Chapter 12

A Case Study of Tidal and Planetary Wave Coupling in the Equatorial Atmosphere-Ionosphere System Over India: Preliminary Results

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Abstract The present study examines the role of planetary waves and tides observed at upper mesospheric heights (~90 km) in the day-to-day variabilities of the quiet time ionospheric current system as manifested in ground magnetic field records at the dip equatorial and low latitude stations during the three month period, February–April 2008, when an experimental campaign under CAWSES-India program was conducted. The MF radars at Tirunelveli (8.7°N, 77.8°E) and Kolhapur (16.8°N, 74.2°E) provided the wind observations. The study reveals simultaneous presence of 5- to 6-day and 12- to 16-day oscillations in the radar wind fields and the strength of the equatorial electrojet (EEJ) derived from the geomagnetic field records from Tirunelveli and Alibag. Tidal winds and the amplitude of diurnal variation in the EEJ strength show a reasonably good correlation when 5-day averaged data sets are used. Though limited data were used, the present work will motivate further studies on the atmosphere – ionosphere coupling at low latitudes with extended data sets.

12.1 Introduction

Planetary-scale waves like tides, global-scale normal modes and equatorial Kelvin waves play an important role in the dynamics of the mesosphere-lower thermosphere (MLT) region at low latitudes (Vincent, 1993). It has been hypothesized in the past that if a global-scale wave with large amplitude and fairly long vertical wavelength propagates into the ionosphere from below, it should drive an electric current system at E-region heights through the dynamo action with a period of the global-scale wave (Richmond, 1995; Forbes, 1996, for reviews on this subject). This wave-like feature causes perturbations in geomagnetic field that could be recorded on ground (Forbes and Levoroni, 1992; Kohsiek et al., 1995; Gurubaran et al., 2001; Pancheva et al., 2006, 2008; Ramkumar et al., 2006, 2009, to state a few). The F-region of the ionosphere is also known to respond to dynamical forcing occurring at planetary scale wave periods (Forbes and Leveroni, 1992; Chen, 1992; Parish et al., 1994; Forbes et al., 1997; Altadill et al., 1998; Takahashi et al., 2006; Abdu et al., 2006; Pancheva et al., 2006, to state a few). Recent work suggests a role for the E-region dynamo electric fields influenced by nonmigrating tides to cause longitudinal variations in brightness and latitude of F-region airglow bands as well as F-region electron density distribution at low latitudes (England et al., 2008, for example).

Understanding the variabilities of ionospheric parameters at E-region dynamo and F-region heights in terms of variabilities in tides and planetary waves during magnetically quiet times has been a major unresolved issue during the past. It is not known what conditions exist at various altitudes in the MLT region and below, that permit these large-scale waves to reach the dynamo heights and have an influence on the ionospheric variablilities. Whether eddy dissipation due to waves propagating from below undergoing long-period modulation and whether composition changes taking place at turbopause altitudes can drive such variabilities are issues that need to be addressed. It is also not

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known whether any part of the wave spectrum that contributes to the ionospheric variabilities is composed of waves that are generated in-situ.

Aiming to address the vertical coupling of atmosphere-ionosphere system by means of tides and planetary waves, we initiated an analysis of simultaneous observations of MLT winds from the two low latitude MF radar sites, Tirunelveli (8.7°N, 77.8°E) and Kolhapur (16.8°N, 74.2°E), available for about 2 years (2008–2009). Confining the analysis to the Indian sector for the time period February–April 2008 when an experimental campaign under the national CAWSES program was conducted, this work examines whether long-period oscillations at planetary wave time scales in the radar winds are accompanied by variations at similar periodicities in the strength of the equatorial electrojet current system as manifested in the ground geomagnetic field data sets obtained from the two magnetometer sites in India, Tirunelveli, the dip equatorial station and Alibag (18.6°N, 72.9°E, geographic; 9.75°N magnetic) located off the dip equator. We also examine whether any variations in the diurnal and semi-diurnal tide amplitudes are correlated with the daily range in the EEJ strength during this period.

The objective of this exercise was not to perform an extensive analysis of radar winds and geomagnetic field variations but to focus on one small time segment during which simultaneous wind observations from two low latitude sites in the same longitude sector are available. Further analysis to be carried out by the authors will extend this exercise to much larger global data sets.

12.2 Selection of Data

The medium frequency (MF) radar at Tirunelveli has been providing continuous data on winds in the height region 80–98 km since 1992 (Rajaram and Gurubaran, 1998). A similar radar has been operating continuously at the low latitude station, Kolhapur, since December 2007. A CAWSES-India experimental campaign was conducted during February–April 2008. Results to be presented in this work were obtained from the radar and magnetometer data sets collected during this campaign.

The wind measurements, sampled for every 2 min, are averaged for each hour and used for further analysis. Though winds are measured every 2 km, the data acceptance rate, which is based on several rejection criteria (Briggs, 1984b), is sufficiently large only above 88 km. Radar measurements at Tirunelveli made at higher heights (above 94 km) are constrained by the influence of electric fields and the radar tends to measure the electron drift motion driven by intense electric field rather than the neutral wind (Gurubaran and Rajaram, 2000). Traditional harmonic and Morlet wavelet analysis methods are applied to the radar data to retrieve information on tidal and planetary wave characteristics. Data sets from the two sites are also subjected to cross-wavelet analysis to extract common periodicities representing distinct wave events occurring at the same time over the two sites.

