PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 64 (2002) 1455–1463

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Structural changes in the tidal components in mesospheric winds as observed by the MF radar during afternoon counter electrojet events

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Abstract

In this paper we examine the relationship between the tidal characteristics as observed by the MF radar at Tirunelveli (8.7°N, 77.8°E, geographic; 0.3°N magnetic dip) and the occurrence of afternoon counter electrojet (ACEJ) events. A reduction in the diurnal tide activity and/or an enhancement of semi-diurnal tide amplitude is observed on many of the ACEJ days. A clear anticorrelation is seen between the afternoon electrojet strength and the amplitude of the semi-diurnal tide in the solstitial months of June and July, 1995. The results presented herein provide observational support to the earlier numerical models that consider the interplay of various tidal modes in the evolution of equatorial ionospheric current system whose extreme manifestation in ground-geomagnetic field variations being the reversal of the electrojet in the afternoon hours.

Keywords: Tidal components; Tidal modes; Equatorial electrojet; Counter-electrojet; Dynamo region

1. Introduction

The equatorial electrojet (EEJ) is an intense band of eastward electrical current flowing at ~ 105 km during daytime in a narrow latitudinal belt around the dip equator. This reflects in the daily variation of the horizontal component (H) of Earth's magnetic field which shows a positive deviation during the day with a maximum at around noon (Onwumecheli, 1997). Sometimes a negative deviation in H occurs due to the reversal in the direction of the current system from the normal eastward flow to westward which is often called 'counter electrojet' (CEJ) (Mayaud, 1977, for a review). A CEJ can occur either in the morning or in the afternoon; we shall refer to these as morning (MCEJ) and afternoon counter-electrojet (ACEJ), respectively. ACEJ events have attracted many researchers for many of their complexities that include their variable nature and difficulties in identifying causative mechanisms responsible for their generation. Though the morphological behaviour of ACEJ has been studied in detail by several workers in the last three decades (Marriott et al., 1979, for a review), the causative mechanisms for its occurrence still remain an unsolved problem.

There are two schools of thought that have attempted to identify the process responsible for the ACEJ. Earlier workers believed that it is the height-varying local winds that cause the reversal in the current system. Though such winds can produce altitudinal changes in the vertical polarization field (Reddy, 1989), the desired effects are pronounced not at the equator, but at latitudes > 2° (Richmond, 1973, for example). Raghavarao and Anandarao (1980) proposed that gravity-wave-associated vertical winds can cause the reversal. The second school of thought looks for a mechanism that is global in nature. Global-scale tidal winds with appropriate phase combination were shown to reverse the currents in the afternoon hours (Forbes and Lindzen, 1976; Marriott et al., 1979; Stening, 1989). Hanuise et al. (1983) and later Singh

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1364-6826/02/$ - see front matter
PII: S1364-6826(02)00109-8

and Cole (1987) incorporated a three-dimensional numerical model that evaluates the role of tidal modes in causing the observed changes in the magnetic field variations associated with the ACEJ.

The experimental evidences for the role played by the dynamical processes in causing ACEJ as suggested by the above theoretical studies are awaited. Continuous measurements of neutral winds in the equatorial dynamo region are yet to be made. Rocket experiments are occasional and they prove to be expensive. Radar measurements within the dynamo region (100–110 km) are constrained by the influence of electric fields over the measured drifts. In this region, the radars tend to measure the electron drift motion driven by intense electric fields rather than the neutral wind.

With the installation of a partial reflection medium frequency (MF) radar at Tirunelveli (8.7°N, 77.8°E geographic; 0.3°N dip), continuous data on neutral winds close to the dynamo region (84–98 km) are available since 1992. This experimental set-up provides an opportunity to examine the mesospheric wind and tidal characteristics possibly associated with the electrojet during different electrodynamical conditions. With more MF radar systems coming up in different longitudinal sectors in the equatorial and low-latitude belt, there is scope for using this network in studies for the understanding of the dynamical and electrodynamical coupling associated with many of the equatorial ionospheric processes.

2. Observations

The wind data utilized in the present study were acquired by the MF radar operating at Tirunelveli in the spaced antenna mode. The system details, mode of operation and the method of wind determination are the same as described by Vincent and Lesicar (1991). Important results on the mean winds and tidal climatalogies observed over Tirunelveli were reported earlier (Rajaram and Gurubaran, 1998; Gurubaran and Rajaram, 1999). Hourly values of wind measurements in the altitude region 84–98 km were first subjected to meaningful statistics (Rajaram and Gurubaran, 1998) before subjecting the data to further analysis. Since all hourly slots may not be filled for altitudes below 84 km, this region is not included in the present analysis.

