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Mesospheric planetary wave signatures in the equatorial electrojet

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[1] Using five years (1994–1998) of simultaneous and collocated measurements of horizontal winds associated with mesosphere and lower thermosphere (MLT) region and geomagnetic field measurements in the Indian geomagnetic dip equatorial region, an extensive experimental study has been made on the influences of mesospheric planetary waves on the equatorial electrojet (EEJ). The winds are measured using medium-frequency (MF) radar (1.98 MHz) located at Tirunelveli. The EEJ strength is determined by measuring the geomagnetic field strength at both the geomagnetic dip and off-dip equatorial stations, Trivandrum and Alibag, India. By noting the simultaneous time evolution of spectral signal (Morlet wavelet analysis) in both the EEJ strength and mesospheric winds at 88 km, it is found that mesospheric planetary waves with periodicities of 2–25 days often do propagate up to the ionospheric dynamo region and have their influences on EEJ strength. Sometimes only one of the parameters shows strong spectral signal in this periodicity range. It is also observed that often the diurnal oscillation in EEJ strength and mesospheric winds exhibits coherent variations in amplitude when the signature of mesospheric planetary-scale oscillations is found in the EEJ strength. Also, it is found that variations in high-energy solar radiations (F10.7 is used as a proxy) can influence the EEJ strength at planetary timescales. This leads to an interesting question. What actually causes the vertical coupling between ionosphere and atmosphere through upward propagating planetary waves to be operative only during some (and not all) of the episodes?

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1. Introduction

[2] In a steady state and isothermal conditions without any dissipation, some planetary-scale waves (periodicities near 2, 5, 10 and 16 days) exist as freely propagating, normal-resonant modes or Rossby modes in the lower atmosphere [*Madden*, 1979; *Salby*, 1981a, 1981b, 1984; *Hirota and Hirooka*, 1984; *Yang and Hoskins*, 1996]. Normally, the existence of all these normal modes is restricted within about the first three scale heights (typical scale height ~7 km) of the troposphere and stratosphere [*Salby*, 1981a]. Above this height, the dynamic states of the atmosphere are such that resonant responses at the mentioned periodicities cannot be sustained [*Meyer and Forbes*, 1997]. Sometimes, under favorable conditions particularly during winter, the lower atmospheric planetary waves may penetrate up to the higher-altitude regions (60–120 km) of mesosphere and lower thermosphere (MLT) [*Charney and Drazin*, 1961; *Andrews et al.*, 1987]. And these mesospheric planetary waves may propagate even above 100 km and influence the ionospheric current system there in the dynamo region and consequently show their signatures also in ionospheric parameters [*Brown and Williams*, 1971; *Grasnick and Entzian*, 1973; *Schwentek*, 1974; *Fraser and Thorpe*, 1976; *Cavalieri*, 1976; *Fraser*, 1977; *Brown and John*, 1979; *Parkinson*, 1982; *Takeda and Yamada*, 1989; *Pancheva et al.*, 1991, 2006; *Forbes and Leveroni*, 1992; *Chen*, 1992; *Yi and Chen*, 1993; *Parish et al.*, 1994; *Lastovicka et al.*, 1994; *Rangarajan*, 1994; *Apostolov et al.*, 1994, 1995, 1998; *Kohsiek et al.*, 1995; *Apostolov and Altadill*, 1996; *Meyer and Forbes*, 1997; *Forbes et al.*, 1997; *Forbes and Zhang*, 1997; *Abraham et al.*, 1998; *Altadill et al.*, 1997, 1998; *Altadill and Apostolov*, 1998; *Pancheva and Lastovicka*, 1998; *Gurubaran et al.*, 2001; *Ramkumar et al.*, 2001, 2006; *Abdu et al.*, 2006].

[3] Most of the previous observational studies on coupling processes in the mesosphere and lower thermosphere (MLT) region and the ionosphere lacked the simultaneity in the relevant data sets. In the present work, we report the influences of mesospheric planetary-scale waves on the Equatorial Electrojet strength by using collocated and simultaneous measurements of both the parameters. Using medium frequency (MF, 2 MHz) radar and geomagnetic field measurements in the Indian dip equatorial region, we make an attempt in the present paper to find the presence of signatures of mesospheric planetary waves in equatorial electrojet (EEJ) in the years from 1994 to 1998. In brief, the EEJ is an enhanced current system with intensity of the order of 200 A/m flowing at about 105 km over the dip equator. More information on EEJ currents and the measurement methods adopted in the present work can be found in the work of *Onwumechili* [1997]

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and *Ramkumar et al.* [2006]. They discussed in detail also on how the wind dynamics associated with MLT region can have influences on ionospheric parameters. We present in this paper a detailed analysis of the interactions between EEJ and MLT region wind dynamics using extensive data sets of MF radar winds over Tirunelveli and of geomagnetic field variations over the dip and off-dip equatorial stations, Trivandrum (TRI) and Alibag (ABG), India for years 1994–1998. To determine the strength of EEJ currents, first the few hours averaged midnight values are subtracted from the day time values of the measured H component (meridional component associated with eastward flowing currents) of the geomagnetic field strength on every day at each of the stations separately. Then hourly averaged ΔH values are constructed. The EEJ strength is then determined by subtracting the hourly averaged ΔH values measured at Alibag from that measured at Trivandrum (TRI-ABG). The mesospheric wind dynamics is determined with the help of a medium frequency (MF, 1.98 MHz) partial-reflection radar located at the Indian dip equatorial site, Tirunelveli (8.7°N, 77.8°E geographic; 0.5°N magnetic dip). This radar has been monitoring continuously the middle atmospheric dynamics since 1992. More information on these types of MF radars can be found in the work of *Vincent and Lesicar* [1991]. For every 2-min period, one altitude profile of wind velocities is measured. Hourly averaged values (maximum 30 points per hour) are used for further Fourier analyses and the few data gaps are linearly interpolated in the present work. As a good percentage of data is recorded at around 88 km, which is taken as the reference height at which the mesospheric planetary waves are examined. The signatures of mesospheric planetary waves in EEJ strength are identified by noting the significant spectral power in EEJ strength during the same interval of time when the winds at 88 km showed significant power at the corresponding planetary time scales. It is assumed that the planetary waves detected at 88 km actually propagate up to the dynamo region and influence the ionospheric current system there at planetary time scales.

2. Observations and Results

[4] Figure 1 (bottom) shows the power spectra of EEJ strength and zonal winds at 88 km for the period of 10 April to 22 May 1996. It may be noted that significantly strong spectral power near the periodicity of ~6.5-day occurs in both the mentioned parameters. And, while the zonal wind shows significantly strong 22-day oscillation, the EEJ strength shows strong but less than the 90% confidence level spectral amplitude. Further, except for a few days in the first 10 days, the geomagnetic activity was calm as the daily planetary Ap index was mostly less than 10 in this period. And there is no reason for this geomagnetic activity to produce 22-day oscillation in EEJ strength in this period. This illustration gives an indication that the mesospheric planetary waves might have propagated up to the EEJ dynamo region and have modulated the current system associated with EEJ at these planetary timescales.

[5] The contour plots of Figure 2 (see also Figures 8–10) show the time evolution of normalized power spectrum, determined by Morlet wavelet analysis method [*Torrence and Compo*, 1998], for EEJ strength and both the zonal and meridional winds at 88 km in the years from 1994 to 1998. In the years 1994 and 1998, only the first and second halves, respectively, are considered as there are large data gaps in the remaining period of these two years. In Figures 2, 8, 9, and 10, the top, middle and bottom plots show the power spectrum, respectively, for EEJ strength, zonal and meridional winds at 88 km. The vertical axes denote the Fourier period of oscillation, corresponding to the "Morlet wavelet" scales, ranging from a fraction of a day to 22 days. The horizontal axes denote the period of observation. The contours inside the thick dashed lines are above the 95% confidence level of the background red-noise spectrum. The power spectra shown are above the white noise level. Such power spectrum can be obtained by plotting it in units of variance of the given time series (4096 h (~171 days) for each half of the years) of data. The global (4096 h) red noise spectrum is also calculated by using univariate, lag-1 autoregressive model of the given time series and the 95% confidence level shown in Figures 2, 8, 9, and 10 is actually about three times this background red noise level. The contour values start from red noise level to above the 95% confidence level. While plotting so, the red noise spectrum is also divided by the same variance of time series since the obtained spectral powers are already normalized by the variance. As a note, the values marked on contours (Figure 2; see also Figures 8–10) will not match sometimes the exact values of normalized power because of some conveniences adopted while plotting the

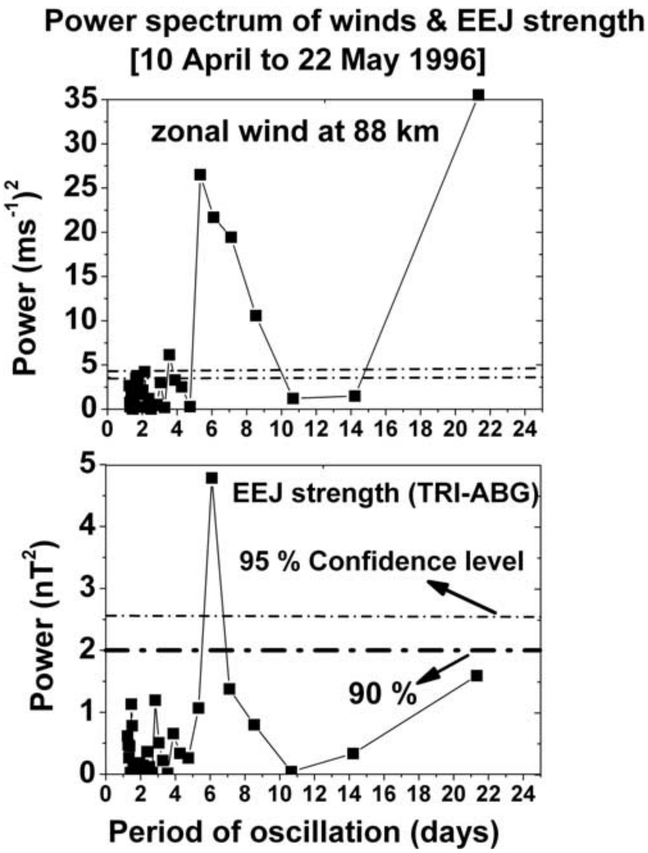

Figure 1. Power spectrum of (top) the zonal winds at 88 km and (bottom) (ΔH [TRI-ABG]) EEJ strength during the period of 10 April to 22 May 1996.