The variations in the three components of the geomagnetic field are being recorded by a network of magnetic observatories of Indian Institute of Geomagnetism located from the magnetic equator to the northernmost Indian latitudes. Tirunelveli is a station located close to magnetic dip equator and is under the influence of the equatorial electrojet (EEJ), which is an intense band of eastward electric current flowing at an altitude of $\sim$105 km during daytime in a narrow latitudinal belt ($\pm 3°$) around the dip equator and superposed over the normal Sq current system, whereas Alibag is a station outside the electrojet belt and is solely under the influence of the Sq current system. It is a usual practice to take the difference in the horizontal magnetic field variations over the two sites as representing the strength of the EEJ (Kane, 1973; Anderson et al., 2002). By considering the difference in the horizontal magnetic field variations, any contribution from the distant magnetospheric currents that vary over a much larger spatial scale than the distance between the two low latitude stations is minimized.

Pancheva et al. (2006) described a novel method designed for studying the variability of the geomagnetic field with periods of planetary waves. With the supposition that the variability of the geomagnetic components with the period of the planetary waves appears as a modulation of the quiet-day diurnal cycle, this method invokes a decomposition of the data using a concrete mean diurnal variation instead of a standard sine function. The perturbation amplitude then is evaluated as a deviation from the mean diurnal cycle thus defining how the diurnal cycle is modulated at planetary wave periods. In a later study Pancheva et al. (2008) adopted this method to extract 5- to 6-day periodicities in the geomagnetic field variations. In this work we use this method to extract the signatures of planetary waves in the geomagnetic data sets.

12.3 Results

We begin by showing results from the Morlet wavelet transforms that were performed on the hourly mean data on winds at 90 km over Tirunelveli and Kolhapur and examine the dominant long-period planetary-scale waves that might be present over the two radar sites. For the sake of convenience, we have divided the scale of the long-period wind spectra into two period ranges: (i) 2- to 10-day period range and (ii) 10- to 20-day period range. Because the comparative analysis with geomagnetic data is restricted to February–April 2008 period, we examine the results from this exercise for this period in Figs. 12.1 and 12.2.

In the period range of 2–10 days (Fig. 12.1), two bursts of wave occurrences in both zonal and meridional wind components are noticed at Kolhapur (bottom panels) at periods close to 7 and 6 days, respectively, around day numbers 60 and 90. The meridional wind over Tirunelveli (top right panel) exhibits peaks at similar periods noticed in the corresponding wind field over Kolhapur. In the zonal component over Tirunelveli (top left panel), intense bursts of wave activity are seen at periods close to 6 days around day numbers 35 and 60. The 5-day wave is known to be a global scale Rossby mode (gravest symmetric Hough mode of westward propagating zonal wavenumber 1) detected in radar and satellite observations (Riggin et al., 2006, for example), whereas the 6-day wave is a Kelvin wave signature often observed at low latitudes (Pancheva et al., 2008, for example). With the limited data sets presented here, however, we are not able to identify what planetary wave modes drive the observed wind perturbations.

In the 10- to 20-day period range (Fig. 12.2), a large-amplitude wave at ~16-day period in the zonal wind is clearly evident over both Tirunelveli and Kolhapur (top left and bottom left panels) between day numbers 20 and 70 days. In the meridional component (top right and bottom right panels), a somewhat weaker wave event can be detected at periods closer to 12 days near day number 90 over both sites. Between day numbers 30 and 50, enhancement in wave intensity can be noticed at periods close to 12 days over Tirunelveli and at ~14 days over Kolhapur. The quasi-16-day wave is known to be one of the classical normal modes with an eigen period of 12.5 days that are expected to be Doppler shifted to greater periods in the realistic non-zero background flow (Forbes, 1995). The quasi-16-day wave, its characteristics and its long-term variability over Tirunelveli were studied earlier (Sridharan et al., 2003).

We next examine the geomagnetic field variations during the period February–April 2008 with the objective of detecting long-period oscillations in them and examining whether they are associated with planetary waves observed in radar winds at those times. The chosen period falls during the quiet phase of the 11-year sunspot cycle, though there was 27-day recurrent geomagnetic activity with moderate geomagnetic storms accompanied by sudden storm commencement occurring around 26 March 2008 (day number 85) and 22 April 2008 (day number 112). The geomagnetic activity index, Ap, registered largest values (in the range 20–40) around 2, 10 and 29 February (day numbers 33, 41 and 60, respectively), 9 and 27 March (day numbers 68 and 85, respectively) and 6 and 23 April (day numbers 96 and 113, respectively). The geomagnetic field at low latitudes would then show enhanced variations at these times different from their quiet-time behavior.

In Fig. 12.3a, b we depict the 1-min values of the variations in the horizontal component (ΔH) of the geomagnetic field recorded at Tirunelveli and Alibag, the difference field representing the strength of the equatorial electrojet and the Dst representing the strength of the magnetospheric ring current that would contribute to the low latitude geomagnetic field variations. Apart from the significant day-to-day variations, we also notice the disturbed time response of the geomagnetic field at these latitudes whenever Dst decreased below –50 nT (the days between vertical lines in Fig. 12.3a, b indicate those disturbed periods). However, these disturbance signatures are greatly suppressed in the difference fields representing the EEJ strength (shown in the bottom panels). We utilize the latter parameter in our further analysis.