The magnetic data are from the Indian Magnetic Data (IMD) volumes published by the Indian Institute of Geomagnetism for the years 1993–1996. The usual method of representing the EEJ strength (Kane, 1973) is adopted in the present work: the electrojet strength is derived from the differences between the magnetic field variations obtained from Trivandrum (8.5°N, 77°E, geographic; 0.5°N dip) and Alibag (18.6°N, 72.9°E, geographic; 12°N dip). Trivandrum is a coastal station located close to the axis of EEJ and is also under the influence of Sq current system, whereas Alibag is a coastal off-equatorial station under the influence of Sq current system only.

3. Data analysis

In order to identify the relationship, if any, between changes in the tidal components (refer to solar tides only unless otherwise stated) in zonal wind and the geomagnetic field variations, successive groups of quiet ACEJ and non-ACEJ events ($A_p < 12$) were identified for the years 1993–1996. The groups of ACEJ and non-ACEJ days are the following: 6–8 December 1995 with A_p values 4, 4 and 2, respectively; 9–11 December 1995 with A_p values 9, 5 and 4 (hereinafter referred to as group A); 5–7 March 1996 with A_p values 8, 7 and 11; 8–10 March 1996 with A_p values 6, 4 and 2 (referred to as group B). In addition to obtaining tidal estimates from the corresponding 3-day composite mean winds we also considered individual ACEJ and the nearest non-ACEJ days in order to obtain more cases. Fifteen pairs of individual, quiet, ACEJ and non-ACEJ days are selected and the tidal amplitudes are computed for these days for comparison.

4. Results

Fig. 1 demonstrates the temporal variation of the EEJ strength for the days in groups A and B (details given above) and pairs A and B (two pairs of ACEJ and non-ACEJ days are taken from the selected 15 cases and shown as examples). In general, the enhancement starts generally at around 0600–0800 EMT (Meridian Time at 75°E) with a maximum at noon. On ACEJ days, one can note the strength of electrojet to reach the maximum at around 1000 EMT which is earlier than that on non-ACEJ days and a decrease after 1000 EMT to values well below the nighttime level in the afternoon (1300–1500 EMT) which is later followed by a recovery to the nighttime value at around 1800 EMT. Unusually, large afternoon depressions (40–50 nT) below the nighttime level are noticed for two of the days during March 1996. The day-to-day variability of the EEJ strength is extreme during the period 9–11 December 1995. On 10 March 1996 and 24 July 1993 there were morning counter electrojets noticed in the ΔH variations. On a quiet day in June 1996 the electrojet did not develop fully as the maximum field variation was only 10 nT. In the afternoon hours the electrojet reversed with a maximum depression of ~ 35 nT at 1500 EMT.

We now proceed to examine the tidal characteristics observed by the MF radar over Tirunelveli on the groups/pairs of days under consideration. Figs. 2a and b show the height variation of the amplitude and phase of the diurnal (bottom panel), semi-diurnal (middle) and ter-diurnal (top) tide components in zonal wind on ACEJ days (line with solid squares) and on non-ACEJ days (line with open triangles) for the groups A and B, respectively. In general, the amplitude and phase of all the tidal components during ACEJ days are substantially different from those on non-ACEJ days. The amplitude of the diurnal component is reduced at lower