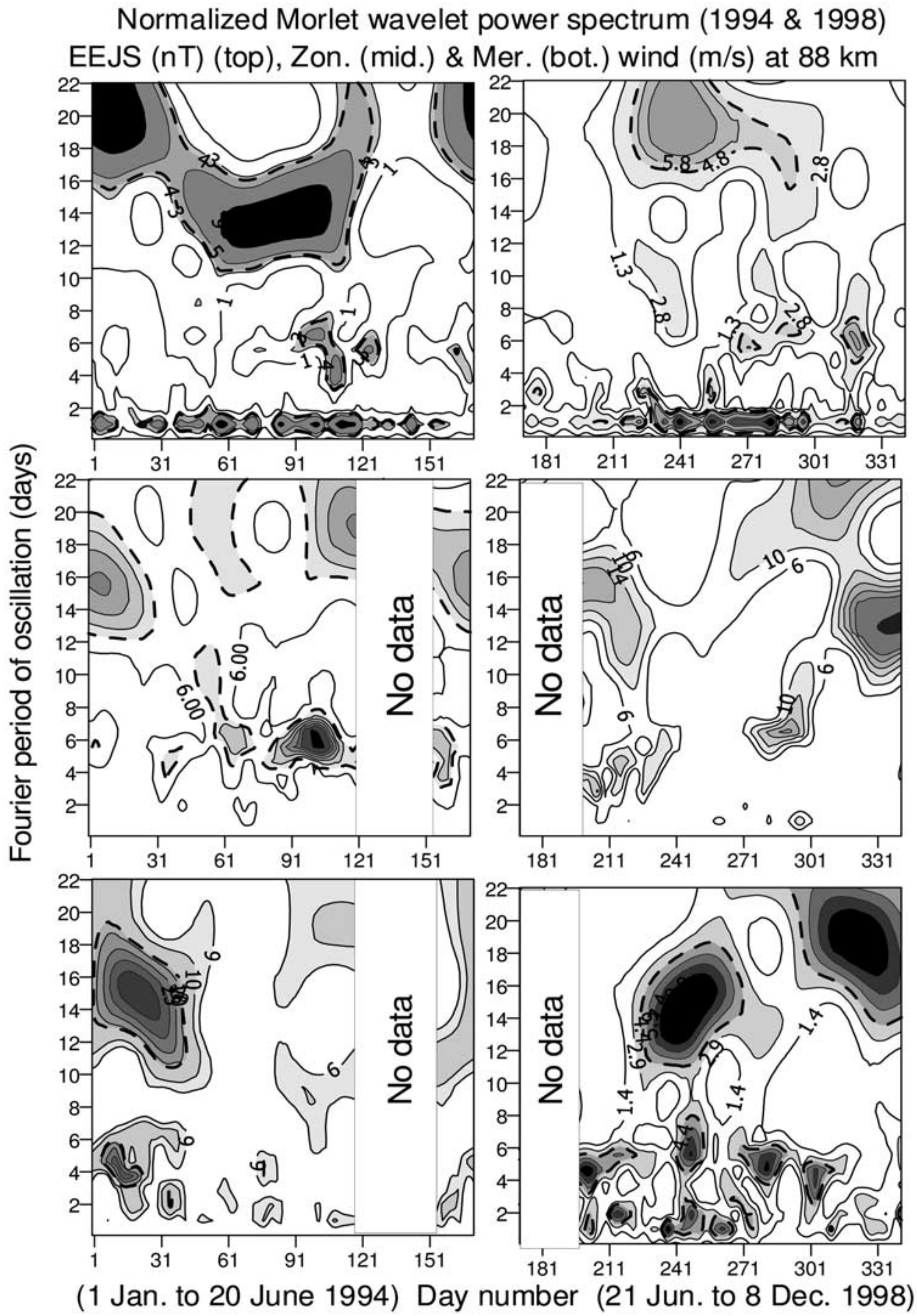

Figure 2. Time evolution of the power spectrum determined by Morlet wavelet analysis method for the periods of (left) 1 January to 20 June 1994 and (right) 21 June to 8 December 1998. (top) EEJ strength, (middle) zonal winds, and (bottom) meridional winds at 88 km. The contours inside the thick dashed contour lines are above the 95% confidence level.

contours. Nevertheless, the meaning of statistical significance of spectral peaks has not been changed on any account.

3. Results for 1994 and 1998

[6] From Figure 2, it may be noted that the diurnal oscillation in EEJ strength is strong and the ~2-day oscillation in EEJ strength (Figure 2, top) during the late northern summer months of mid-August and mid-September is preceded by some ten days the ~2-day planetary waves in meridional wind component (Figure 2, bottom). However, the periodicity observed in the EEJ strength is slightly higher (near 3 days) than that of the winds, which is difficult to interpret in terms of direct effect of upward propagating mesospheric ~2-day waves. Either the oscillations in EEJ strength and winds are completely independent or a triggering mechanism generated in the dynamo region might have contributed to the significant quasi–two-day oscillation (QTDO) in EEJ strength.

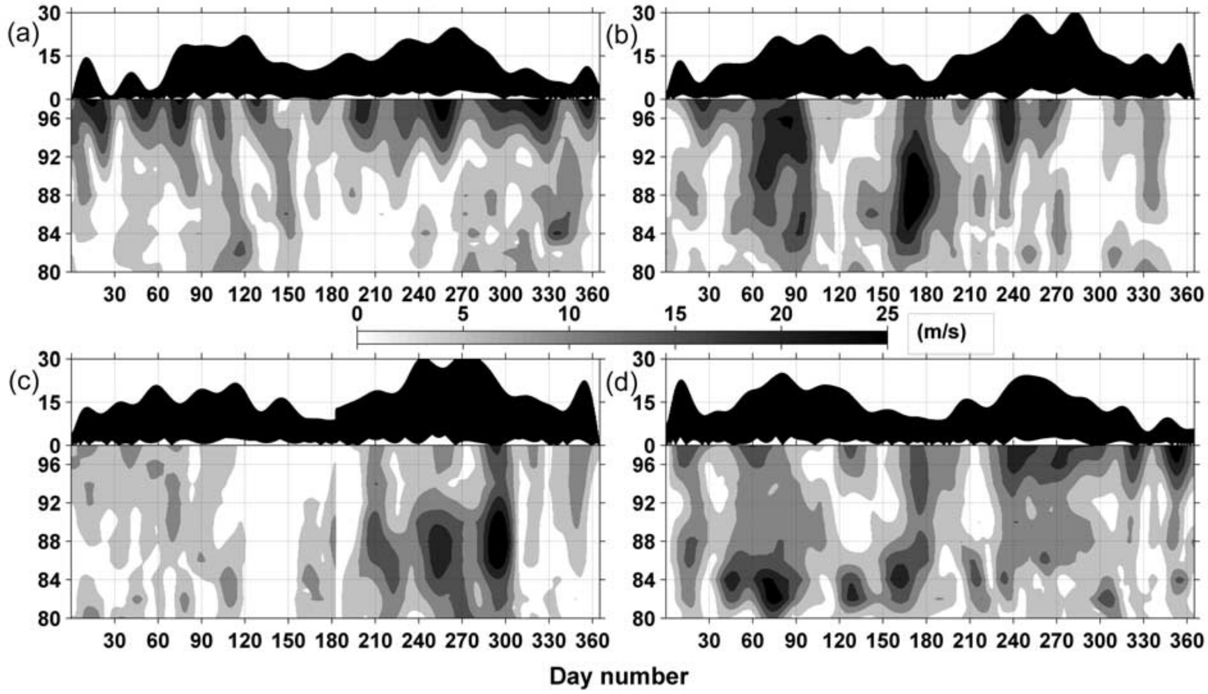

Figure 3. Time (x-axes, day number) versus height (80–98 km) contour plots of filtered (23- to 25-hour periodicity band) zonal wind velocity (m/s) and the EEJ strength (nT, above the contour plots) for the years (a) (1996), (b) (1997), (c) 1994 (I 182.5 days) and 1998 (II 182.5 days), and (d) 1995.

It may be triggered by forcing of such oscillation in mesosphere linked with a particular region of globe and with further independent development in EEJ dynamo region [*Apostolov et al.*, 1995].