Past results on the short-term periodic variation in the solar wind have revealed a broad spectral peak around 27-days and distributed over a range of 22–32

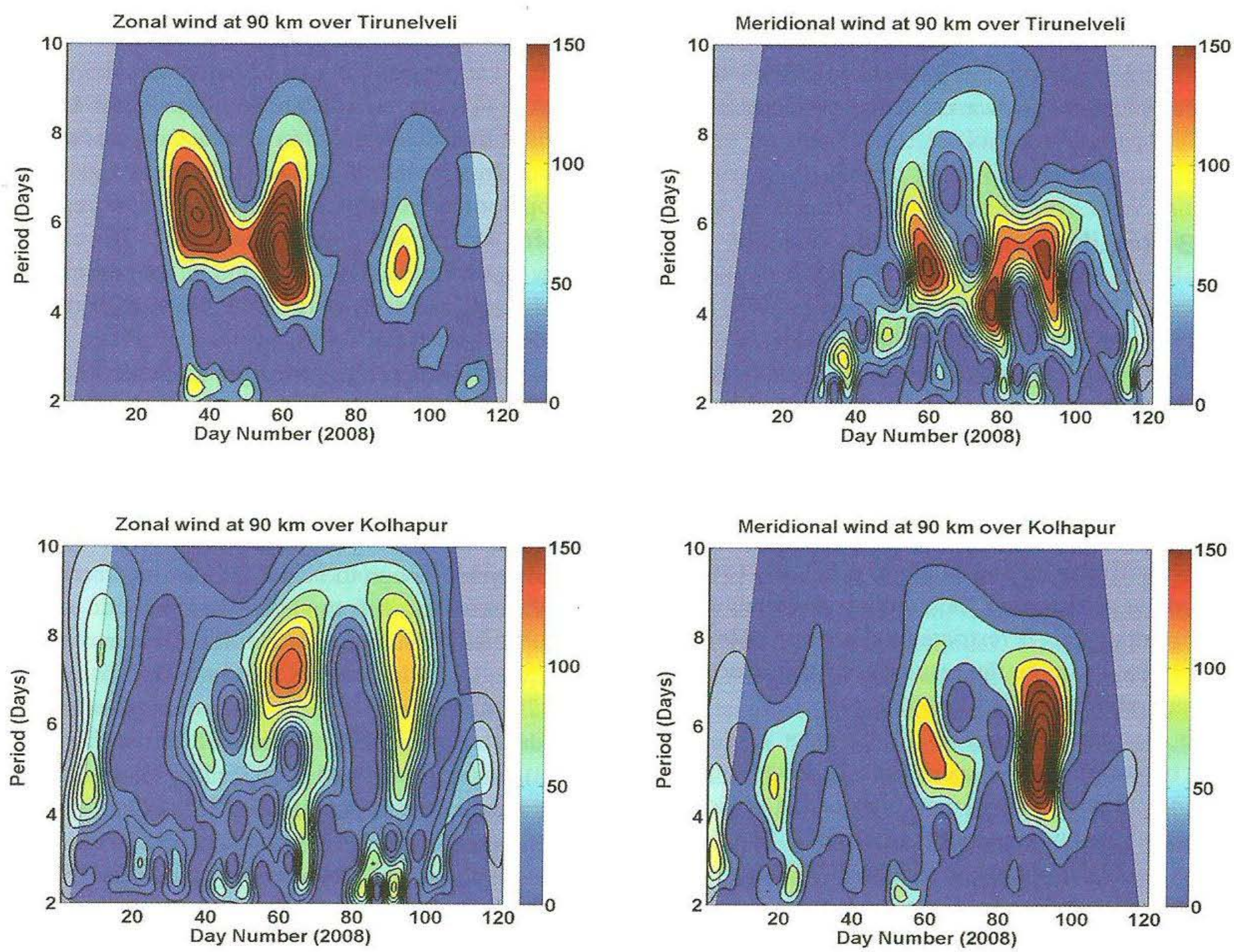

Fig. 12.1 Wavelet power spectra for zonal (shown on the *left panels*) and meridional winds (panels on the *right*) at 90 km over Tirunelveli (*top panels*) and Kolhapur (*bottom panels*) for the period range 2–10 days

days and a sharp and distinct peak at 13.5 and 9 days (Nayar, 2006; Lei et al., 2008, for example). Specifically, Lei et al. (2008) report a 9-day recurrence of fast streams in the solar wind having origin in solar coronal holes distributed roughly 120° apart in longitude and that modulates geomagnetic activity and thermospheric densities at 9-day period. It is expected that the geomagnetic activity would exhibit these spectral features in its response to solar wind variations. Any analysis attempting to determine planetary wave influence on ionospheric current systems and geomagnetic field variations will have to take into account this aspect of the terrestrial response to changes in solar output. In particular, the geomagnetic field variations at lower latitudes are dominated by magnetospheric current systems that get amplified during the main phase of the geomagnetic storms and are influenced by electric fields and resulting current systems due to direct penetration of polar cap electric fields to the equator (Kikuchi et al., 1996) and disturbance wind dynamo triggered by auroral Joule heating and ion-drag acceleration (Blanc and Richmond, 1980). It is anticipated that such disturbances of solar origin would produce a zonally symmetric response in the geomagnetic field whereas travelling planetary waves would induce zonally propagating features in the ground geomagnetic field variations (Pancheva et al., 2008).

