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Day-to-day variability of geomagnetic hourly amplitudes at low latitudes

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SUMMARY

A study of the variability of the amplitude of *Sq* at a fixed hour from one day to the next at nine stations from the dip equator to about 22° north of it has produced interesting results. The amplitude and sign of the variability change virtually randomly, making the mean practically zero. The variability occurs at all hours of the day. Its magnitudes in the components *D*, *H* and *Z* have the same diurnal variation, which peaks in the noon period like *Sq*(*H*) in low latitudes, and a weak seasonal variation that peaks at the June solstice (local summer). It is demonstrated that changes in the current intensities of the equatorial electrojet (EEJ) and the worldwide part of the *Sq* (*WSq*) current layers have contrasting phases and can sometimes be in antiphase. Indeed, the changes are mostly independent. Inclusion of the magnetic element *D* revealed that the EEJ current system has not only an east–west but also a north–south component. The study shows that the meridional component of the EEJ current intensity evidenced at the Kodaikanal and Annamalainagar stations is an integral part of the zonal component at Trivandrum. This confirms the results of Rastogi (1996) and validates those of Onwumechili (1997). The results suggest that ionospheric conductivity mainly controls the magnitude, while the electric field and ultimately winds mainly control the phase and randomness of the day-to-day variability of the hourly amplitudes of *Sq*. The random component is attributed to local and/or regional atmospheric winds, probably of gravity wave origin.

Key words: equatorial electrojet, *Sq* amplitudes, variability, worldwide *Sq* currents.

1 INTRODUCTION

Many authors have studied various aspects of the variabilities of geomagnetic regular variations. The variability of the solar-cycle variations of the geomagnetic solar daily variation *S* and lunar daily variation *L* are evident in Chapman, Gupta & Malin (1971). The variability of *S* with regard to the 27-day solar rotation is considered by Briggs (1984). Various aspects of the variability of the seasonal variations of *S* are evident in Campbell (1982), Onwumechili, Oko & Ezema (1996) and Oko, Onwumechili & Ezema (1996).

The day-to-day variabilities of the daily ranges of geomagnetic solar quiet daily variation (*Sq*) and its associated ionospheric parameters in low and middle latitudes have been studied by many authors, including Chapman & Stagg (1929, 1931), Osborne (1966, 1968), Ogbuehi, Onwumechili & Ifedili (1967), Schlapp (1968), Greener & Schlapp (1979), Hibberd (1981, 1985), Butcher & Brown (1981a,b), Schlapp & Mann (1983), Briggs (1984), Mann & Schlapp (1985, 1987, 1988), Brown (1986), Hibberd & Davidson (1988), Schlapp, Mann & Butcher (1988) and Phillips & Briggs (1991). Similarly, the studies of day-to-day variabilities of the *Sq* daily ranges and associated ionospheric parameters in the equatorial zone included those of Forbush & Casaverde (1961), Osborne (1962, 1963, 1964, 1966, 1968), Ogbuehi & Onwumechili (1964), Onwumechili & Ogbuehi (1965, 1967), Onwumechili (1967), Ogbuehi *et al.* (1967), Hutton (1867a,b), MacDougall (1969, 1979a,b), Burrows (1970), Kane (1971) and Mann & Schlapp (1988).

The variability of the phase of *Sq* on abnormal-phase quiet days (APQDs or AQDs) in the equatorial zone and its important implications have been studied by Onwumechili (1967), Last, Emilia & Outhred (1976), Sastri & Murthy (1978) and Sastri (1981a,b, 1982). APQDs in middle latitudes, and their wide-ranging and intriguing implications have been thoroughly studied by Brown & Williams (1969), Brown (1974, 1975, 1986), Butcher & Brown (1980, 1981a,b), Brown & Butcher (1981), Butcher (1982a,b,c, 1987) and Schlapp *et al.* 1988). The study of APQDs has illuminated several aspects of *Sq* in both the equatorial and the mid-latitude regions. The hour-to-hour variability of *Sq* on a given day has also been studied by Schlapp (1973).