[7] Sometimes, when the mesospheric planetary waves cannot pass through the mesopause region up into the ionospheric dynamo region because of filtering processes, they can still have their influences on the ionospheric parameters through modulating the vertically upward propagating diurnal or semidiurnal tides as they have in general large vertical wavelengths. So, it is necessary to check first whether the mesospheric winds and the EEJ strength show similar tidal oscillations simultaneously when the tidal winds are strong in the mesosphere. Figures 3a–3d show the contour plots of time variation (x-axes; day number) of height profiles (80–98 km) of amplitude (m/s) of diurnal tide (23- to 25-hour band oscillation) in zonal wind velocity for the years 1994/8, 1995, 1996, and 1997. In Figure 3c, the first and second 182.5 days correspond to the years 1994 and 1998, respectively. Actually absolute values of the filtered hourly data are plotted and in the x-axes are shown the day number of observation. The corresponding amplitude of diurnal tide in EEJ strength (nT) is illustrated above the contour plots of winds. Similarly, Figures 4a–4d illustrate the diurnal tide in meridional wind velocity, and Figures 5a–5d and 6a–6d illustrate semidiurnal tide oscillations in zonal and meridional winds.

[8] It may be noticed that in the ends of July (day number [dn] 210), August (dn 240) and September (dn 270) 1998, there is a clear association between the enhancements in diurnal tide amplitude in meridional (Figure 4c) but not in zonal winds (Figure 3c) in the heights of 80–88 km and in the EEJ strength. Hence, it may be speculated that the quasi–two-day oscillation found in EEJ strength may be associated with mesospheric ∼2-day oscillation modulated by diurnal but not by semidiurnal tidal (Figures 5c and 6c) winds in July–September. Earlier, as an observational report using MF and meteor radars at five stations, geomagnetic field measurements at 23 stations and ionosondes at seven stations, *Pancheva et al.* [2003] showed the 2-day mesospheric planetary wave influences on ionospheric currents and *F* region plasma in midlatitudes. The possible mechanism they suggested was planetary wave modulation of semidiurnal tides.

[9] In the interest of finding such enhancements near 2-day oscillation in solar high-energy radiations that can effectively increase the ionization and hence the conductivity in the lower *E* region ionosphere, it is plotted in Figure 7 the time series of filtered (2–3 day band) daily solar 10.7 cm flux values (F10.7) (see Figure 7d), which is the representative of solar high-energy radiations like Extreme Ultraviolet (EUV) radiations, X rays, etc. Figure 7a corresponds to the year 1998. It is observed that ∼2-day oscillation in F10.7 values are enhanced during the said corresponding period of August but not in September 1998, indicating that the ∼2-day oscillation in EEJ strength sometimes might also be due to these solar flux variations.

[10] Sometimes the equinox months are favorable for the existence of planetary-scale oscillations in EEJ strength. For example, during the northern spring equinox month of April, the prominent ∼5- and 6.5-day oscillations in EEJ strength are accompanied by similarly enhanced oscillations in zonal winds (Figure 2, middle), again indicative of the influence of upward propagating mesospheric planetary waves on EEJ currents. Again the diurnal tide in meridional wind (around day number 105 in Figure 4c) but not in zonal wind

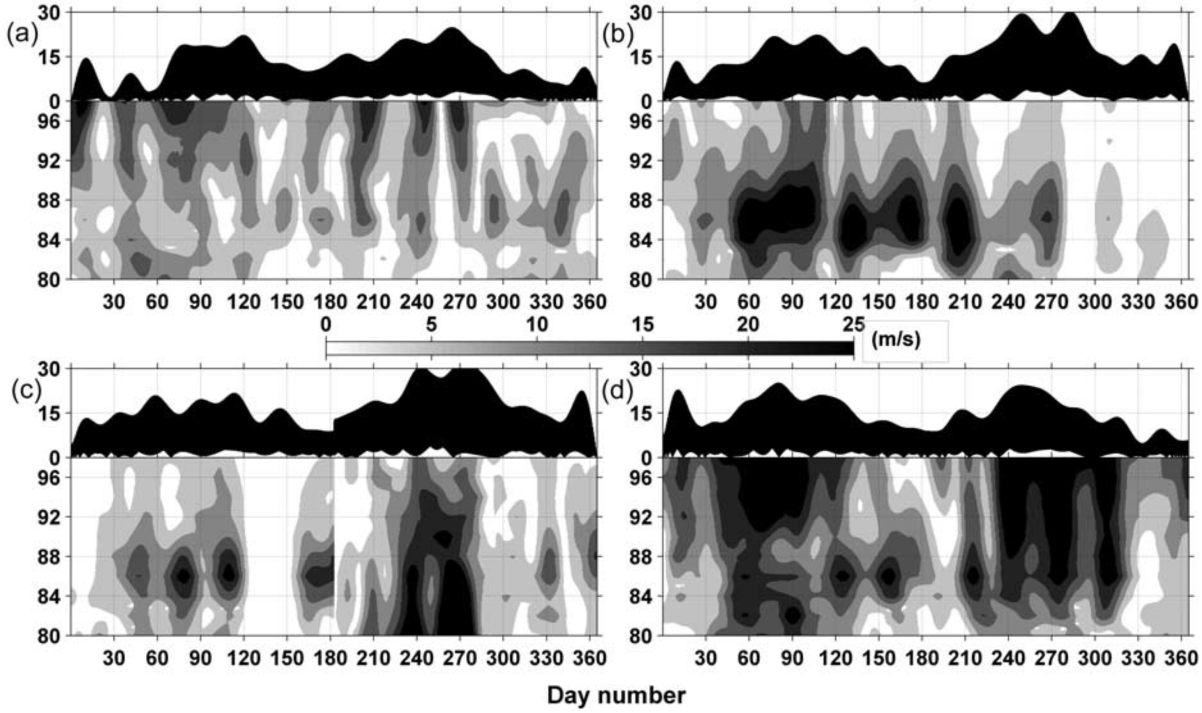

Figure 4. Same as Figure 3 but for meridional wind velocity.

(Figure 3c) in the heights of 84–90 km and the EEJ strength shows close correspondence in amplitude enhancement during this period, indicating that planetary wave modulated tides in winds might have contributed for the ionospheric planetary wave oscillations. And regarding solar influences, the 4- to 6-day (Figure 7e; 1994) but not the 6- to 7-day band (Figure 7b) oscillation in solar 10.7 cm flux shows enhancement in April 1994, indicating that the high-energy solar fluxes might have made some contribution to the 5- and 6.5-day oscillation in EEJ strength. Similarly, during the northern fall equinox month of October and the winter month of November in 1998 (Figure 2), the near 6- and 6.5-day oscillations in EEJ strength are accompanied by ∼6-day oscillation in zonal wind and 5-day oscillation in meridional wind in October but not in November. However, in November, the solar flux values show enhancement for the

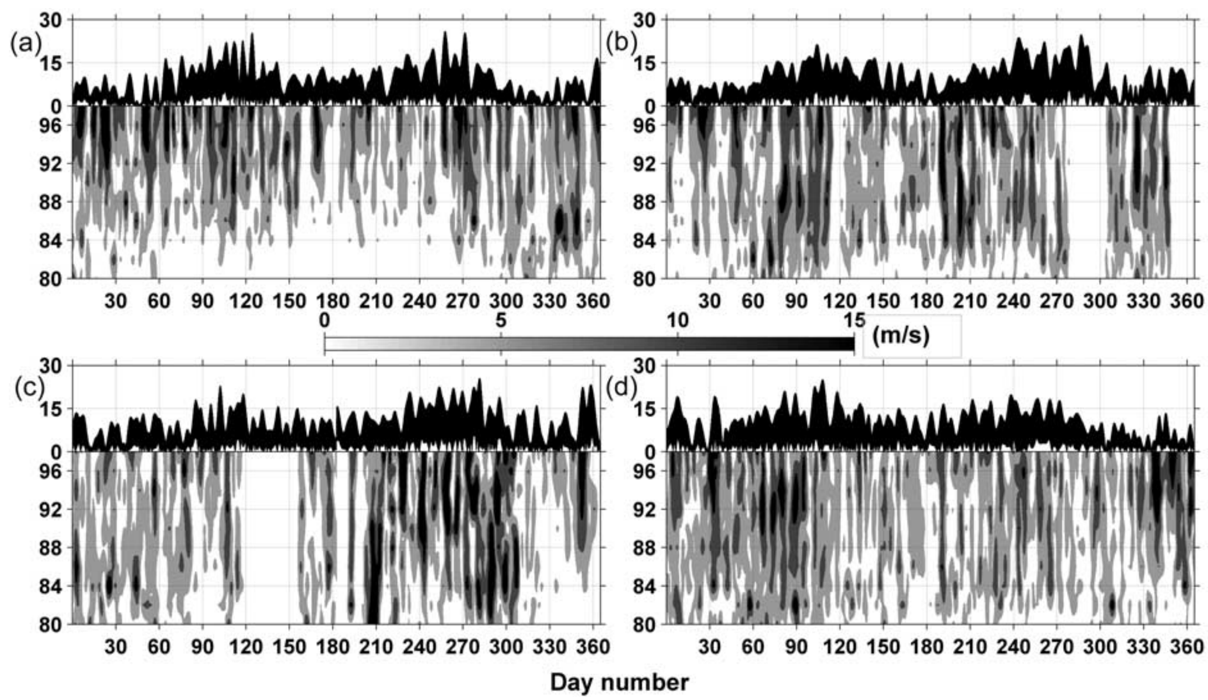

Figure 5. Same as Figure 3 but for semidiurnal tide.