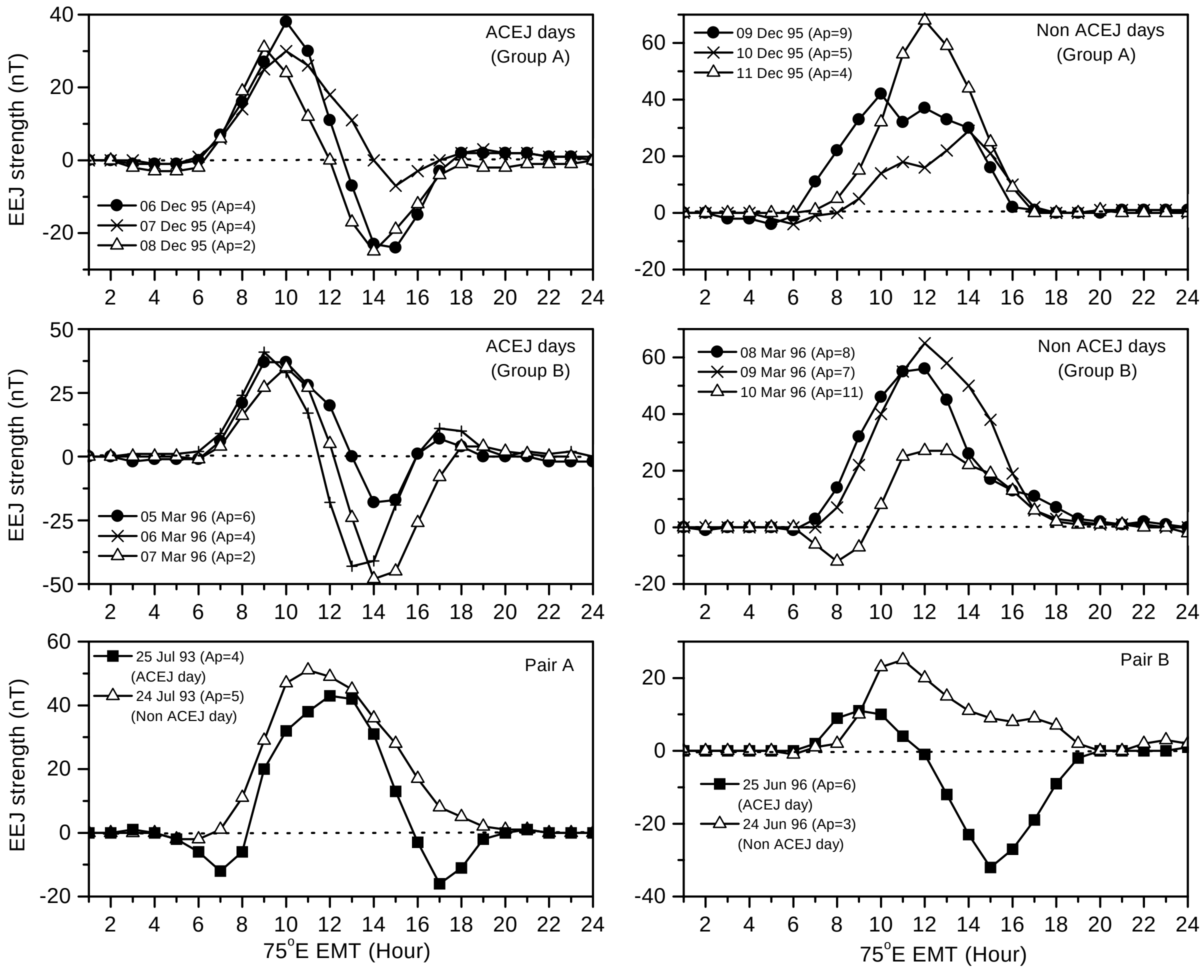

Fig. 1. Temporal variation of the EEJ strength for the days of groups A and B (see text for details).

heights (86–94 km) on non-ACEJ days. Between 5 and 10 March 1996 (group B) the diurnal tide amplitude increases from ~ 5 m/s at lower altitudes to ~ 20 m/s at 98 km for both ACEJ and non-ACEJ days. A noteworthy feature in Figs. 2a and b is that the semi-diurnal tidal component has a larger amplitude during ACEJ days than on non-ACEJ days in both the groups. On the ACEJ days of group B the semi-diurnal amplitude increases from 10 to 23 m/s at 96 km. Phase profiles of semi-diurnal tide show negative slope on non-ACEJ days of group A indicating downward propagation. As their phase profiles indicate, large vertical wavelengths are noticed for ACEJ days in group A. Phases of semi-diurnal tide at higher altitudes on days of group B show less variation with height in both ACEJ and non-ACEJ days. The amplitude of the ter-diurnal tide is also larger in both the cases considered with a tendency of larger amplitudes on ACEJ days than on non-ACEJ days.

In Table 1 we present a list of quiet ACEJ and the non-ACEJ events followed or preceded by ACEJ events selected from 4 years (1993–1996) of magnetic data together with the response of tidal amplitudes. In this table, unlike in Figs. 2a and b, only individual pairs of ACEJ and non-ACEJ days are considered. A_p values and the indices S and M denoting strong (> 20 nT) and moderate (between 10 and 20 nT) depression below night-time level in H on ACEJ days are also given for reference. In this table 10 events are during the summer (May–August), 3 during winter and 2 during the equinoctial months. The changes observed in the amplitude profiles of the tidal components on ACEJ and non-ACEJ days are given.

An examination of the table shows that an enhancement of semi-diurnal tide on ACEJ events occurred only during a few of the events but 11 out of 15 of the events are associated with a suppression of diurnal tide amplitude. Of the other four, one event is associated with the increase of diurnal tide amplitude on ACEJ days but the semi-diurnal tide amplitude is also increased in all the heights. In another event, there is no significant change observed in diurnal tide