The studies of the variability of the current centre and focus of the worldwide part of *Sq* (*WSq*) include those of Chapman & Bartels (1940), Hasegawa (1960), Matsushita (1960, 1967), Hutton (1967b), Schlapp (1976), Malin & Gupta (1977), Butcher & Brown (1980, 1981b), Butcher (1982b), Campbell (1989) and references therein, and Onwumechili *et al.* (1996). There have also been studies of the variability of the equatorial electrojet (EEJ) current centre and focus, including those of Osborne (1962, 1964, 1966, 1968), Ogbuehi & Onwumechili (1964), Onwumechili (1967), Onwumechili & Ogbuehi (1967), Burrows (1970), Cain & Sweeney (1972, 1973), Fambitakoye & Mayaud (1976a), Oko *et al.* (1996) and Ratanova *et al.* (1997).

The variability of the current intensity and total forward current of the EEJ and *WSq* current layers, as well as the variability of their landmark distances and structural parameters, has been studied by Onwumechili & Ogbuehi (1967), Fambitakoye & Mayaud (1976b), Suzuki (1978, 1979), Onwumechili & Agu (1981), Takeda (1984, 1985), Takeda & Araki (1984), Onwumechili (1985), Anandarao & Raghavarao (1987), Raghavarao & Anandarao (1987), Onwumechili, Agu & Ozoemena (1989), Onwumechili (1992a,b,c), Ezema, Onwumechili & Oko (1996), Oko *et al.* (1996) and Onwumechili *et al.* (1996). An *in situ* direct measurement of the day-to-day variability of the EEJ current parameters by means of rockets was described by Onwumechili (1992a).

The results of these numerous studies of *Sq* variabilities are too extensive to be reviewed here. We therefore single out the findings most relevant to this paper. The variabilities of the *Sq* daily ranges at two stations in the EEJ zone (referred to as 'E stations') correlate positively and very highly. The variabilities of the *Sq* daily ranges at two low-latitude stations in the worldwide part of the *Sq* zone outside the influence of the EEJ (referred to as 'L stations') also correlate positively and very highly. However, the variabilities of the daily ranges of the EEJ field at E stations and of *Sq* at L stations correlate insignificantly; the correlation could be slightly positive or slightly negative, even when the two stations are on the same longitude. Indeed, a number of the studies state confidently that the variabilities of the current intensities of the EEJ and *WSq* current layers are independent.

The above review lists the various aspects of *Sq* variabilities that have been studied. There is as yet no study of the variability of *Sq* amplitudes at a fixed local time hour from one day to the next. In response, the objective of this paper is the study of the variabilities of the hourly amplitudes of *Sq* from day to day in terms of the geomagnetic declination D, the horizontral component H and the downward vertical component Z. The study covers all 24 hr of the day at stations from the dip equator to 22.3° north of it. It therefore affords an opportunity to study the variabilities in the EEJ and *WSq* zones and to compare them.

2 DATA

The data are from eight Indian observatories lying along a longitude of $76.82 \pm 2.8°$E for the solar-activity-minimum year of 1986. The coordinates of the stations are given in Table 1, where δ is the actual distance of each station in degrees latitude from the local magnetic dip equator. L distorts the actual distance δ because it is non-linear. The equation in the caption of Table 1 relating L and δ is a very rough first-order approximation for the region. From the values of δ and L, it is clear that the data from Hyderabad (H), Alibag (A), Ujjain (U), Jaipur (J) and Sabhawala (S) represent the worldwide part of the *Sq* (*WSq*) field, while the data from Trivandrum (T), Kodaikanal (K) and Annamalainagar (M) represent the combination of the equatorial electrojet (EEJ) and the *WSq* magnetic fields. As is widely customary (Rastogi 1989), the data differences Trivandrum minus Alibag (T − A), Kodaikanal minus Alibag (K − A) and Annamalainagar minus Alibag (M − A) are taken to represent EEJ magnetic fields. Although 1986 was a magnetically very quite year, we analysed the quieter ($Ap \leq 6$) days.

The Indian data were supplemented with the 1962 data from the low-latitude observatory of Muntinlupa in the Philippines. In particular, this was used to compare the variabilities of geomagnetic hourly amplitudes during quiet and moderately disturbed periods. The geographic coordinates of the Muntinlupa station are 14.37°N, 121.02°E; the dip latitude δ is 7.2°N; and the geomagnetic coordinates are 3.2°N, 190.8°E. The distribution of the data among their Ap groups is given in Table 2. The quiet-period days are generally limited to

Table 1. Coordinates of the eight Indian observatories whose 1986 data were analysed. $L = -0.2872 + 1.2387\delta$ to a rough approximation.