A periodogram analysis of geomagnetic field variations recorded at Tirunelveli and Alibag reveal a 13.5-day oscillation accompanied by an equally strong 9-day oscillation occurring during the campaign period (not shown here). These peaks have been identified to

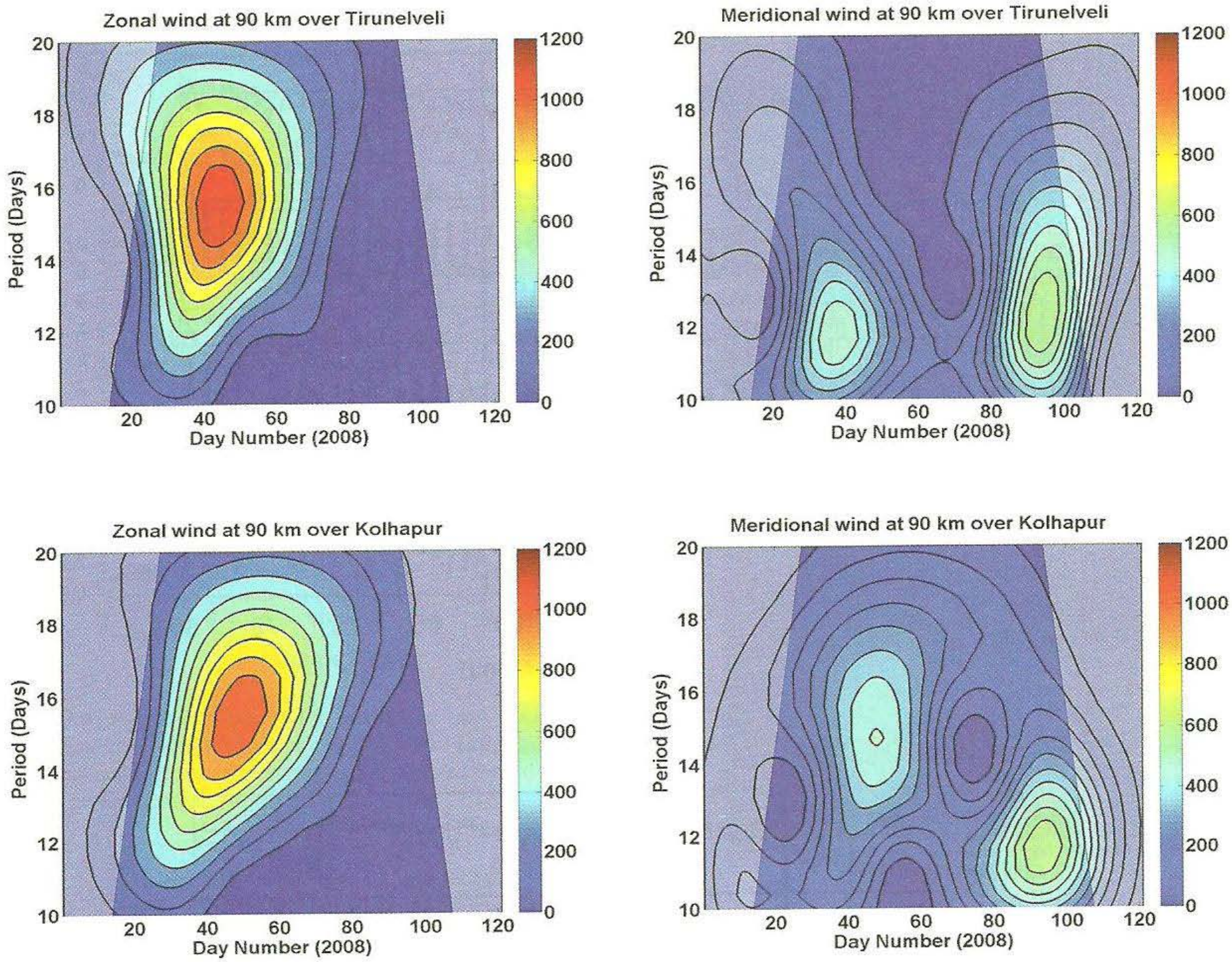

Fig. 12.2 Same as Fig. 12.1 but for the period range 10–20 days

arise due to the impact of intermittent streams of solar wind of coronal hole origin. It may be noted that amplitude spectra in the difference field representing the strength of the EEJ do not show these peaks (Fig. 12.4, bottom panel).

In the analysis of geomagnetic field variations, the method of Pancheva et al. (2006) is first applied to the difference in the horizontal component of the geomagnetic field recorded at Tirunelveli and Alibag, yielding a time series in which the diurnal variations are removed in advance and only the departures from the daily variations are represented in the data sets. The hourly differences between the resulting time series for Tirunelveli and Alibag (representing the strength of the EEJ) are then subjected to traditional least squares and wavelet analysis.

Figure 12.4 depicts the amplitude spectra for the zonal and meridional winds at 90 km over Tirunelveli and Kolhapur compared with the amplitude spectrum for the EEJ strength for the period February–April 2008. The 95% confidence levels using a standard method (Nawroozi, 1967) are shown as dashed/dash-dot lines in each of the panels in Fig. 12.4. Examining the zonal wind spectra (middle panels), we notice the presence of pronounced quasi-16-day wave over both sites (estimated amplitudes of 9 m/s over Tirunelveli and 5 m/s over Kolhapur). The amplitudes in the meridional component in this period are somewhat weaker (4 m/s over Kolhapur and below 95% confidence level over Tirunelveli). Examining the EEJ spectrum, we notice a peak with the largest amplitude at 5 days.