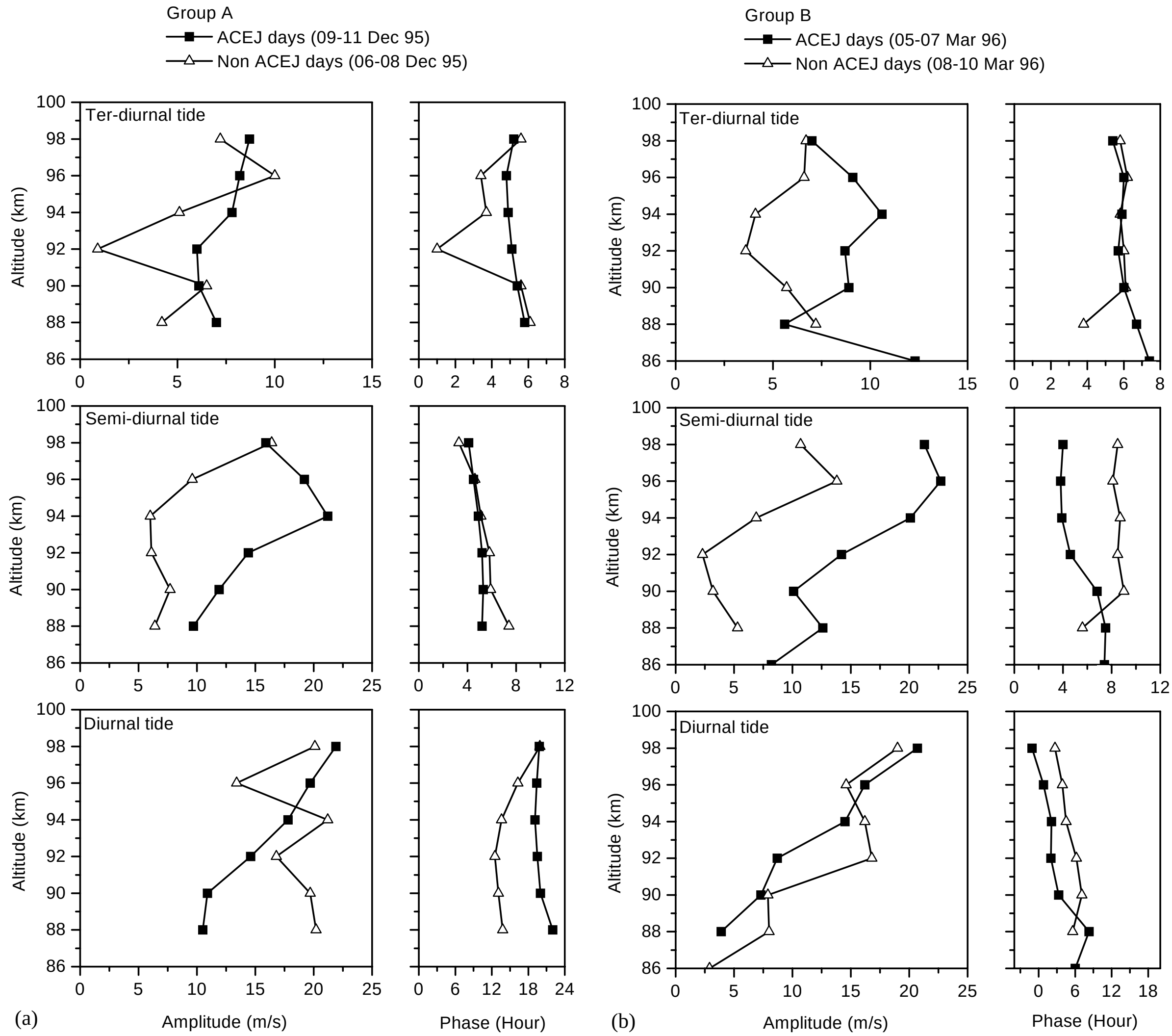

Fig. 2. The height-variation of the amplitude (left) and phase (right) (given in IST) of the diurnal (bottom), semi-diurnal (middle) and ter-diurnal (top) tide components in zonal wind on ACEJ days (line with solid squares) and on non-ACEJ days (line with open triangles) of group A. (b) Same as (a) but for the days of group B.

amplitude but the amplitude of semi-diurnal tide is increased above 92 km. On some other occasions there is no significant change observed in diurnal as well as semi-diurnal tide amplitudes.

The above characteristic behaviour of the tidal modes on ACEJ and non-ACEJ days is confirmed with more examples from the selected 15 cases shown in Figs. 3a and b. Following the same order as in Figs. 2a and b, we present the height variation of the amplitude and phase of the diurnal, semi-diurnal and ter-diurnal tide components in zonal wind on ACEJ days (line with solid squares) and on non-ACEJ days (line with open triangles): 24 and 25 July 1993 with A_p values 5 and 4, respectively (hereinafter referred to as pair A), and 24 and 25 June 1996 with A_p values 3 and 6, respectively (hereinafter referred to as pair B). It may be noted that the diurnal tide amplitude is suppressed on ACEJ days when compared to non-ACEJ days of both pairs A and B. Large diurnal tide amplitudes varying in the range 30–40 m/s on 24 July 1993 (non-ACEJ day) are reduced to values in the range 20–30 m/s on 25 July 1993 (ACEJ days). Phase profile shows negative slope on non-ACEJ days of both pairs A and B indicating downward propagation, whereas the phase profiles on ACEJ days are irregular possibly due to an interference between different modes. The amplitude of semi-diurnal tide shows greater values at heights above 88 km on the ACEJ day of pair A when compared to the non-ACEJ day but there is no distinct change in the amplitudes for the pair B. The phase structure of ter-diurnal tide