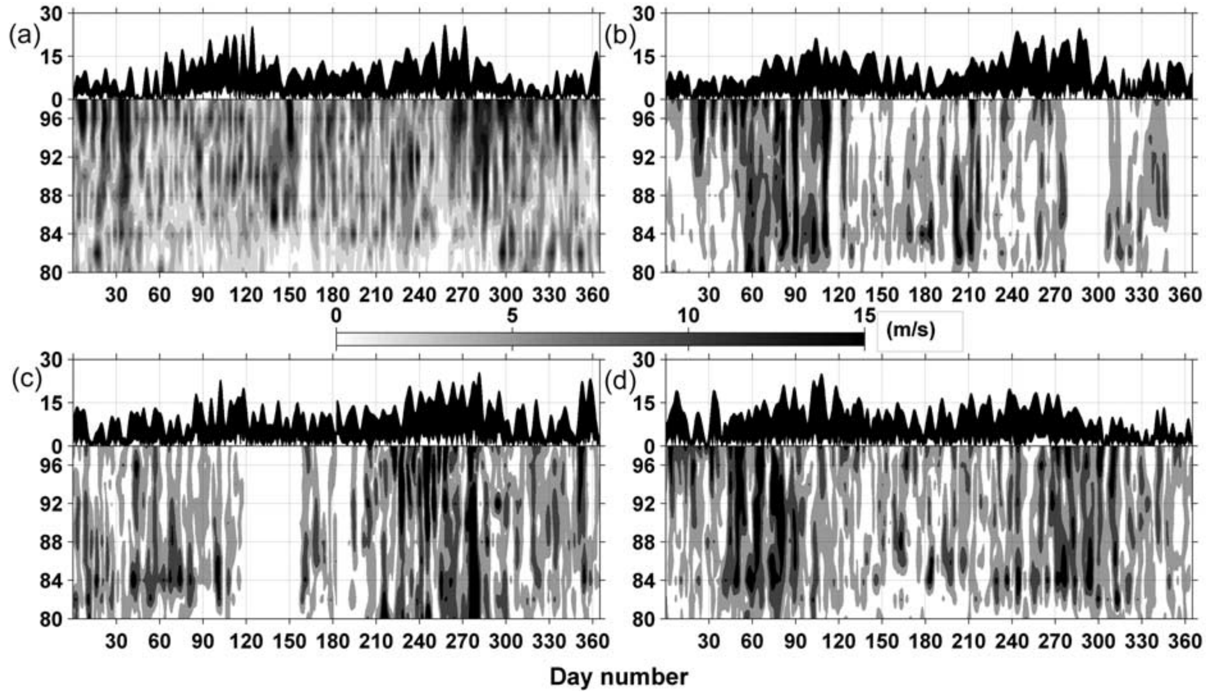

Figure 6. Same as Figure 3 but for semidiurnal tide.

periodicities of 4- to 6- and 6- to 7-day oscillations (Figures 7b and 7e), indicating that sometimes solely the solar fluxes can contribute to the planetary-scale oscillations in ionospheric parameters.

[11] Furthermore, during February, March, April and June, while the zonal winds show prominent ~5-day oscillation, the EEJ strength shows only a weak amplitude oscillation near this periodicity (Figure 2). It is worth noting here that both the diurnal and semidiurnal tides in winds are weak in strength and also there is no correspondence between the variations in tidal signatures between the winds and the EEJ strength during these months (Figures 3c, 4c, 5c, and 6c). Similarly weak EEJ strength is accompanied by significantly strong meridional wind near the 6-day oscillation in the beginning of September. On the contrary, in October, while the EEJ strength shows enhanced 6- to 7-day oscillation, the zonal wind shows only weak 6- to 7-day oscillation and the meridional wind shows significantly strong spectral amplitude near 5 days periodicity. And, in November, the strong 6-day oscillation in EEJ strength is not accompanied by any signal in both the zonal and meridional winds.

[12] Considering long-period oscillations, it may be noted that in both the winter (January) and summer months (August and September), the prominent ~17- to 22-day oscillation in EEJ strength occurred concurrently with prominent ~12- to 18-day oscillation in mesospheric winds (Figure 2). In winter, both the zonal and meridional winds and in summer only the meridional winds show significant spectral power near the periodicity of 12–18 days. And the F10.7 shows enhanced fluxes only in the winter month of January 1994 but not in August–September 1998 (Figure 7a).

[13] Moreover, these 16-day (12- to 22-day band) oscillations do appear with significant amplitudes in both the mesospheric winds and EEJ strength simultaneously during equinox periods also (Figure 2). For example, in April, both the EEJ strength and zonal winds but not the solar flux (Figure 7a) shows significant oscillations with periodicity centered near 20 days, indicative of the possible direct mesospheric planetary wave influences on EEJ currents in the dynamo region. But in June, while the zonal wind shows distinct ~18-day oscillation, the EEJ strength shows significant oscillation near 20 days, indicating shift in frequency of planetary waves while propagating from mesosphere to EEJ dynamo region heights. As an evidence for the presence of significant oscillations in only one of the parameters, it is noted that the enhanced ~11- to 16-day oscillation in EEJ strength during February to April (Figure 2) is not accompanied by similar type of enhancements in mesospheric winds and the solar flux values. Conversely, during November–December, the prominent ~14- to 20-day oscillation in meridional wind is not accompanied by similar oscillation in EEJ strength. In these periods, the diurnal tide amplitudes are weak in both the zonal and meridional winds (Figures 3c and 4c). However, in December, out of two events only one event shows simultaneous enhancements in amplitudes of semidiurnal tide in the winds and the EEJ strength (Figures 5c and 6c).

4. Results for 1995

[14] Figure 8 illustrates the same parameters as in Figure 2 but for the year 1995. It is noted in meridional wind that few cycles (burst like) of ~2-day oscillations occur intermittently in all the seasons of the year 1995. In EEJ strength, however, only weak oscillations are found in July and August and significant oscillation in the first ~10 days of October. And the solar flux values indicate enhancements in ~2-day oscillation only in February and March 1995 (Figure 7d). Further,

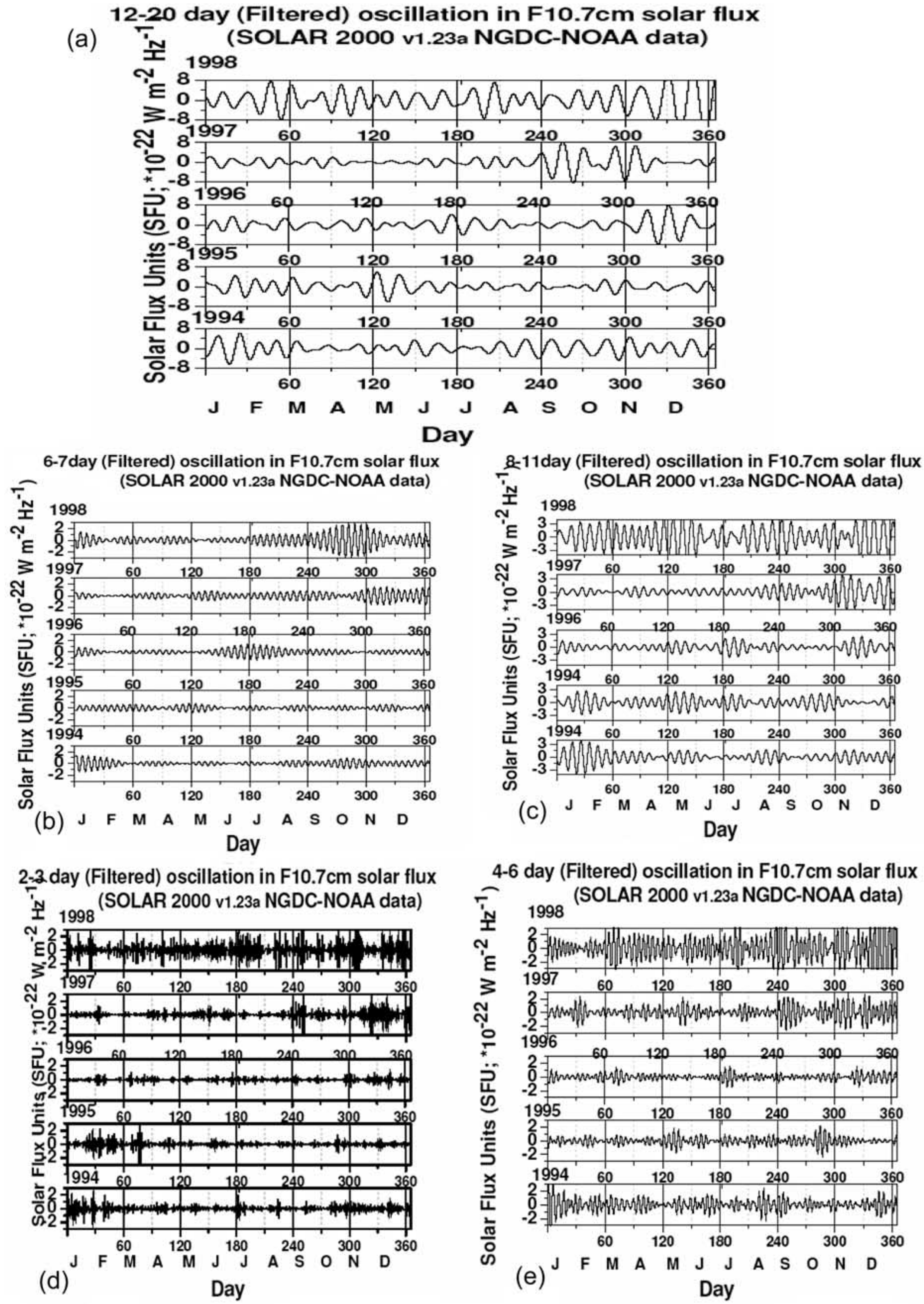

Figure 7. Filtered time series of daily solar 10.7-cm flux values for 1994, 1995, 1996, 1997, and 1998. Periodicity band of: (a) 12- to 20-day band, (b) 6- to 7-day band, (c) 8- to 11-day band, (d) 2- to 3-day oscillation, and (e) 4- to 6-day band.