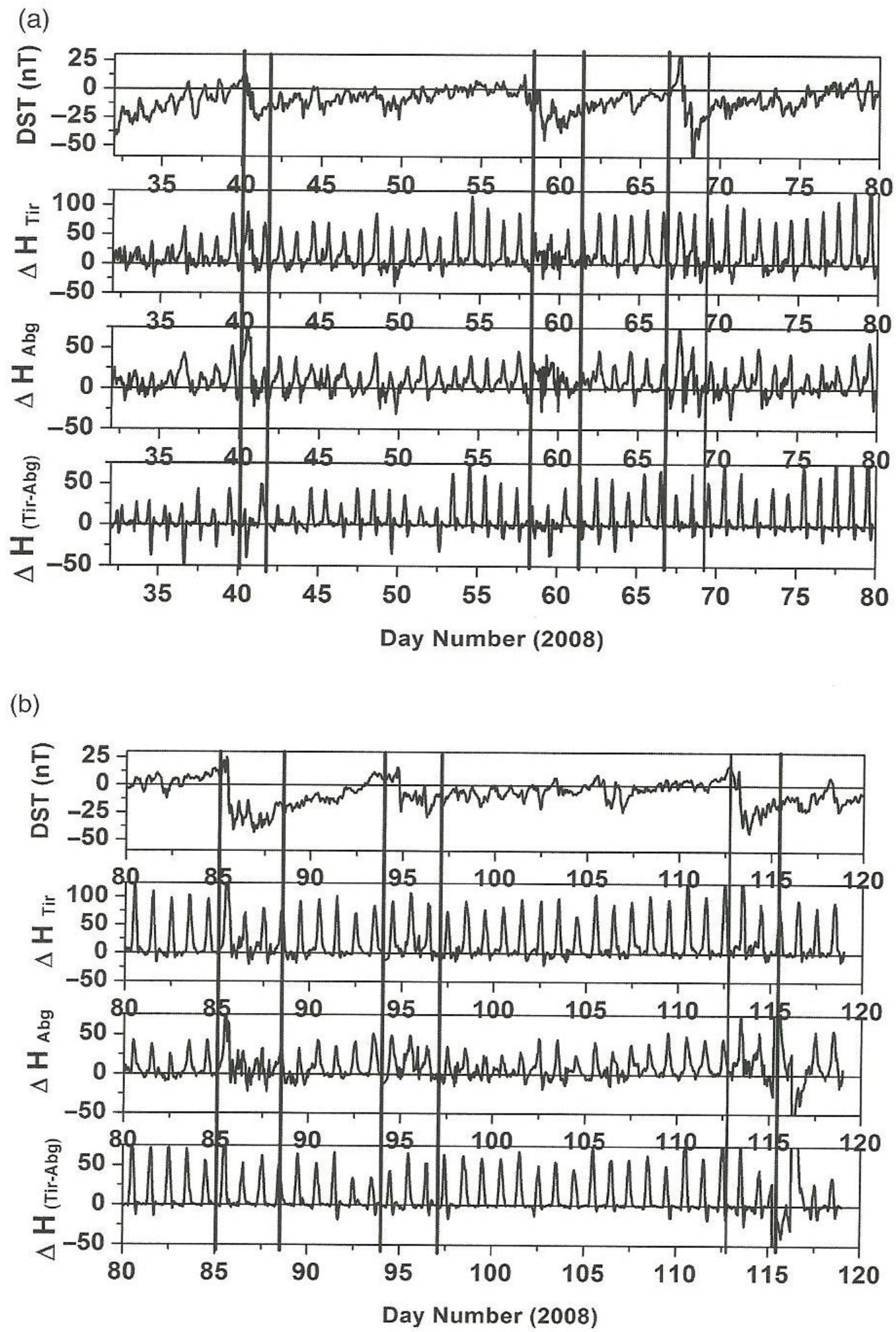

Fig. 12.3 (**a**) The variations in the horizontal component of the geomagnetic field measured at Tirunelveli and Alibag, the difference between the two components and the Dst index (*top panel*) for the period between the day numbers 30 and 80. (**b**) Same as Fig. 12.3a but for the period between the day numbers 80 and 120

In Figs. 12.5 and 12.6 we depict the wavelet spectra for the EEJ strength along with the cross-wavelet spectra for wind fields over Tirunelveli and Kolhapur. A noticeable feature in the wavelet power spectrum for the ground geomagnetic field records shown as colored contours in Fig. 12.5 is the presence of short-period oscillations in the period range of 3–8 days occurring near day numbers 50, 70 and 95. A closer examination

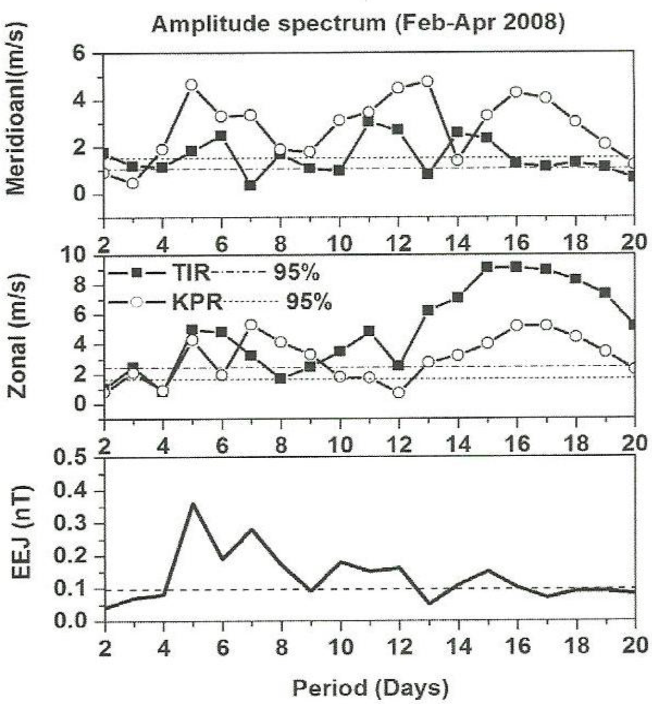

Fig. 12.4 Amplitude spectra for meridional (*top panel*) and zonal (*middle panel*) winds at 90 km over Tirunelveli and Kolhapur and EEJ strength (*bottom panel*) derived from data sets for the period February–April 2008