Table 1
A list of quiet ACEJ and the nearest non-ACEJ events are selected from 4 years (1993–1996) of magnetic data together with the response of tidal amplitudes

Sl. no.	Non-ACEJ events/ ACEJ events	A_p	Changes in diurnal tide amplitude during ACEJ days when compared to non-ACEJ days	Changes in semi-diurnal tide amplitude during ACEJ days when compared to non-ACEJ days	Changes in ter-diurnal tide amplitude during ACEJ days when compared to non-ACEJ days
1	18.07.93/17.07.93	5/3 S	Suppression is observed in most of the heights	No significant change is observed	No significant change is observed
2	24.07.93/25.07.93	4/5 M	Suppression is observed in the height region 88–98 km	Enhancement is observed in the height region 82–98 km	No significant change is observed
3	30.07.93/31.07.93	6/6 S	No significant change observed	Enhancement is observed in the height region 82–98 km	No significant change is observed
4	14.08.93/13.08.93	2/4 S	Suppression is observed in the height region 88–98 km	No significant change is observed	Slight decrease is observed in the height region 88–98 km
5	23.11.93/24.11.93	7/5 M	Enhancement is observed in the height region 90–98 km	Enhancement is observed in the height region 82–98 km	Slight increase is observed in the height region 88–98 km
6	23.01.94/24.01.94	7/4 M	Suppression is observed in the height region 88–98 km	Enhancement is observed in the height region 80–98 km	Slight increase is observed in the height region 88–98 km
7	23.11.94/24.11.94	4/4 M	Suppression is observed in all heights except at 98 km	Enhancement is observed in the height region 90–98 km	Enhancement is observed in the height region 80–98 km
8	18.03.95/19.03.95	4/4 M	Suppression is observed in the height region 88–98 km	No significant change is observed	No significant change is observed
9	11.05.95/12.05.95	6/6 M	No significant change is observed	Enhancement is observed in the height region 92–98 km	Suppression is observed in most of the heights
10	27.05.95/28.05.95	6/6 S	Suppression is observed in the height region 80–98 km	No significant change is observed	Enhancement is observed in the height region 80–98 km
11	02.08.95/03.08.95	5/6 S	Suppression is observed in the height region 80–98 km	No significant change is observed	No significant change is observed
12	24.06.96/25.06.96	6/3 S	Suppression is observed in the height region 80–98 km	No significant change is observed	No significant change is observed
13	09.07.96/10.07.96	2/4 M	Suppression is observed in the height region 88–98 km	No significant change is observed	Decrease is observed in the height region 92–98 km
14	26.7.96/27.07.96	5/3 S	Suppression is observed in the height region 88–98 km	No significant change is observed	Increase is observed in the height region 88–98 km
15	06.10.96/07.10.96	2/4 M	No significant change is observed	No significant change is observed	No significant change is observed

shows irregular structure on both the days of pair A. But the phase structure of ter-diurnal tide for the days of pair B indicates downward trend with a large vertical wavelength on 25 June 1996 (ACEJ day) and shows irregular phase structure on 24 June 1996 (non-ACEJ day) which may be due to very small amplitudes at intermediate heights that may lead to inaccurate phase estimation.

Earlier model results suggest that the $(1,-2)$ diurnal tide is the principal contributor to the dynamo current (Marriott et al., 1979). It is nearly impossible to establish its presence from a single observing site though the phase profiles may still provide some indications for the presence of the dominant mode vis-á-vis the (1,1) mode versus the other possible modes. We examined the phase profiles of the diurnal tides for all the selected 15 groups of days. We notice a clear downward phase propagation with vertical wavelengths in the range 25–30 km in accordance with the 'classical' (1,1) mode at least on few of the non-ACEJ days (24 November 1993, 23 November 1994, 24 June 1996, 9 July 1996, 26 July 1996) but not on ACEJ days. The phase profiles on other days show irregular structures indicating the superposition of different modes, possibly (1,1) and $(1,-2)$ modes,