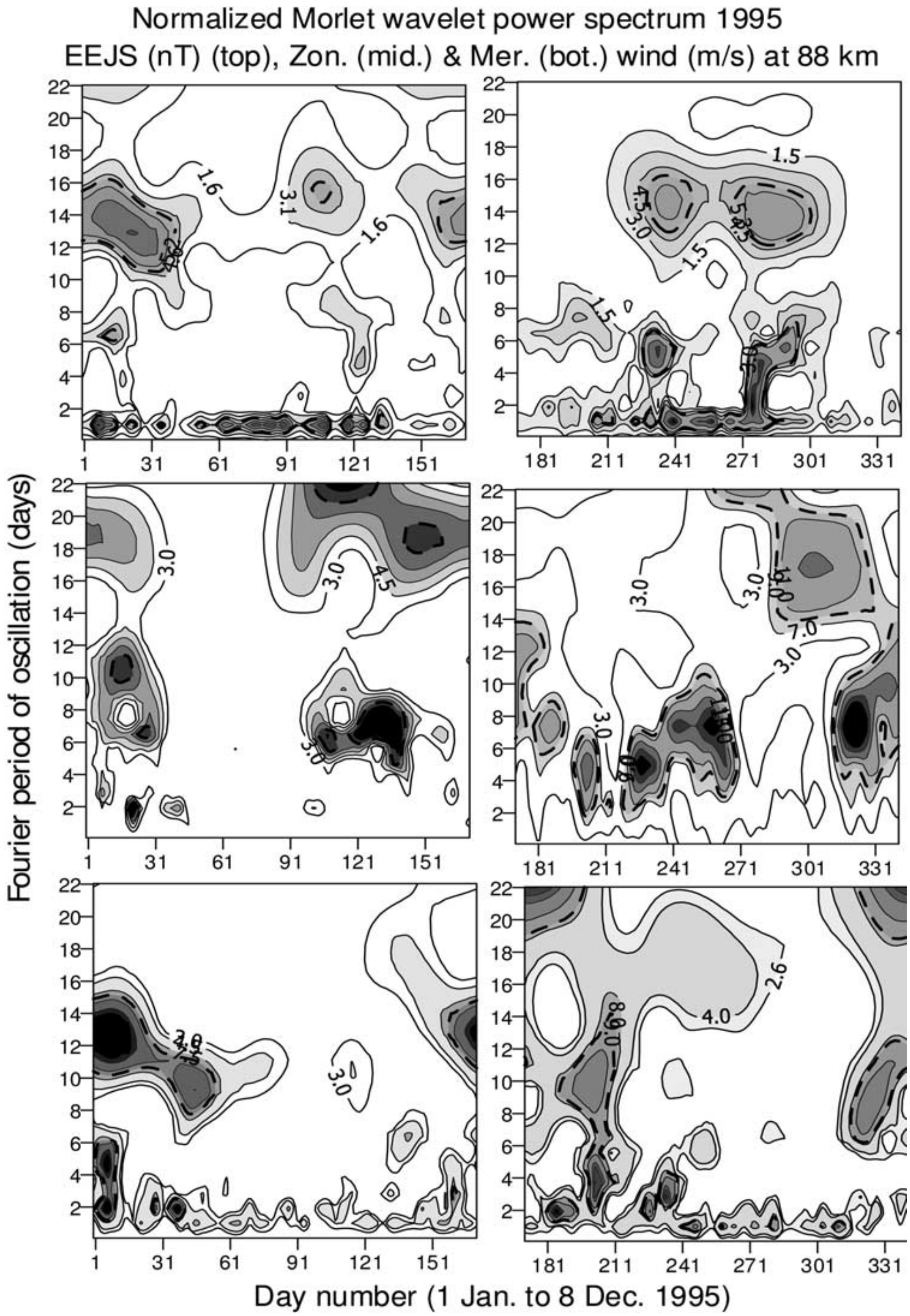

Figure 8. Same as Figure 2 but for the year 1995.

during July–September and November, the zonal wind shows prominent spectral power for a wide spectrum of periodicities near 3, 5, and 6.5 days. In September and November, the zonal wind shows significant power also near the periodicity of 10 days. In the case of EEJ strength, only August and October are favorable to show the enhanced amplitudes of oscillations near the periodicities of 5 and 6.5 days. In October, the solar flux in the periodicity band of 4–6 days (Figure 7e) also shows the enhancement. Furthermore, while the meridional wind shows significant ~10-day oscillation in February and November–December and in July, the EEJ strength shows only weak wave signature in February. And the ~6- to 8-day oscillation found in zonal wind in April and May is not accompanied by similar enhancements in EEJ strength. It is worth noting here that the diurnal tide amplitude in zonal wind velocity (Figure 3d) is weaker in these months in the heights of 86–94 km. Even though the amplitude is stronger in meridional winds (Figure 4d) and having good association with diurnal oscillation in EEJ strength, the absence of 6- to 8-day oscillation in EEJ strength stresses the importance of strong diurnal tide amplitude of zonal winds near the mesopause region for strong electrodynamical coupling between the mesosphere and the lower *E* region ionosphere. Except for few events in March, the association between the time variation of semidiurnal tide in both the zonal and meridional winds and the EEJ strength is poor for the whole of the year 1995 (Figures 5d and 6d).

[15] For long-period wave oscillations, a good correlation between ~14-day oscillation in meridional winds and EEJ strength occurs in January and June, respectively, during which there is a good association between the diurnal oscillation in meridional winds and the EEJ strength (Figure 4d). In the case of semidiurnal tide, only the zonal wind in January has some association with EEJ strength (Figure 5d and 6d). The zonal wind, however, shows significant spectral power near the periodicity of 19 days (Figure 8) in June. During this period no significant enhancement is observed in the solar flux values in the periodicity band of 12–20 days (Figure 7a). Further, in April, when the EEJ strength shows strong spectral power near the periodicity of 15 days, the zonal wind shows significant power near the periodicity of 20 days. Moreover, in August and October, the EEJ strength but not the solar flux values (Figure 7a) show enhanced spectral power near the periodicity of 15 days. In the case of winds, however, the meridional component shows less significant power in the periodicity range of 14–20 days in August. And the zonal wind shows strong spectral power in the periodicity range of 15–20 days from mid-October through November.

5. Results for 1996

[16] Similar to Figure 8, the contour plots of power spectra in Figure 9 illustrate the mesospheric wave activities and their associated signatures in EEJ strength for the year 1996. In February and April of this year, oscillations near the periodicity of ~5 and 6.5 days in EEJ strength but not in solar flux values (Figures 7b and 7e) are accompanied by planetary waves in zonal wind. During these periods, the time variation of amplitude of diurnal tide in zonal (Figure 3a) and meridional winds (Figure 4a) and the semidiurnal tide in zonal wind (Figure 5a) has good correlation with EEJ strength, indicating that the mesospheric planetary waves might have propagated to EEJ dynamo region heights through the modulated tides. But in July–September, these periodic oscillations in zonal wind are not accompanied by similar enhancements in EEJ strength variations and in these months the association between the time variation of diurnal and semidiurnal tides in winds and EEJ strength is rather poor (Figures 3a, 4a, 5a, and 6a). While the significant ~16-day oscillation in EEJ strength but not in solar flux values (Figure 7a) is accompanied by significant ~20-day oscillation in meridional wind in January, in May and August it is accompanied by zonal wind ~20-day oscillation. But the strong ~14- to 22-day oscillation in June and November–December in meridional and zonal winds, respectively, is not accompanied by similar enhancements in the EEJ strength variations. During these periods, the association between diurnal tide amplitude in winds and the EEJ strength is rather poor (Figures 3a and 4a). Similarly, the prominent ~10- to 15-day oscillation in zonal wind in August is also not accompanied by similar variations in EEJ strength (Figure 9).