Observatory	Geographic latitude (°N)	Geographic longitude (°E)	Dip latitude		Geomagnetic latitude (°N)	Geomagnetic longitude (°E)
			δ (degrees)	$\tan^{-1}(Z/2H) = L$ (degrees)		
Dip equator	8.09	76.82	0.0	0.0	−1.5	147.45
Trivandrum	8.29	76.57	0.20	0.20	−1.2	146.4
Kodaikanal	10.23	77.47	2.14	2.15	0.6	147.1
Annamalainagar	11.36	79.68	3.28	3.44	1.4	149.4
Hyderabad	17.42	78.55	9.33	11.22	7.8	148.9
Alibag	18.63	72.87	10.54	13.26	9.5	143.6
Ujjain	23.18	75.78	15.09	18.55	13.5	147.0
Jaipur	26.92	75.80	18.83	22.81	17.3	147.4
Sabhawala	30.37	77.80	22.28	27.26	28.8	149.8
Mean		76.82				147.45
Standard deviation		2.80				2.0

Table 2. Distribution of days at Muntinlup among Ap groups.

Quiet days		Moderately disturbed days	
Ap	Number	Ap	Number
≤ 6	115	9–10	24
7	29	11–15	70
8	21	16–20	35
9	9	21–30	31
10	6	31–40	18
		41–50	4

$Ap \leq 8$. The days with $Ap = 9$ and 10 were included only in the relatively more disturbed months of April, August, September and October, for the purpose of using enough days for statistical analysis in every month. Otherwise, days with $Ap = 9$ and 10 were grouped as moderately disturbed.

The midnight hourly value C_0 of a magnetic component is defined as the mean of the hourly values C_t for the local time hours $t = 1$ and $t = 24$, where C represents the elements D, H and Z. The Sq amplitude c_t for the hour t is the difference between the hourly value C_t and the midnight value C_0. Thus

$$C_0 = \frac{1}{2}(C_1 + C_{24}) \qquad \text{and} \qquad c_t = C_t - C_0 . \tag{1}$$

Therefore, for the hour t, c_t represents d_t for the amplitude of D, h_t for the amplitude of H, and z_t for the amplitude of Z. The variabilities of these hourly amplitudes for the hour t from the day i to the next day $(i+1)$ are

$$d_{t(i+1)} - d_{ti}, \quad h_{t(i+1)} - h_{ti}, \quad z_{t(i+1)} - z_{ti} . \tag{2}$$

For each element, the sequence of 24 values of this variability for $t = 1$ to 24 defines the diurnal variation of the variability from day i to day $(i+1)$.

It is important to consider the magnitude of the variability in eq. (2), without regard to sign. From such a consideration we get the sequence for the 24 hr of the day:

$$SV_i(C) = \frac{1}{24} \sum_{t=1}^{24} |(c_{t(i+1)} - c_{ti})| , \tag{3}$$

and the sequence for $(n+1)$ days at hour t:

$$SV_t(C) = \frac{1}{n} \sum_{i=1}^{n} |(c_{t(i+1)} - c_{ti})| , \tag{4}$$

where SV stands for the sequential variability (Onwumechili 1992a), C stands for D, H and Z and c stands for d, h and z. Only consecutive days are used in obtaining the differences in eq. (2). Thereafter, the sequence of available differences is averaged as in eq. (4).

3 TEMPORAL VARIATION OF DAY-TO-DAY VARIABILITY OF HOURLY AMPLITUDES

3.1 Diurnal variation of day-to-day variability of hourly amplitudes

The diurnal variation defined in eq. (2), for the variability of Sq hourly amplitudes on two consecutive days, was determined and plotted for 1986 January 4 and 5, and from January 11 to 17. We can only show a few of the resulting graphs. The diurnal variation of Sq day-to-day variability shown in Fig. 1 is for D at Alibag, in Fig. 2 it is for Z at Annamalainagar and in Fig. 3 it is for the difference in H at Annamalainagar and Alibag. The selection attempts to feature the three elements D, H and Z as well as the WSq field (Alibag D), the combined EEJ and WSq fields (Annamalainagar Z) and the EEJ field [M(H) − A(H)].

For all three fields WSq, EEJ and their combination, the general features of the diurnal variation of the variability of Sq hourly amplitudes are similar and may therefore be described together, before their comparisons. The variabilities occur day and night but are more conspicuous in the daytime. In nearly all cases the variability between a given pair of days is different from the variability between any other two days. For the same pair of days the variabilities in different elements at the same station are also different. There are variabilities in both amplitude and phase, which seem to change randomly. Consequently, the mean variability for the nine days in any element of any field is practically zero.