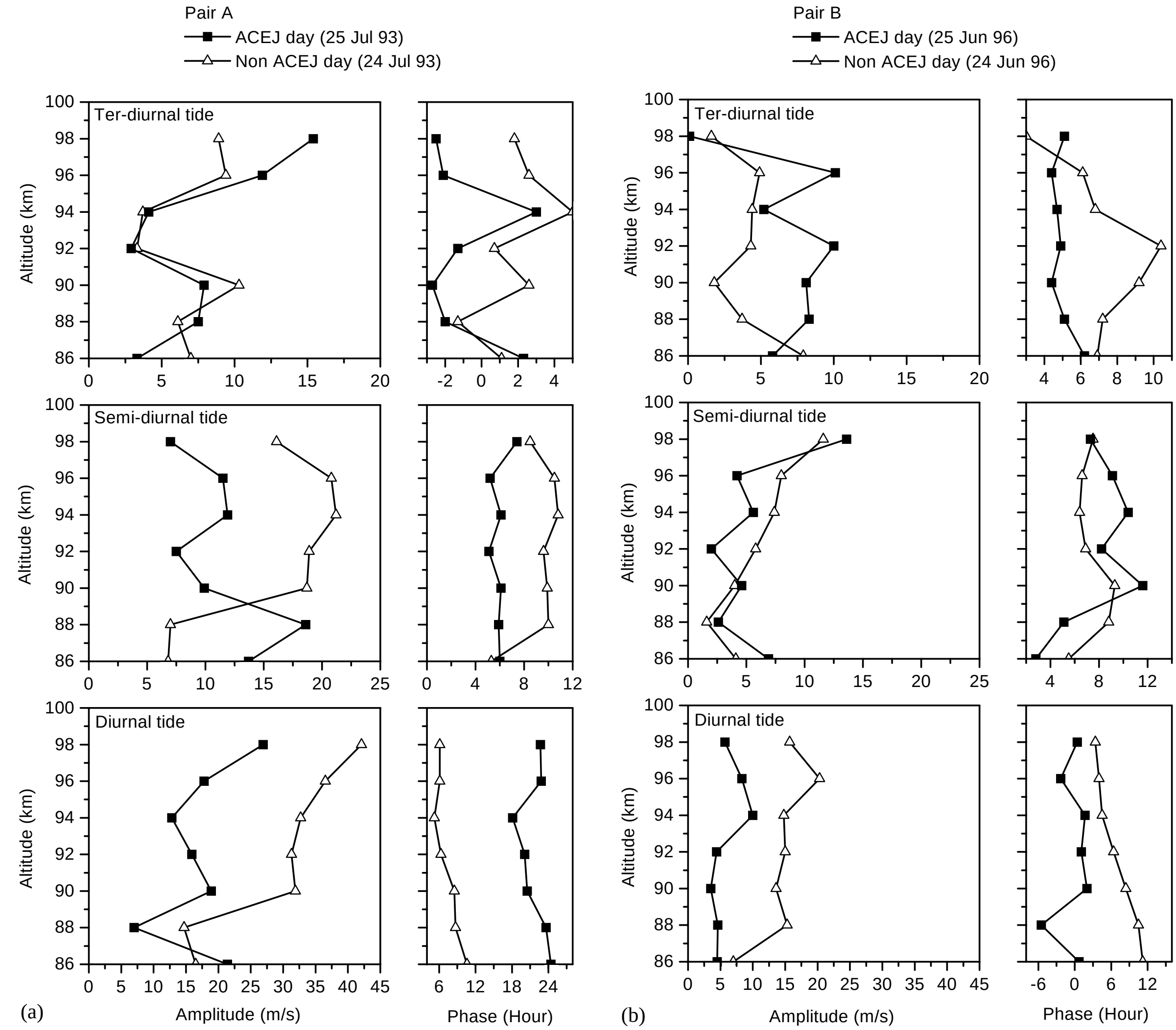

Fig. 3. (a) Same as Fig. 2(a) but for pair A. (b) Same as Fig. 2(a) but for pair B.

as observed by Somayajulu et al. (1993) from their meteor scatter measurements carried out at Trivandrum.

Since it is known that ACEJ events are more frequent in solstices and the semi-diurnal tide contribution to the equatorial electric field is expected to be large during these months (for example, Marriott et al., 1979), the tidal characteristics during the solstitial months (June and July) of 1995 are considered for a close examination of their day-to-day variabilities and their possible association with the ACEJ occurrence. Fig. 4 shows the comparison of afternoon (mean of 1400–1700 h values) EEJ strength (middle panel) with A_p index plotted in the top panel. The diurnal (extreme bottom) and semi-diurnal tide (second from bottom) amplitudes at 86 km are also plotted in Fig. 4 for comparison. Amplitudes in both zonal and meridional directions are represented in the comparison plot. Harmonic analysis subjected to the composites of 3-day means (centred on each day) yield estimates of the tidal amplitudes which are plotted for every day. It may be noted that there are sequences of more than 10-day duration when the A_p value was < 10, for example, day numbers 155–166 and 183–196. The ΔH variation during these sequences of days may very well be controlled by the neutral atmospheric tidal processes as the magnetospheric influences will be reduced during these days. The tidal amplitudes in the meridional direction are larger on some days, whereas the amplitudes in the zonal direction are larger on the rest of the days. The difference in the zonal and meridional amplitudes is less for the diurnal tide when compared to the semi-diurnal tide amplitudes.