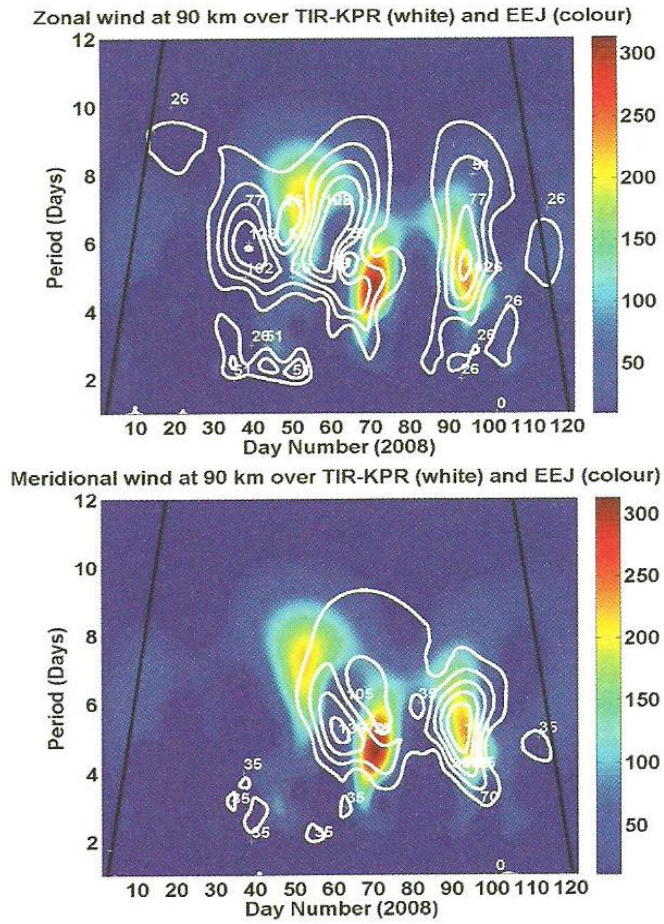

Fig. 12.5 Cross-wavelet spectra for the zonal and meridional winds over Tirunelveli and Kolhapur (shown as *white* contours) and wavelet spectra for the EEJ strength (shown as *colored* contours) for the period range 2–10 days

of results obtained from the wind observations (shown as white contours in Fig. 12.5, zonal wind in the top panel and meridional wind in the bottom panel) reveals the presence of a 5-day wave signature in the MLT meridional wind component around day numbers 60 and 95. In the zonal component, there are peaks close to 6 days near day numbers 40 and 60 that are not seen in the EEJ strength.

In the 10–20 day period range results for which are shown in Fig. 12.6, a 10- to 12-day oscillation is predominantly present in the EEJ strength between day numbers 60 and 100. The cross-wavelet spectrum for the meridional wind field does reveal a peak close to 12 days near day number 90. A quasi-16-day wave was detected earlier in the zonal wind component centered at day number 45. Though the EEJ strength initially reveals a peak close to 15 days near day number 45, the peak occurrence shifted to smaller periods as days progressed.

As the last exercise in this work, we examined the tidal winds at 90 km over Tirunelveli and compared the amplitude variations with the corresponding variation in the diurnal range in the EEJ strength. The range or the maximum amplitude of the diurnal variation in EEJ is expected to represent the strength of the electrojet on any given day. Figure 12.7 shows the results from this exercise. In the top panels, we compare the diurnal range with the amplitude of the diurnal tide in meridional wind at 90 km on the left and on the right we compare the same with the amplitude of the semi-diurnal tide. The scatter plots for the two parameters are shown in the bottom panels. Lines joining circled symbols in the top panels represent the diurnal range and lines joining filled squares represent the tidal amplitudes. The tidal amplitudes were obtained from composite hourly averages from a 5-day window sliding at one-day intervals. The values representing daily range in EEJ are 5-point running averages to the daily values obtained from ground magnetometer data.

The comparison plot shown in Fig. 12.7 reveals a reasonably good correlation (correlation coefficients