The use of 'phase' here deserves careful attention. The Sq magnetic field is produced by Sq currents. These Sq currents change in intensity (magnitude or amplitude) as well as in direction (phase). Accordingly, the resulting Sq magnetic field also changes in intensity as well as in direction. The components of the magnetic field D, H and Z have their directions defined but can still change in sign (180° change in phase). An increase in the intensity of the current increases the amplitude of H and Z even if the direction of the current is unchanged. On the other hand, even if the intensity of the current is unchanged, a change of its direction such that its north–south component increases while its east–west component decreases can lead to an increase in the magnitude of D and a decrease in the magnitude of H. It follows that changes in the magnitude of D, H and Z can be responses to the changes in the amplitude or phase of the total Sq magnetic field, which derive from changes in the intensity or phase of the Sq currents.

Here we use 'random' in its ordinary meaning of 'lacking a definite plan, purpose or pattern'. Random variabilities of D, H and Z arise from random changes of the intensity and or direction of the Sq currents, originating from changes in conductivity or electric field. Because the conductivity is not expected to change randomly, the random aspect of the variabilities suggests that they arise from winds which generate the driving electric fields through the dynamo process.

We now compare the variability of the WSq field as seen at Alibag with the variability of the combination of the EEJ field and the WSq field as observed at EEJ-zone stations, and also with the EEJ field alone, represented by Annamalainagar (ANA) minus Alibag (ALI). The variability of ALI(H) is very different from that of ANA(H) and also very different from that of [ANA(H) − ALI(H)]. Similarly, the variability of ALI(Z) is very different from the variabilities of ANA(Z) and [ANA(Z) − ALI(Z)]. But the variability of D does not conform to this pattern. The variability of ALI(D) sometimes resembles that of ANA(D) to some extent, but not always. On the other hand, the variability of ALI(D) is sometimes in antiphase with that of [ANA(D) − ALI(D)], but not always. The application of the techniques of time-series analysis might improve the comparisons. But as far as we can see, in general these comparisons are consistent with the results of the many studies of the daily ranges of Sq mentioned in Section 1.

It remains to compare the variability of the EEJ field with

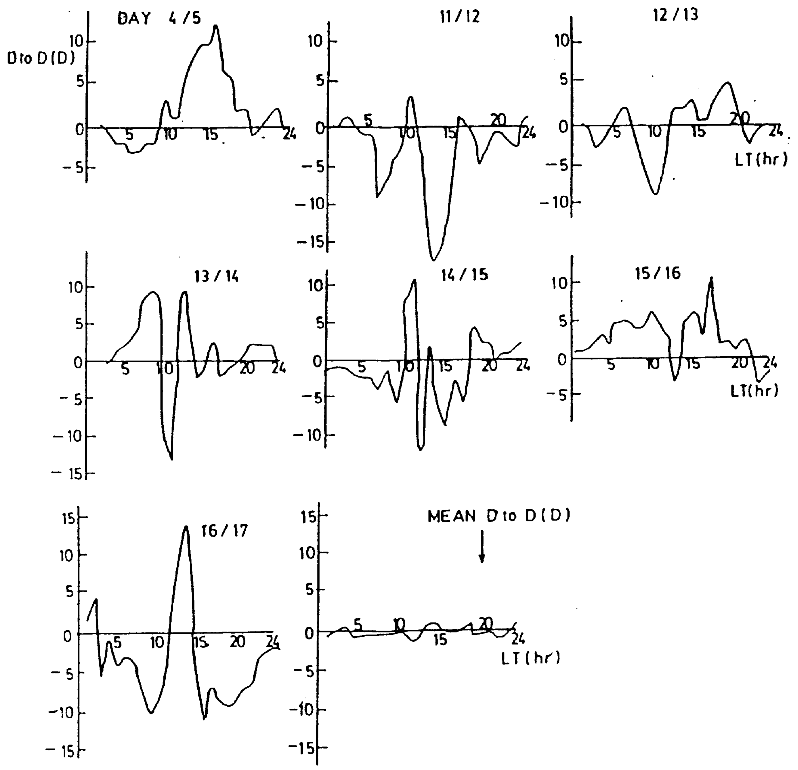

Figure 1. Diurnal variation of day-to-day variability of hourly amplitudes of $Sq(D)$ at Alibag in units of 0.1 min, for seven pairs of quiet days in January 1986 and their mean.

that of the observed combination of EEJ and *WSq* fields at an EEJ-zone station. In each of the three elements *D*, *H* and *Z*, the observed variability at Annamalainagar resembles to some extent the variability of the corresponding EEJ field at ANA represented by (ANA − ALI). For *H* and *Z* this is consistent with the results of previous studies of the daily ranges of *Sq*. Our result here suggests that the variability of *D* at Annamalainagar has a considerable part due to the EEJ field, as in the case of *H* and *Z* at this station.