It is apparent from the figure that on day numbers 162 and 192 the amplitude of the semi-diurnal tide in the zonal direction is more than 15 m/s. Around these days, the

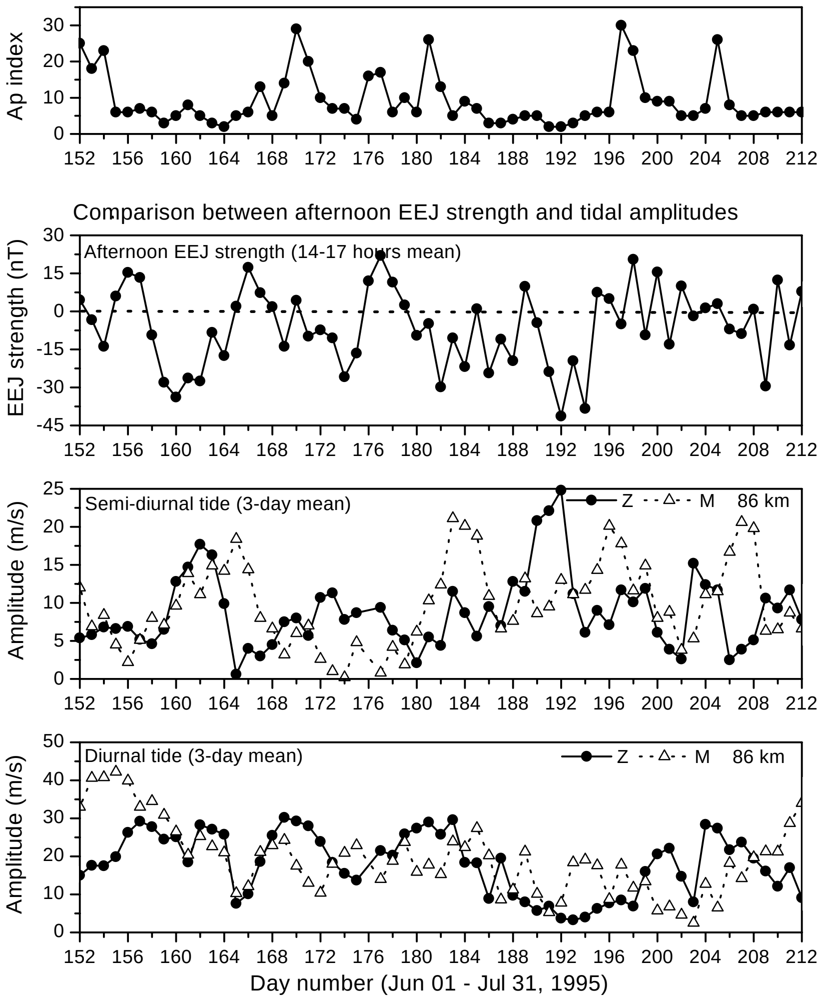

Fig. 4. A comparison of afternoon (mean of 1400–1700 hour values) EEJ strength (second from bottom) with diurnal (bottom) and the semi-diurnal tide (first from bottom) amplitudes derived from the composites of 3-day mean. Ap index plotted in the top panel for reference.

afternoon electrojet shows large negative values (30 nT and more). The depression was less (20–30 nT) on days when the semi-diurnal tide amplitude was around 10 m/s (day numbers 173, 183 and 209). A noticeable feature in the diurnal tide behaviour is that beginning on day number 184 the amplitudes are consistently < 15 m/s up to day number 198. Largest negative depression (~ 40 nT) in the afternoon EEJ strength occurs on day numbers 192 and 194 when the diurnal tide amplitudes are negligibly small (< 5 m/s). Though in the solstice months of June and July, 1995, semi-diurnal enhancement during CEJ days is very prominent, it does not stand out as a prominent feature in the solstice months of other years. It may be noted from Fig. 4 that a 10–15 day modulation is present in the ACEJ strength. This might be due to the modulation of tidal winds by a 16-day planetary wave, an important dynamical feature of the middle atmosphere (Mitchell et al., 1999).

In spite of the limitations of the experimental technique and the complex nature of the occurrence of the counter electrojet events the present work demonstrates that on many CEJ days the semi-diurnal tide amplitude at mesopause heights is enhanced and the diurnal tide amplitude is reduced. For some cases these features occur together and on some other occasions they occur separately.

5. Discussion

The influence of tidal modes in causing CEJ events has been stressed by several workers (Forbes and Lindzen, 1976; Marriott et al., 1979; Stening, 1989; Stening et al., 1996, to state a few). The suppression of diurnal tide amplitude on ACEJ days was earlier reported by Somayajulu et al. (1993) who considered successive groups of ACEJ days and control days (non-ACEJ days). Our findings reported in the present work are consistent with the results obtained by Somayajulu et al. (1993). The latter considered only one pair of ACEJ and non-ACEJ days, whereas we have examined a large number of groups of days. Our analysis reveals the suppression of diurnal tide amplitude in most of the events (11 out of the 15 cases considered) thus reiterating the results obtained by Somayajulu et al. (1993). The latter observed quasi-sinusoidal variation in the phase of the diurnal component on CEJ days which was suggested to be due to the superposition of different modes of diurnal tide, possibly (1,1) mode and the evanescent $(1,-2)$ mode. In the present work, the phase profiles of diurnal tide in most of the ACEJ and some of the non-ACEJ days show irregular structure which indicate interference effects of tidal modes as suggested by Somayajulu et al. (1993).