6. Results for 1997

[17] The contour plots of Figure 10 depict the power spectrum for the year 1997. Strong ~6.5-day oscillation in EEJ strength is accompanied by weak signal in zonal wind at 88 km but not in solar flux values (Figures 7b and 7e) in April. During this period, the diurnal and semidiurnal tide amplitude in winds (Figure 3b, 4b, 5b, and 6b) is weaker and poorly correlated with that in EEJ strength. In June, the significant ~6.5- to 9-day oscillation in EEJ strength but not in solar flux values (Figures 7b, 7c, and 7e) is accompanied by similarly enhanced oscillations in zonal wind. Further in November, both the zonal wind and EEJ strength and the solar flux values (Figure 7b and 7e) show strong ~6.5-day oscillation, but in August while the zonal wind shows significant ~6.5-day oscillation, the EEJ strength shows only less significant variations. Here it is observed weak correlations between the activity of diurnal and semidiurnal oscillation in winds and the EEJ strength (Figures 3b, 4b, 5b, and 6b). Moreover, the enhanced ~5-day oscillation (zonal) in July–September and ~6.5- and 9-day oscillations (meridional) in January are not accompanied by any significant oscillations in EEJ strength. In the case of long-period oscillation, it is noted that in January (Figure 10) the distinct ~15-day oscillation in zonal wind accompanies prominent ~18-day oscillation in EEJ strength but not in solar fluxes (Figure 7b). And also the tides are weak in this month, indicating that the mesospheric planetary-scale waves might have propagated directly to the ionospheric region and have influenced the electrojet current systems. But the significant ~16- to 22-day oscillation in zonal wind and 10- to 18-day oscillation in meridional wind from mid-April to mid-May are not accompanied by any variations in EEJ strength. Again the lack of significant tidal amplitudes in winds may be the reason why the mesospheric planetary wave oscillations cannot be seen sometimes in the EEJ strength (Figures 3b, 4b, 5b, and 6b). The equinoctial maximum in EEJ strength is mostly associated with maximum ionization and hence in the resulting enhanced conductivity and currents of the ionosphere [*Tarpley*, 1973]. However, *Stening* [1991] pointed out that strong and symmetric semidiurnal tidal winds also can contribute significantly to the equinoctial maximum before the noon-time EEJ strength. This point is well justified in the present observation of distinct enhancement of amplitude of semidiurnal winds during the equinox periods (Figures 5 and 6). Here some caution has to be kept in mind that although the 12 h harmonic of the EEJ strength (Figures 5 and 6) also shows equinoctial maximum, it may get easily influenced by counter equatorial electrojet, geomagnetic storm and other space weather related events. It is taken as future scope of research to explain in detail on how these events can distort or have their influences on this 12 h harmonic of the EEJ strength. Similarly, during November, the strong ~15-day oscillation in both the components of horizontal wind is not accompanied by any variations in EEJ strength. Conversely, the significant oscillation in EEJ strength near the periodicity of 19 days from mid-May to June and of 15 days in July is not accompanied by any variations in mesospheric winds as well as in solar fluxes (Figure 7a).

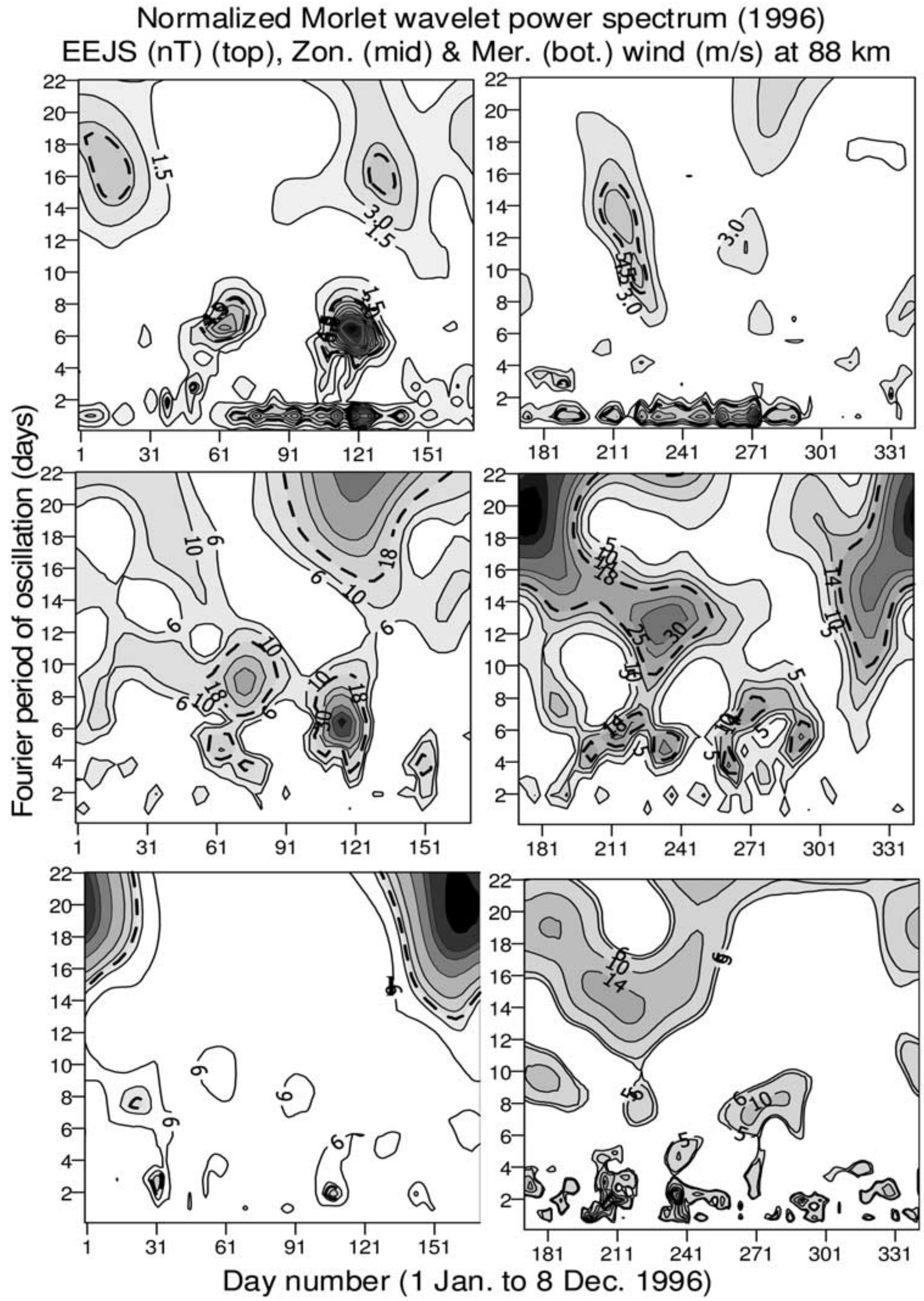

Figure 9. Same as Figure 2 but for the year 1996.

[18] The equatorial Kelvin waves are dominant in the equatorial region and the wave amplitudes are strong normally in zonal winds in this region. It is thought that the interference of planetary Rossby waves (with strong magnitudes in meridional wind component also) with equatorial Kelvin waves makes sometimes the wave amplitudes of particular modes be strong only in one component, either zonal or meridional at a particular time. Because of the constructive or destructive interference, when a particular mode of planetary wave has weak amplitude in one component at lower heights such as 80–90 km, the same wave may have stronger amplitudes at higher heights in the dynamo region. This could cause strong wave amplitude in one component that has clear association with enhanced EEJ strength at one time and similarly strong wave amplitude in other component being associated with enhanced EEJ at other times.

7. Discussion

[19] In brief, many of the planetary waves appearing in the MLT region are proposed to be originating in troposphere and stratosphere, where the atmosphere shows resonant

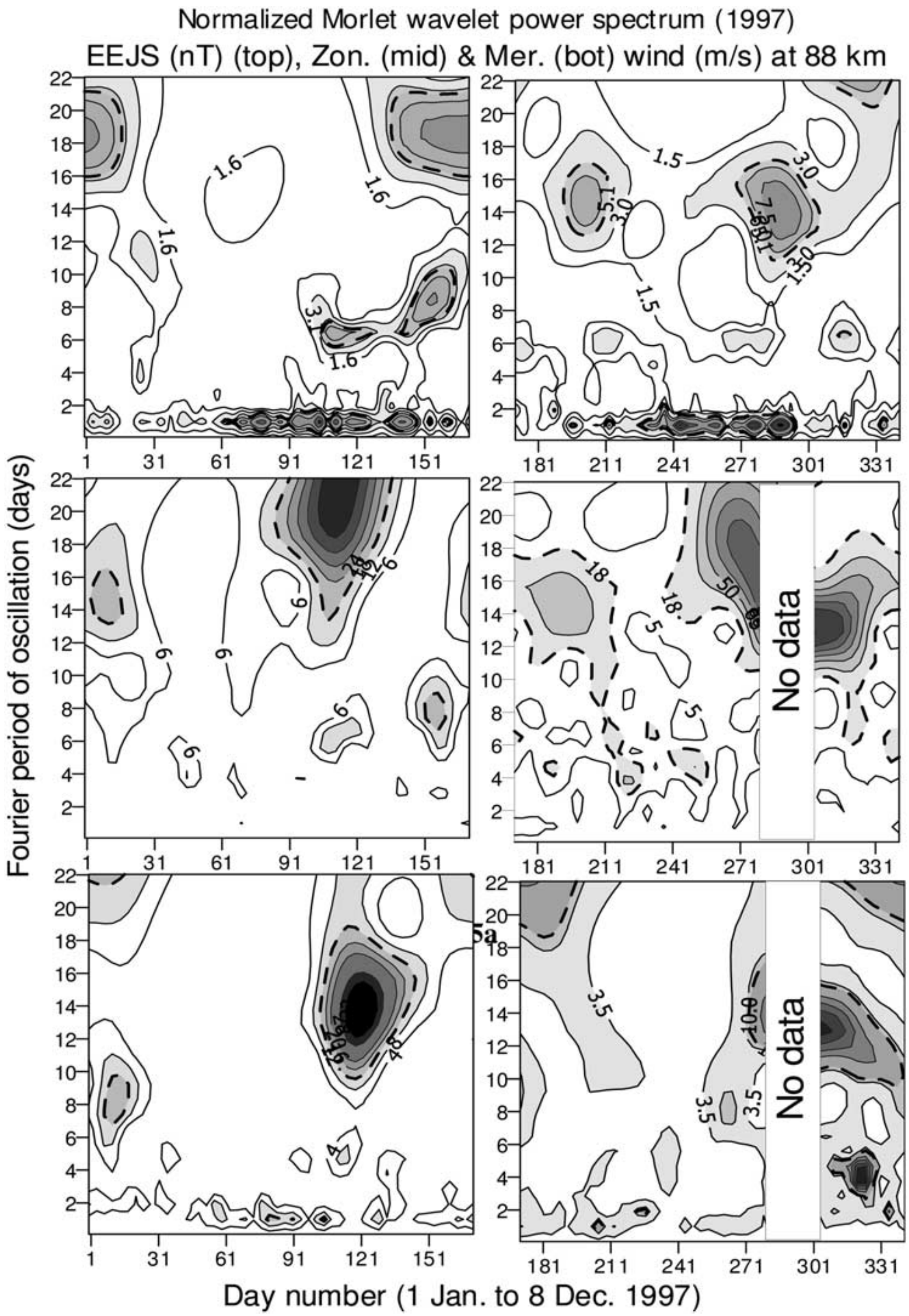

Figure 10. Same as Figure 2 but for the year 1997.