Therefore our result for *D* is at variance with the erstwhile assumption that the EEJ produces a negligible *D* field because it is regarded as essentially an eastward current. This new result is, however, in accord with two recent papers. Onwumechili (1997) has produced the current vortex of the EEJ. It shows that the north–south component of the EEJ current is maximum at the latitude of its focus, at about 3° dip latitude. From Table 1, Annamalainagar is close to the focus of the EEJ and should record the near-maximum north–south current intensity and *D* field of the EEJ. Rastogi (1996) has found experimental evidence of the *D* field of the EEJ at Annamalainagar and reports that it is smaller at stations above and below the latitude of Annamalainagar. The findings in these two papers constitute explanations of our result.

3.2 Diurnal variation of magnitudes of day-to-day variability of hourly amplitudes

The random variation of the phase of variability of the amplitude of *Sq* makes it very difficult to study its magnitude. Onwumechili (1992a) therefore defined the sequential variability (*SV*), with which we can conveniently study the magnitudes of the day-to-day variability of *Sq* amplitudes without regard to sign. The sequence of values of SV_t in eq. (4), averaged for n days for each hour t ($t = 1$ to 24), where n is for a month, a season or a year, gives the diurnal variation of the magnitudes of the day-to-day variability of the hourly amplitudes of *Sq*, averaged for the month, the season or the year as the case may be.

Fig. 4 shows the diurnal variation of SV_t for the month of January 1962 at Muntinlupa. It shows that the magnitudes of day-to-day variability arising from *WSq* in all three elements *D*, *H* and *Z* have the same diurnal variation, similar to the diurnal variation of $Sq(H)$ in low latitudes. The diurnal variations for quiet periods and moderately disturbed periods are similar, except that they fluctuate more in the disturbed periods. The variation is minimum and fairly flat at night and it peaks in the range 1000–1400 local time. This is surprising because in low latitudes the diurnal variations of $Sq(H)$, $Sq(Z)$ and $Sq(D)$ are normally different.

We illustrate the diurnal variation of SV_t in the Indian sector with the data for July 1986 in Fig. 5. This agrees with the diurnal variation in quiet periods at Muntinlupa. Indeed, it extends our information on the the variations of the fields because we are now in a position to judge the variabilities of the *WSq* field from the five *WSq*-zone stations numbered 4 to 8 in Fig. 5, the EEJ field from the difference fields numbered 9 to 11, and their combinations observed at the three EEJ-zone stations numbered 1 to 3. It is remarkable that all three elements of each of the three fields have the same diurnal variation, which is like $Sq(H)$ at low latitudes. The diurnal