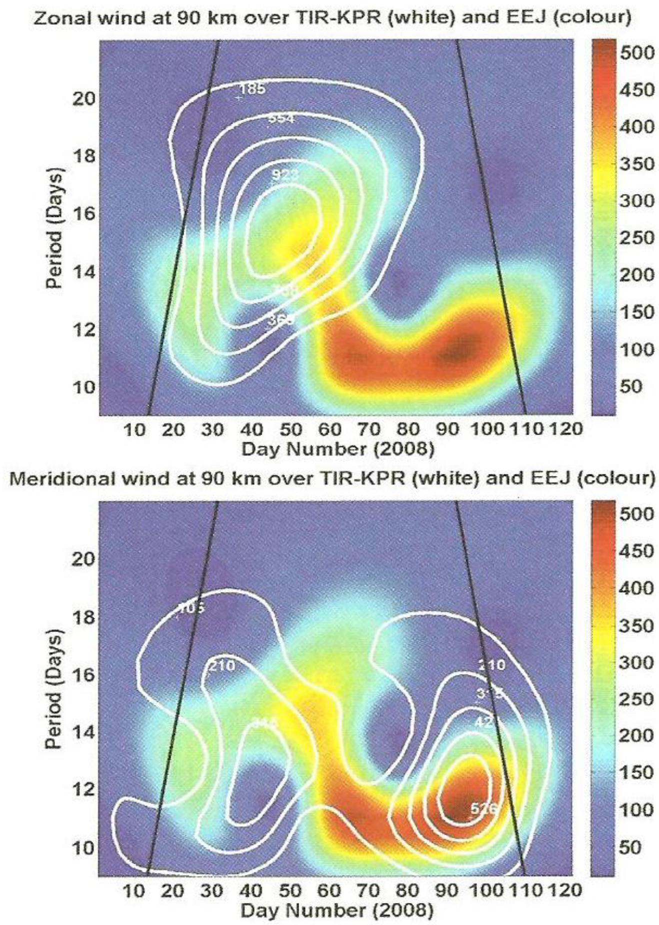

Fig. 12.6 Same as Fig. 12.5 but for the period range 10–20 days

indicated in the bottom panels are statistically significant at 95% confidence level) between the tidal wind fields at 90 km over Tirunelveli and the daily range in the horizontal component of the geomagnetic field representing the EEJ strength. Part of the uncorrelated field variations could be ascribed to a few moderate geomagnetic storms that occurred during this 3-month period. Though in this exercise we have not removed those days from the correlation analysis performed, we do not believe that exclusion of those days will drastically modify the correlation coefficients noticed in Fig. 12.6.

12.4 Discussion and Conclusion

Several reports in the past have emphasized the role of tides and planetary waves in contributing to the day-to-day variations in ionospheric parameters (Briggs, 1984a, for a review on this aspect). Apart from the solar flux variations that involve a periodicity at 27 days and its harmonics, the planetary waves at periods between 2 and 20 days are either expected to participate directly in the dynamo action or modulate the tidal winds at lower altitudes and the modulated tides then induce variations in electric fields and current systems at planetary wave time scales (Forbes, 1996). It is also likely that changes in the neutral composition at turbopause altitudes induced by planetary waves might influence the conductivity variations at dynamo altitudes (Mikhailov, 1983) but this aspect needs to be explored in detail.

In this work for the first time we have exploited the availability of simultaneous MLT radar wind observations from two low latitude sites in the Indian sector to address the vertical coupling of atmosphere-ionosphere system at equatorial and low latitudes during an experimental campaign conducted during February–April 2008 under CAWSES-India program. The goal of this initial study was to identify common periodicities between the radar observations of winds and geomagnetic field variations representing the strength of the equatorial electrojet with the supposition that some of the variabilities of the EEJ current system could be linked to the variabilities of tides and planetary waves observed at MLT heights. Results from this exercise are anticipated to provide motivation to carry out further elaborate studies on the dominant wave events detected during this campaign using global data sets as were carried out by Pancheva et al. (2006, 2008).

For the sake of convenience, the time scales considered in this work were divided into (i) 2- to 10-day and (ii) 10- to 20-day period ranges. The diurnal variations in the north-south component of the geomagnetic field were removed in advance and the residual time series were subjected to Morlet wavelet transform. The analysis clearly identifies the signature of a planetary wave of period 5 days occurring during the first fortnights of March and April (centered at day numbers 70 and 95 as revealed by the colored contours in Fig. 12.3). The cross-wavelet spectra in winds reveal enhanced spectral energy at a period of 6 days during the first fortnight of February but this period is not well expressed in the EEJ strength.

Pancheva et al. (2008) examined the 6 day wave extracted from global data sets on MLT winds and ground geomagnetic field variations. That analysis revealed the simultaneous presence of a 6-day