responses (Rossby modes) near the periodicities of ~2, 5, 10 and 16 days [*Salby*, 1984]. All these normal modes are in general westward propagating planetary waves. In realistic atmosphere, however, the period of oscillations may sometimes be Doppler shifted by the nonzero background winds. For example, *Forbes* [1995] showed that the Eigen periods of 5, 8.3 and 12.5 days might have Doppler shifted to the observed periods of 5.6, 10.2 and 17.1 days, respectively, for a nominal prevailing eastward wind of 10 m/s. As a source of excitation, the ~2-day wave is a manifestation of (3, 0) Rossby gravity normal mode, randomly forced in the lower thermosphere [*Salby*, 1981a, 1981c]. And, these ~2-day waves could also be due to baroclinic instability of the westward jet in the summer stratosphere and lower mesosphere [*Plumb*, 1983; *Pfister*, 1985]. In the case of 5- and 16-day waves, they may be induced by heating owing to moist convection in troposphere [*Yasunobu*, 1999; *Miyoshi and Hirooka*, 1999]. Further, there are two other transient types of oscillations in MLT region with periodicities near 3.5 and 6.5 days. While the ~3.5-day oscillations are eastward propagating ultra fast Kelvin waves (zonal wave number 1), the 6.5-day oscillations are westward propagating unstable modes (zonal wave number 1) excited in situ in the mesosphere [*Kovalam et al.*, 1999; *Clark et al.*, 2002].

8. Quasi–2-day Oscillation

[20] Further, in the case of ~2-day oscillation in EEJ strength, it is noted in the present study that often the period of oscillation (least squares method) in EEJ strength is centered near 48 h (not shown here), which is in agreement with earlier observations by *Rangarajan* [1994]. However, in mesospheric winds, the periodicity varies between 40 and 60 h; predominantly near 52 h in zonal winds but near 46 h in meridional winds (not shown here). These varied periodicities in mesospheric winds were also reported by earlier observations [*Craig and Elford*, 1981; *Salby*, 1981c; *Cevolani and Kingsley*, 1992]. *Rangarajan* [1994] attributed the difference in periodicity of ~2-day oscillations between EEJ strength and mesospheric winds to the local wind effects. Since the winds associated with planetary waves at near off-EEJ latitudes are more effective than the winds at EEJ latitudes in modulating the ionospheric currents, the winds detected over the equatorial (EEJ latitudes) regions need not always show its influence on the EEJ current system when the winds are different in these two latitude regions. While the EEJ currents are modulated by planetary waves at off-EEJ latitudes, the winds associated with planetary waves in the equatorial regions might have been modified owing to the abnormal amplitudes of local winds. That may be the reason for the observed difference between the periodicity of oscillations in EEJ strength and mesospheric winds.

[21] Moreover, to explain the discrepancy in wave numbers between quasi two day oscillation (QTDO) in the F region ionosphere (zonal wave number, k = 1) and middle atmosphere (k = 3), *Apostolov et al.* [1995] proposed a triggering mechanism in ionosphere. It is sometimes triggered by forcing of such an oscillation in the mesosphere linked with a particular region of globe and with further independent development in *F* region. In addition, *Forbes et al.* [1997] suggested that energy and momentum deposition by the ~2-day waves in the mesosphere/lower thermosphere could cause winds in the dynamo region that could interact with strong diurnal/semidiurnal (zonal wave number, k = 1 or 2) oscillations of the ionosphere. Such interaction could bring about the observed different wave numbers.

9. Quasi–3-day (2.8- to 3.8-day Band) Oscillation

[22] Oscillations with periodicity range of 2.8–3.8 days is identified as ultra fast Kelvin waves (UFK) in mesosphere and lower thermosphere (MLT) [e.g., *Salby et al.*, 1984; *Riggin et al.*, 1997; *Kovalam et al.*, 1999; *Yoshida et al.*, 1999; *Sridharan et al.*, 2002]. Normally they are trapped in the equatorial regions (called equatorial Kelvin waves) and propagate in eastward direction with phase speeds exceeding 100 m/s. The zonal wave number is reported to be often one. The present observational study illustrates that mostly during the spring equinox and summer months, the EEJ strength shows strong ~3-day oscillations (Figures 2 and 9). And that they are often accompanied by similar variations in mesospheric winds at 88 km.

[23] In the present work we observed maximum amplitudes of about 11 m/s (mostly in zonal winds) and vertical wavelengths in the range of about 60–100 km for these ultra fast Kelvin waves (not shown). And the EEJ strength shows maximum amplitude of about 9 nT with period of oscillation near 3 days. Earlier, *Parish et al.* [1994] reported enhanced ~3-day oscillations in EEJ strength (H component of geomagnetic field variation, ΔH), measured at Huancayo, Peru (South America), during January/February 1979. They attributed these oscillations in EEJ strength to the influence of upward propagating mesospheric waves. These past observations along with the present work indicate that the ~3-day oscillations in mesosphere may sometimes (particularly during equinox and summer months) be able to propagate up to the dynamo region heights and modulate the ionospheric current system existing there [*Takahashi et al.*, 2007].

10. Quasi–5-day (4.5- to 5.5-day Band) Oscillation

[24] Similar to ~3-day oscillations, the present observational study illustrates that the signatures of ~5-day mesospheric planetary waves in EEJ strength occur favorably during the spring equinox (March and April) and late summer months (July and August) (Figures 2, 8, 9 and 10). Earlier, *Parish et al.* [1994] observed, from 15 August to 8 November 1979, strong spectral peaks near the period of 6 days in geomagnetic field variations. They suggested that the mentioned spectral peaks in ΔH measurements might be due to the influence of the upward propagating ~5-day normal (1, 1) modes [*Salby*, 1981a, 1981b, 1981c]. These modes were observed to have periods in the range of 4.5 to 6.2 days in troposphere and stratosphere [*Rodgers*, 1976; *Madden and Stokes*, 1975; *Madden*, 1978]. Moreover, using the data obtained during 1977–1990, *Yi and Chen* [1993] observed strong 5-day oscillation in f_oF2 values in the crest region of equatorial ionization anomaly (EIA) during northern summer and equinox months of May and September, respectively.

11. Quasi–6.5-day (6- to 7-day Band) Oscillation

[25] Observations of the present work for the ~6- to 7-day band of oscillation show that the signatures of mesospheric planetary waves in EEJ strength occur predominantly during March and April. Next to these months, the significant wave signatures in EEJ strength occur during July to September. Rarely, the wave signatures in EEJ strength occur during November to January (Figures 2, 8, and 10). As a comparison, using data obtained during 1977 to 1990, *Yi and Chen* [1993] observed strong 7-day oscillation in f_oF2 values in EIA during May and September. *Clark et al.* [2002] observed using HRDI measurements that the 7-day waves in zonal winds showed low-latitude response primarily during equinoxes (favorably fall equinox) and at higher latitudes the waves occurred as sporadic events.

[26] In the present work we observed for the ~6.5-day oscillation in zonal winds maximum amplitudes of about 19 m/s with vertical wavelength of the order of about 70 km in the spring equinox month of April (not shown). The EEJ strength showed maximum amplitudes of about 7 nT for these ~6.5-day oscillations (not shown). In general, the

amplitudes in meridional winds are less than in zonal winds. At F region heights, the maximum probability of occurrence of the ~6.5-day oscillations in ionospheric parameters was during local summer, but the maximum amplitudes occurred during equinox periods [*Altadill et al.*, 1997; *Apostolov et al.*, 1998; *Altadill*, 2000]. *Apostolov et al.* [1998] proposed the following processes to explain the presence of 3- and 6.5-day oscillations in f_oF2 values.

[27] 1. Nonlinear interaction among the principal 2-, 5-, 9-, and 16-day oscillations.

[28] 2. A nonchaotic drift of periods of the 2- and 5-day oscillations into periods of 3 and 6.5 days.

[29] 3. Excitation of 3- and 6.5-day oscillations independent of 2- and 5-day bands.

12. Quasi–10-day (8.5- to 11-day Band) Oscillation

[30] Observations on ~10-day oscillations in both the EEJ strength and mesospheric winds indicate that both the summer and winter months are favorable for the existence of signatures of mesospheric planetary waves in EEJ strength. Earlier, these ~10-day oscillations in ΔH measurements were reported by *Parish et al.* [1994] in the period from 15 August to 8 November 1979. Using the data obtained during 1977–1990, *Yi and Chen* [1993] observed strong 10-day oscillation in f_oF2 in the crest region of EIA in the summer months. On the basis of the analysis of 10 years of geomagnetic data obtainedfrom beyond the northern mid latitudes, *Kohsiek et al.* [1995] observed significant spectral peaks near 10 days. They suggested that the upward propagating lower atmospheric planetary waves might have induced this ~10-day oscillation in the geomagnetic data time series. Regarding the wave characteristics of the ~10-day oscillation in winds in summer, maximum amplitude of about 12 m/s and vertical wavelength of the order of 70 km are observed for zonal winds in the present work (not shown). The amplitude of meridional winds is generally smaller than that of zonal winds. Sometimes, however, both the components show similar amplitudes. In the case of EEJ strength, maximum amplitude of about 5 nT is observed.