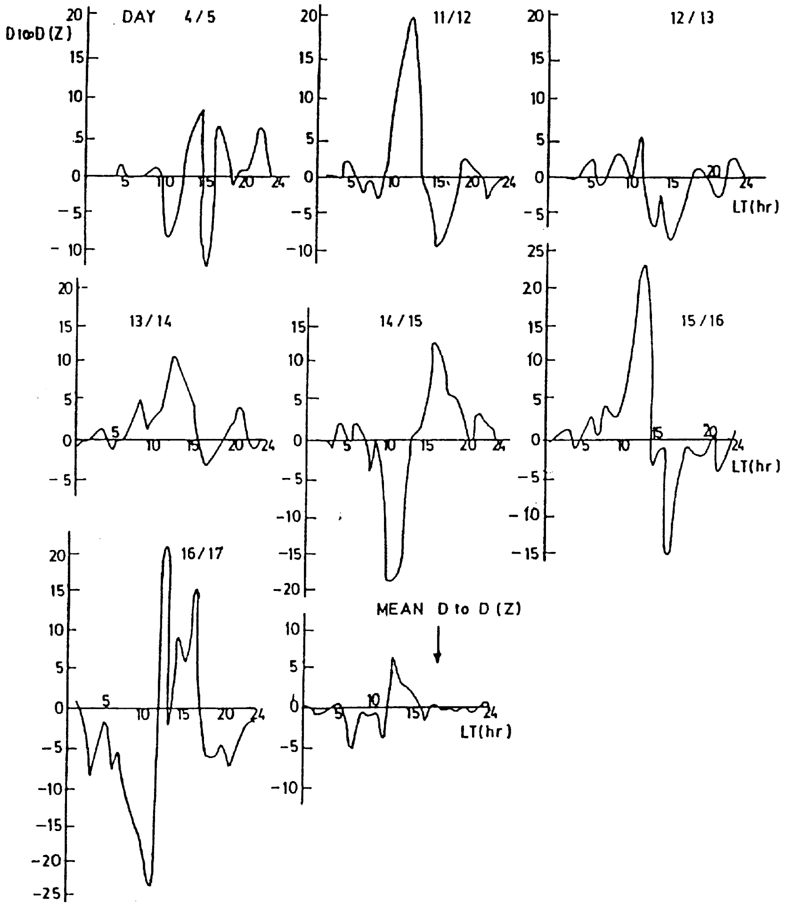

Figure 2. Diurnal variation of day-to-day variability of hourly amplitudes of *Sq*(*Z*) at Annamalainagar in units of nanotesla, for the same quiet days as in Fig. 1, and their mean.

variations of SV_t in the other months are similar to those shown for January in Fig. 4 and July in Fig. 5.

The diurnal variation of the magnitude of the day-to-day variability of the hourly amplitudes of *Sq* suggests solar control through plasma density and ionospheric conductivity. Recalling the fourth paragraph of Section 3.1, we infer that both of the factors determining the current intensity, i.e. the conductivity and electric field, play important roles in the variability of the hourly amplitudes of *Sq*. While changes in the electric field control the phase and randomness of the variabilities, the magnitude of the ionospheric conductivity controls the magnitude of the variabilities.

3.3 Seasonal variation of sequential variability of hourly amplitudes

The data from Muntinlupa were used to examine the seasonal variation of the magnitudes of the day-to-day variability of the hourly amplitudes of *Sq*. Plots of the monthly means indicated an annual variation with a peak in June (local summer). As this was not always clear, the means for the Lloyd seasons are plotted in Fig. 6. This shows a clearer seasonal variation, with a local summer peak in all three elements for quiet periods. For moderately disturbed periods the seasonal variation is consistent with this, but not so clearly, because the value for *H* at the December solstice exceeds the value at the June solstice. Thus, in general, at Muntinlupa the quiet-time seasonal variation of the magnitude of day-to-day variability is the same as that of the magnitude of *Sq*(*H*).

In this section we also present the average of *SV* for the hourly amplitudes of *Sq*. Table 3 gives the annual mean magnitudes of the day-to-day variability of hourly amplitudes of *Sq* at Muntinlupa observatory in 1962. It is only *H* that has a significantly greater value in moderately disturbed periods than in quiet periods. This is because *H* is the most disturbed element in low latitudes.

In Table 4 we give the monthly means of *SV* for *D*, *H* and *Z* in June, October and December 1986 at eight Indian observatories and also for T − A = Trivandrum − Alibag, K − A = Kodaikanal − Alibag and M − A = Annamalainagar − Alibag.

Table 3. Annual mean magnitude of day-to-day variability of hourly amplitudes of *Sq* at Muntinlupa observatory in 1962.

	D (0.1 min)	*H* (nT)	*Z* (nT)
Quiet days	4.5 ± 0.9	7.8 ± 1.1	4.2 ± 0.8
Moderately disturbed days	4.9 ± 0.5	21.2 ± 7.8	5.1 ± 1.4