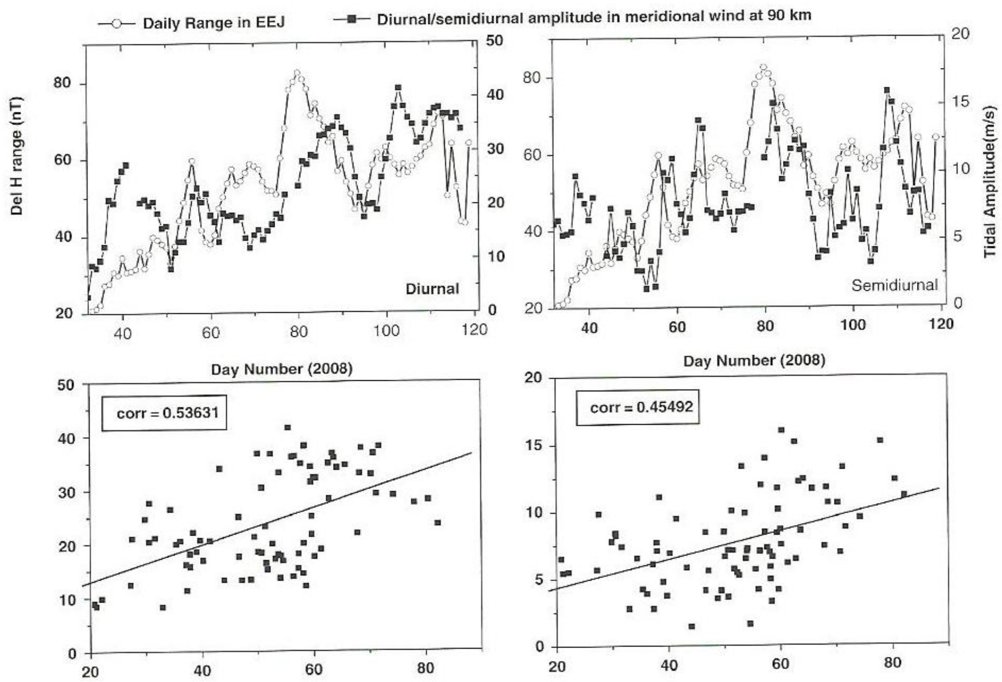

Fig. 12.7 Comparison for the diurnal range in the EEJ strength and diurnal and semi-diurnal amplitudes of meridional wind at 90 km over Tirunelveli for the period February–April 2008 (*top panels*). The *bottom panels* depict the corresponding scatter plots

wavenumber 1 westward propagating Rossby wave and a wavenumber 1 eastward propagating Kelvin wave during the chosen observation interval. The presence of these waves at stratospheric heights was confirmed in the National Center for Environmental Prediction (NCEP) reanalysis data sets on geopotential height and zonal wind at 30 and 10 hPa levels. The limited data sets used in the present analysis cannot establish whether the 6-day and 5-day perturbations in the geomagnetic field were caused by either of the two travelling waves that might have been present at those times.

A quasi-16-day wave was the dominant dynamical feature in the MLT zonal wind during the February–March 2008 period as expressed in the cross-wavelet results depicted in Fig. 12.6. The period of this wave in the meridional wind occurring around the same time was close to 12 days. Further, there was one more burst of this wave activity in the meridional wind centered around day number 95. It may be noted in this context that the wave period of the quasi-16-day wave was earlier reported to vary with height and time in a range of 12–24 days (Luo et al., 2002). There were also differences in amplitudes and periods between zonal and meridional wind components and between various sites noticed in the previous report (Luo et al., 2002). A variety of atmospheric conditions like temperature and background winds and the location of the node positions as prescribed by the Hough functions seem to govern the wave characteristics observed over any site. Whether the 16-day type of oscillation noticed in EEJ strength in the present work is related to the quasi-16-day wave observed in MLT wind observations will be a matter of investigation in a future study to be carried out by the authors.

Much of the day-to-day changes in the ionospheric current systems are expected to be driven by the day-to-day variations in the upward propagating tidal modes (Briggs, 1984a) but past studies were not able to bring out any clear relationship between the tidal winds observed at upper mesospheric heights and the strength of the ionospheric current system in day-to-day time scales because of the random nature of the variations (Phillips and Briggs, 1991, for example). The results presented in Fig. 12.7 demonstrating the correlation between the tidal amplitudes and the amplitude of the diurnal variation in the EEJ strength (expressed as "range") are therefore important in this context. It was possible to correlate the two parameters by considering 5-day composite 24-h means for estimating the tidal amplitudes and 5-day running averages of the range in EEJ strength. This apparent correlation, though observed in a qualitative manner, between the tidal winds and EEJ strength will encourage further studies on short-term tidal variabilities and their influence on EEJ variabilities in similar time scales. It is also worthwhile to examine whether these tidal variabilities extend to other latitudes and longitudes as it is believed that the Sq and the EEJ current systems are driven by large-scale tidal winds though local winds can modify the height and latitude distribution of the current system at certain latitudes (Anandarao and Raghavarao, 1979, for example).

From the Indian sector, Sridharan et al. (2002), for the first time, observed that the normal electrojet reversed (referred to as counterelectrojet (CEJ)) when the semi-diurnal tide amplitudes were enhanced during the solstice months of June and July 1995. A recent analysis from the same group has shown enhancement of semi-diurnal tidal amplitudes and occurrence of CEJ during high latitude northern hemispheric major sudden stratospheric warming events (Sridharan et al., 2009). Such an attempt to correlate the tidal activity with the strength of the afternoon electrojet was successful considering the fact that CEJ's usually occur in groups of 3–5 consecutive days and therefore it is possible to somewhat smooth out the day-to-day variations.

In conclusion, the present work examines the role of tides and planetary waves in driving variabilities of ionospheric dynamo region, though with limited data sets obtained during an experimental campaign. A 5-day oscillation was observed simultaneously in the meridional wind field at 88 km over Tirunelveli/Kolhapur and the EEJ strength during the campaign period, though the zonal winds over the two sites exhibit peaks at 6 days. The EEJ strength also reveals enhanced spectral densities at a period of $\sim$12 days that was observed in the meridional wind component over the two radar sites at around the same time. It is not clear whether the wind oscillations in the meridional wind represent the global planetary waves that might have contributed to the observed variabilities in geomagnetic field records at those planetary wave periods. Further analysis to be carried out by the authors with global data sets will provide insights of this proposed linkage. The tidal variabilities are correlated at least over time scales of 5 days and greater with corresponding variations in the amplitude of the diurnal variation or range in the EEJ strength. Indeed, a recent report that made use of MLT wind observations from Tirunelveli found evidence for the enhancement of semi-diurnal tide amplitude on days marked by afternoon counterelectrojet occurring during polar sudden stratospheric warmings (Sridharan et al., 2009).

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