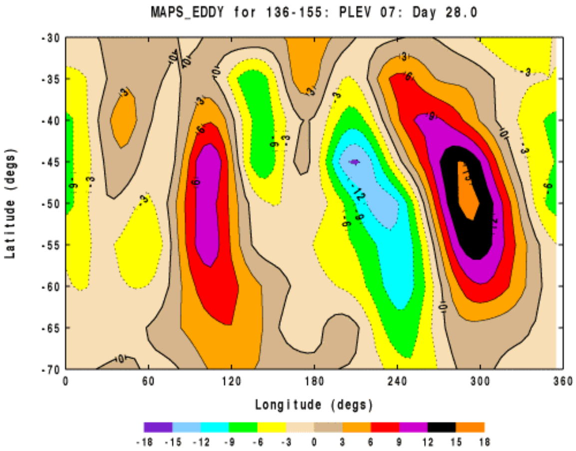
Southern winter solstice II This interval spans L_s ~ 93-111 in the second mapping year, also a period for which GCM's exibit very weak transient eddy activity. The FFSM analysis also yields quite weak eddies, with maximum low-level variance values of ~ 15-20 K^2 and average values much smaller than that; upper level variances do not exceed ~ 30-35 K^2 with much smaller average values.

A wave one disturbance with a period of ~ 8-10 sols is present, along with a westward propagating wave one mode with a period of ~ 1.2 sols. The strongest transient eddy is a wavenumber three mode with a period of about 3.5 sols. This mode has a very shallow vertical structure.

The transient eddy activity is strongest again at lower levels in a region roughly centered on Argyre. A stationary wave one eddy is present at large amplitude, along with a weaker wavenumber two eddy.

Mid-southern winter This interval covers L_s ~ 136-155 during the first mapping year. Analyses of MGS RS data for this time period show relatively strong transient eddy activity, as do at least some GCM simulations. The FFSM analysis for this period yields transient eddy variances at low levels which are as large as ~ 90 K^2, with upper-level values as large as ~ 30 K^2. These mid-winter eddies in the south are thus quite shallow in the vertical.

The bulk of the transient eddy activity during this period is associated with a mode having a period of ~ 2.2-2.5 sols (Fig. 3 below, showing an example of the transient eddy thermal field at ~ 3.7 mb).



This is the same disturbance that has been found in RS data for this season (8). This mode has significant amplitudes at zonal wavenumbers 1-4, with waves 2 and 4 being the largest. The structure of this mode is very shallow, with maximum amplitudes located at the lowest levels at all wavenumbers, in the vicinity of 55 S.

The existence of substantial amplitudes at wavenumbers 1-4 implies a strong storm track structure during this season in the south. The eddy activity is strongest between 180 and 360 E, with the most vigorous activity again located in the vicinity of Argyre. Large amplitude stationary wave one and two disturbances are present in this seasonal interval; the wavenumber 2 eddy has a very shallow structure.

Discussion:

FFSM analysis has been performed on seven different seasonal intervals of TES nadir temperature data, including winter solstice periods in both hemispheres. The results of the analysis confirm the GCM-based prediction of very weak transient eddy activity near winter solstice in the south (1). The northern winter solstice eddies in the first mapping year (following a regional dust storm event) exhibit very large upper-level amplitudes. Prior to winter solstice, a ~ 15-25 sol, wavenumber one disturbance is very prominent at upper levels. Following solstice this disturbance is still present, but a ~ 6-8 sol, wave one mode dominates (this mode being present prior to solstice as well). Earlier in the first year winter, before the dust storm, the transient eddy activity is marked by substantial amplitudes at wavenumbers 1-3. A version of the wave one, 6-8 sol mode is present, along with ~ 2-4 sol and ~ 1.4-1.7 sol modes at both wavenumbers 2 and 3. The early winter eddies have maximum amplitudes substantially further poleward at low levels than those near solstice. This appears to be a consequence of the structure of the mean thermal field – the strongest meridional temperature gradients are located further equatorward near solstice. Fairly strong transient eddy activity exists near spring equinox in the north, but these eddies have much shallower structures than those during the winter season.

The mid-winter season in the south (Ls ~ 136-155) is a very interesting one, in that the low-level eddy activity is quite strong. These eddies are very shallow in nature, which appears to directly reflect the shallowness of the meridional temperature gradients in the zonal-mean flow at this season.

In all the intervals that have been examined to date, the transient eddy activity is very substantially enhanced in certain longitudinal regions. There are strong storm zones, as predicted on the basis of GCM simulations (9). In the north, the storm zones are located in the Acidalia and Arcada regions, which are broad lowlands. In the south, the eddy activity appears to be strongest in a region centered roughly on the Argyre basin. In all cases, the storm zones appear to correlate with trough regions in the zonal flow.

The structure of the transient eddies varies greatly with season and hemisphere. In particular, the eddies in northern winter are extremely deep, with very large amplitudes at upper levels. In early northern winter the eddies are much shallower, and they are shallower yet near spring equinox. In the south, the eddies are relatively shallow in all three of the intervals examined to date. The zonal flow is strongest and the upper level meridional temperature gradients are sharpest near northern winter solstice (in the first mapping year), and such a basic state appears to yield very deep eddies. GCM studies have shown a similar behavior (1).

Along with weak transient eddies near southern winter solstice, GCM simulations have evidenced very large amplitude stationary wave one amplitudes in southern winter. The TES data confirm this basic picture of the southern winter solstice planetary eddies. Near northern winter solstice, the TES data reveal large amplitude transient eddies, as well as fairly large amplitude stationary eddies. GCM studies have found a similar basic picture of the planetary eddies in the two winter hemispheres (1,10).

The observed mid-winter transient eddies in the south are much more vigorous than those near solstice, and preliminary examinations of the TES data appear to show even stronger eddy activity near the southern fall and spring equinox seasons. All of this activity appears to be largely confined to very low levels.

In summary, FFSM analysis of TES nadir temperature data has yielded a basic determination of the planetary eddy properties and structures during seven different seasonal intervals in both hemispheres. The results confirm the basic GCM-based picture of strong northern and weak southern transient eddies during the solstice seasons. Relatively strong eddy activity is present during the middle of southern winter, though it is confined to low levels. Fairly strong activity is present in the north in early winter as well as near spring equinox, though these eddies are much shallower than the very deep ones which are present in the winter solstice season. Storm zones are very prominent in all of the seasonal intervals examined to date.

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