13. Quasi–16-day (12- to 20-day Band) Oscillation

[31] The quasi–16-day band in atmospheric oscillations covers actually the entire range of periodicities from 12 to 20 days [*Madden*, 1978, 1979]. For an atmosphere at rest, the ~16-day wave is associated with 12.3-day period second symmetric rotational normal mode [*Longuet-Higgins*, 1968], sometimes referred to as the (1, 3) mode. But in the presence of realistic mean zonal winds and meridional temperature gradients, the computed resonant response of atmosphere occurs near 16.1 days and exhibits a barotropic structure similar to that of (1, 3) mode in troposphere and lower stratosphere [*Salby*, 1984]. According to classical theory, there are several other normal modes of the quasi–16-day waves: (1) (1, 4) mode has a period of 17.5 days and (2) (2, 4) mode has a period of 11.5 days [*Hirooka and Hirota*, 1985]. Above 30–50 km, the exact period and the horizontal and vertical structures are strongly influenced by background wind and temperature fields through which the waves propagate [*Salby*, 1984].

[32] On the basis of 16 years (1980 to 1996) of observation of middle atmospheric (58 to 105 km) dynamics, using MF radar located at Saskatoon (52°N, 107°W), *Luo et al.* [2000] reported that the quasi–16-day oscillations in mesosphere and lower thermosphere (MLT) occurred mostly in winter seasons. This observation is in agreement with present observational results. Though not often, strong ~16-day oscillation in mesospheric winds occur also in the summer months of May to September (Figures 2, 8, 9, and 10). To explain this characteristic difference between different seasons it may be suggested that during summer the occurrence of ~16-day planetary waves in meridional wind in mesosphere is mainly because of ducting from winter hemisphere near the mesopause region [*Espy et al.*, 1997]. In summer, it is possible that these waves get easily damped before propagating above about 100 km so that they may not be able to influence the ionospheric current system existing there in the dynamo region.

[33] In the present observational study, it is noted that the signatures of mesospheric quasi–16-day (12- to 22-day band) planetary waves occur in EEJ strength often during November to February and sometimes during June–September. Earlier, *Parish et al.* [1994] identified this ~16-day oscillation in ΔH from 15 August to 8 November 1979. They associated this periodicity in ΔH measurements with the influence of upward propagating Rossby normal mode. Moreover, *Forbes and Leveroni* [1992] observed ~16-day oscillation in ionospheric parameters of the equatorial *E*- and *F*-regions in January/February 1979. In addition, using the data obtained during 1977–1990, *Yi and Chen* [1993] observed strong 16-day oscillation in the crest region of EIA in Okinowa, Japan during May and September.

[34] Further, *Kohsiek et al.* [1995] observed significant spectral peaks near 16 days in geomagnetic field variations and suggested that the upward propagating lower atmospheric planetary-scale waves might have induced this ~16-day oscillation in the geomagnetic time series. However, they reported difficulties in determining precisely the zonal wave number and the direction of wave propagation. This is one of the major difficulties in attributing the planetary-scale oscillations in ionospheric parameters to the influence of upward propagating atmospheric planetary waves. To explain this controversy, it was suggested that amid the simultaneous existence of different modes of ~16 day waves in the mesosphere region, only the dominant planetary wave modes would influence the ionosphere parameters. Furthermore, *Kohsiek et al.* [1995] expressed difficulties in determining the proper phase of oscillation in ionospheric parameters because of the interference effects among different modes.

[35] It is to be noted further that oscillations with periodicities near 16 days in ionospheric parameters may also be influenced by oscillations in high-energy solar radiation fluxes with periodicity centered near 13 to 15 days. Potentially, a 13.5-day oscillation in solar extreme ultraviolet (EUV) emissions can cloud the interpretation in terms of a 16-day lower atmospheric planetary wave by virtue of the influence of such periodicities on *E* region conductivity [*Parish et al.*, 1994]. For example, the strong sources of high-energy radiations located some 180 degrees apart on the

solar equatorial longitudes will give rise to ~14-day oscillation in electrical conductivity and hence in Earth's ionospheric currents [*Donnelly and Puga*, 1990]. The spectral power associated with this oscillation may sometimes be greater than for oscillation near 27 days, which is the mean solar rotation period. *Parish et al.* [1994] discussed in detail the influences of high-energy solar radiations (EUV, Lyman alpha, Lyman beta, X rays, etc.) along with mesospheric planetary waves in contributing significant oscillations with periodicities greater than 10 days in EEJ strength.

[36] Sometimes, the appearance of planetary-scale oscillations only in one of the two parameters, EEJ strength or mesospheric winds, is also observed. It is to be noted that in the present work the wind dynamics is determined only below 100 km in the dip equatorial region, whereas the EEJ current flows at about 105 km height. Further, while interpreting the planetary-scale oscillations in EEJ strength in terms of the influence of mesospheric planetary waves, it is assumed that the waves detected below 100 km actually propagate up to the dynamo region heights, where the waves modulate the EEJ currents at planetary timescales. There is also another implicit assumption that the planetary wave winds measured in the dip equatorial region are extended at least within the tropical latitudes. The assumption that normally both the planetary Rossby and equatorial Kelvin waves will have significant amplitudes in the Tropical region when the waves are active appears to be in general true. But the presence of strong local winds in the dip equatorial region may mask the winds associated with planetary or equatorial Kelvin waves to be detected by the radar in this region. Since mostly the winds in the near off-EEJ region are effective in modulating the EEJ currents [*Anandarao and Raghavarao*, 1979], the strength of which, as manifested in the geomagnetic field variations, would be showing the planetary-scale oscillations while the radar in dip equatorial region is measuring strong local winds. That would lead the observation of planetary-scale oscillations only in EEJ strength but not necessarily in the mesospheric winds in the dip equatorial region.

[37] Sometimes, it is also possible that the planetary waves would have been triggered in situ at the off-EEJ latitudes in the dynamo region [*Apostolov et al.*, 1995] and that their oscillations have been manifested in the geomagnetic field variations associated with ionospheric currents. In that case also, the mesospheric winds may not show the planetary-scale oscillations but the geomagnetic field variations would show strong planetary-scale oscillations. Further, during the alternate counter electrojet days, it is possible that the EEJ strength may show strong ~2-day oscillation when the mesospheric winds do not hold any such periodic oscillations [*Rangarajan*, 1994]. In the present study, often, it is also observed that only the mesospheric winds showed the strong planetary-scale oscillations, but not the EEJ strength. In this case, it may be interpreted that the waves detected in the mesospheric winds might have been damped before propagating to the dynamo region heights [*Hagan et al.*, 1993; *Forbes et al.*, 1995]. The lack of large database of wind measurements in the vicinity of the center of the EEJ dynamo region (near 105 km) is a major drawback of any attempt to establish any direct linkage between planetary waves in atmospheric winds and their signatures in EEJ strength. Perhaps in the near future, making such an attempt using satellite (say UARS, TIMED etc.) data may shed some light on this study.

14. Summary and Conclusions

[38] Using five years (1994–1998) of data obtained from MF radar and geomagnetic field measurements in the Indian dip equatorial region, the present paper investigated the presence of signatures of mesospheric planetary waves in the equatorial electrojet (EEJ). The MF radar (operating frequency, 2 MHz) located at the Indian dip equatorial station, Tirunelveli, is utilized to determine the horizontal winds in the mesosphere and lower thermosphere region. Winds measured in the height of 88 km are taken as reference for mesospheric wind dynamics. EEJ strength is determined by taking the difference of geomagnetic field variations measured both at the EEJ station, Trivandrum, and the off-EEJ station, Alibag, following the method described by *Kane* [1973]. The results obtained are summarized below.

[39] 1. Along with ~2-day planetary waves in mesosphere at 88 km, significant ~2-day oscillations in EEJ strength occurred more often during the late northern summer months of July and August and rarely during the winter months. This indicates that the oscillations in EEJ are associated mainly with the influence of upward propagating mesospheric planetary waves.

[40] 2. Mostly during spring equinox and summer months, the EEJ strength showed the signatures of mesospheric quasi 3-, 5-, and 6.5-day oscillations, indicating that the oscillations in EEJ strength might be due to the influence of upward propagating planetary waves.

[41] 3. As a winter and summer phenomena, the simultaneous presence of quasi–10- and 16-day oscillations in both the EEJ strength and mesospheric winds indicates that the mesospheric planetary waves might have played an important role in contributing long-period planetary-scale oscillations in the EEJ strength.

[42] 4. Often the planetary-scale oscillations occurring simultaneously in both the mesospheric winds and the EEJ strength are accompanied by similar and coherent variations in tidal amplitudes (mostly diurnal tide in zonal wind) in the mesospheric winds and the EEJ strength. This indicates that the tides modulated by planetary-scale waves in the mesosphere might influence the ionospheric parameters at these scales when they propagate up to the dynamo region when the mesospheric planetary-scale waves cannot propagate to these heights.

[43] 5. Sometimes the solar flux (F10 cm) variations also induce planetary timescale oscillations in the EEJ strength.

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