Somayajulu et al. (1993) also observed a westward excursion of background wind on ACEJ days. They suggested that a combination of global tidal wind fields which tends to weaken the vertical polarization field in combination with local westward winds is necessary to produce the ACEJ events. Stening et al. (1996) observed that many of the wintertime ACEJ events at Trivandrum are associated with changes in the mean zonal wind at Saskatoon. In our present study based on the 15 pairs of quiet ACEJ and non-ACEJ days selected, we did not observe any noticeable change in the background wind on ACEJ days when compared to non-ACEJ days. In this context, it may be noted that Stening et al. (1996) suggested that the wind systems responsible for driving ACEJ are part of a global system rather than a wind system in the vicinity of the electrojet.

We observed a clear anticorrelation between the semi-diurnal tidal amplitude and afternoon CEJ for the solstice months of June and July 1995. This confirms the earlier model simulations that the semi-diurnal tide plays an important role in the generation of the CEJ event. It may be noted that in the limited data used by Somayajulu et al. (1993) there was no distinct enhancement of semi-diurnal tide noticed at heights near 100 km. The phase profiles revealed positive slope and the authors inferred the presence of higher order modes.

Marriott et al. (1979) based on the theoretical calculations found the diurnal tide to be the dominant generator of eastward electric field during the equinoxes that will account for a normal equatorial electrojet. But, during solstices, the contributions of the semi-diurnal tide, especially the (2,2) mode, to the equatorial electric field are relatively greater. They opined that the solar semi-diurnal tides have a tendency to set up a westward electric field in the afternoon hours of the solstitial season to cause ACEJ, unless this tendency is opposed by the diurnal tide. In our present work, there is a suppression of the amplitude of the diurnal tide on ACEJ days so that its contribution becomes smaller. Rather, this effect will pave way for the dominant semi-diurnal tide to participate in the generation of the westward electric field that would cause the ACEJ.

Stening (1989) calculated ionospheric currents due to the semi-diurnal antisymmetric tides $(2,3)$ and $(2,5)$ and found the currents from $(2,5)$ mode are negligible. Further, the latitude-local time structure of the current density generated from the $(2,3)$ mode seems to explain many of the observed ground-based signatures. Earlier, from the mesospheric radar wind measurements at Adelaide (35°S, 183°E) and Kyoto (35°N, 136°E), Vincent et al. (1988) gave an observational evidence for the dominance of antisymmetric tidal modes over the symmetric modes at heights near 90 km.

6. Conclusion

The tidal characteristics as observed by the MF radar over Tirunelveli in the altitude range 84–98 km during different electrodynamical conditions as reflected in the ground-geomagnetic field variations are examined in this work. Many of the CEJ events tend to occur when the diurnal tide activity is reduced. Since $(1,-2)$ diurnal tide is the principal generator for the dynamo electric fields, a weakening of this tide may contribute to the generation of the ACEJ as shown by earlier simulation results. Though it is impossible to determine whether the observed tidal amplitudes represent $(1,-2)$ mode, the vertical phase structure provides clues to the presence of this mode.

Another important result reported herein in connection with the occurrence of the ACEJ events is that the semi-diurnal tide amplitudes are enhanced during these events. Altitude profiles of groups of ACEJ and non-ACEJ days confirm this feature. When the variabilities of the semi-diurnal tide during the solstitial months of 1995 were examined, we find that the magnitude of the afternoon depression in the ground-geomagnetic field variation varies in tune with the amplitude of the semi-diurnal tide.

Observational results presented in this work favour a tide-induced generation mechanism for an afternoon CEJ event. Though the results are not new, the observations lend support to the modelling efforts in this direction made elsewhere. An extensive analysis with a large database on tides in the mesosphere and lower thermosphere region from several radar sites, supported by numerical simulations, may provide more insights into the various tidal modes that take part in the generation of the reversal of equatorial electric fields and current systems in the dynamo E region.

Acknowledgements

One of the authors (S.S.) thanks the Director, Indian Institute of Geomagnetism (IIG), Mumbai, for a research scholarship. The partial reflection MF radar at Tirunelveli is operated by IIG. Technical assistance provided by K. Unnikrishnan Nair is duly acknowledged. IIG routinely publishes the geomagnetic data obtained from its chain of magnetic observatories in the Indian sector. This work is supported by the Department of Science and Technology, Government of India.

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