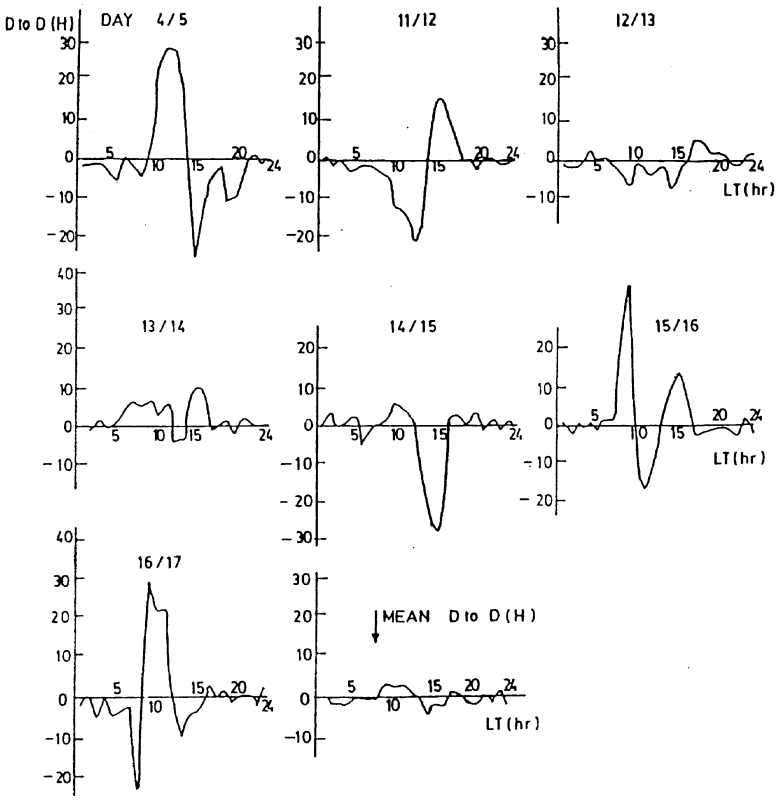

Figure 3. Diurnal variation of day-to-day variability of the difference between the hourly amplitudes of $Sq(H)$ at Annamalainagar and Alibag in units of nanotesla, for the same quiet days as in Fig. 1, and their mean.

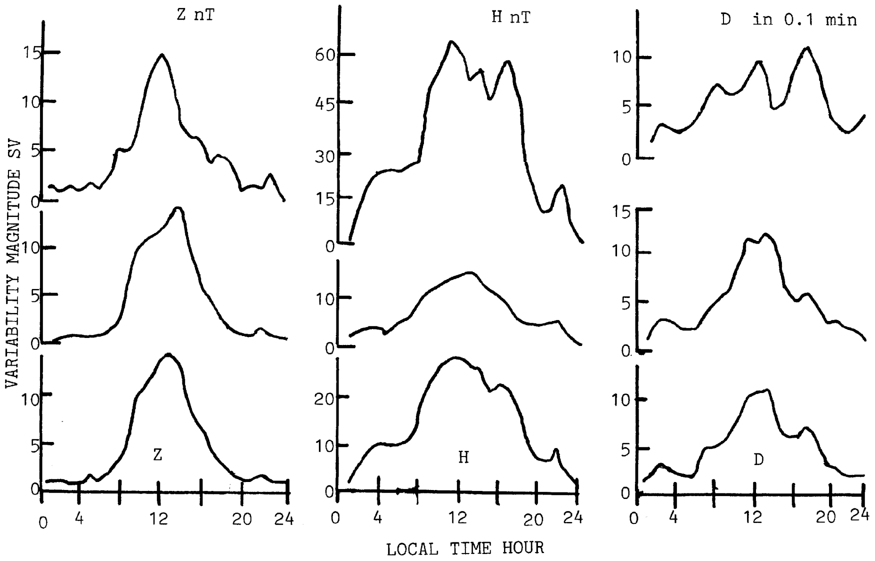

Figure 4. Diurnal variation of the monthly means of the magnitudes (SV) of day-to-day variability of hourly amplitudes of solar daily variations of D, H and Z components at Muntinlupa in January 1962: (top) for moderately disturbed days; (middle) for quiet days; (bottom) for all days.

The table shows submeans for the EEJ field (bottom), the *WSq* field (middle) and their observed combinations at Trivandrum, Kodaikanal and Annamalainagar in the EEJ zone (top). The following inferences may be drawn from Table 4. In all three elements of each of the three fields, the value for June is never exceeded by the values for October and December. This is consistent with the seasonal variation for quiet periods at Muntinlupa in 1962.

The mean values of SV are not obviously enhanced in the EEJ zone. This was also tested with latitudinal profiles of

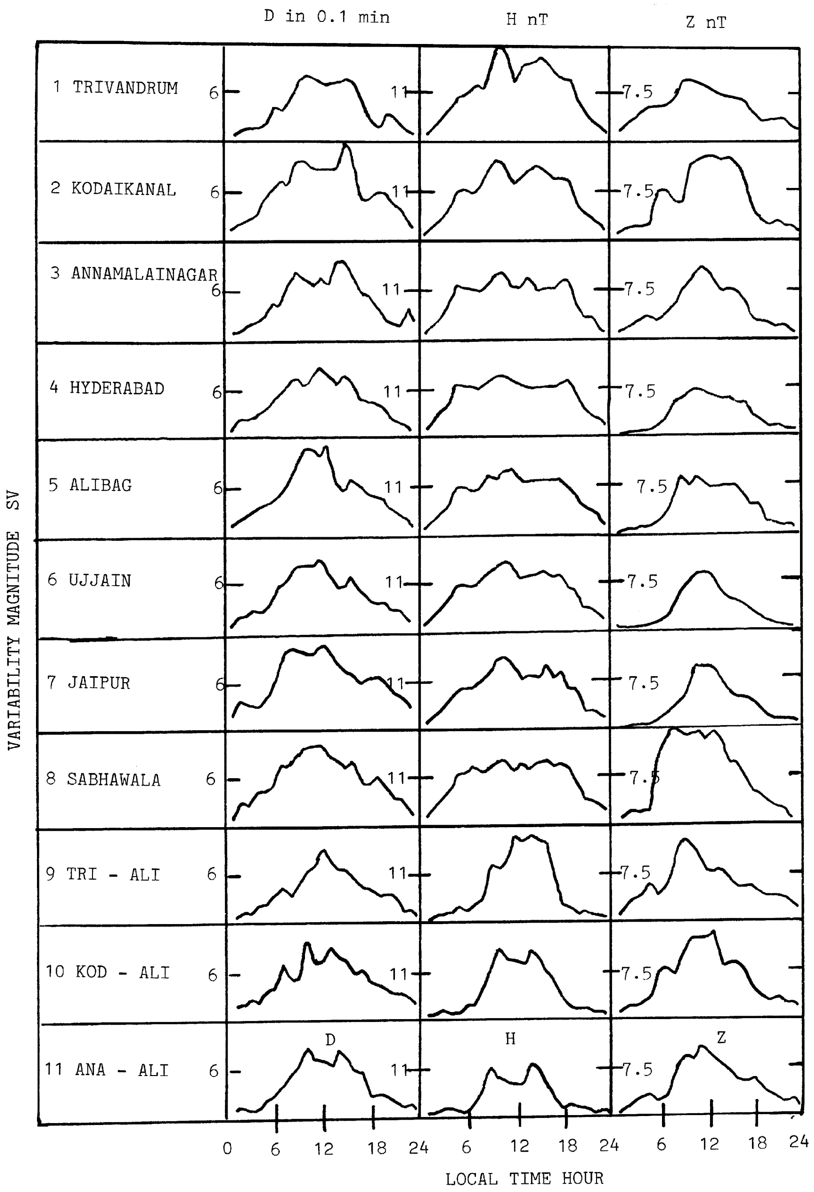

Figure 5. Diurnal variation of the monthly means of the magnitudes (SV) of day-to-day variability of hourly amplitudes of $Sq(D)$, $Sq(H)$ and $Sq(Z)$ at eight Indian stations in July 1986.

$SV(D)$, $SV(H)$ and $SV(Z)$ at 08, 11 and 14 hr local time for each month of the year. Only about 53 per cent of the $SV(D)$, 53 per cent of the $SV(H)$ and 67 per cent of the $SV(Z)$ profiles indicated enhancement in the EEJ zone. For $SV(D)$ and $SV(Z)$, enhancement was judged from the values at Kodaikanal and Annamalainagar only, where the EEJ D and Z are expected to dominate. We note the close magnitudes of the separate and combined variabilities of the EEJ and *WSq* fields. From the argument in the third paragraph of section 3.1 we infer that the variabilities of the EEJ and *WSq* currents are sometimes out of phase and their magnetic fields combine destructively in the EEJ zone.

In each of the three fields and in each of the months in Table 4, the mean $SV(Z)$ is greater than the mean $SV(H)$ and $SV(D)$. This is unexpected and is contrary to the result from Muntinlupa in the Philippines. The Indian result probably arises from anomalies in the Earth's electrical conductivity, to which Z is more susceptible than D and H.

The magnitude of the day-to-day variability in D due to the EEJ shown in Table 4 is, surprisingly, much larger than expected from an eastward current. The relatively large D arises from the north–south component of the EEJ current vortex (Onwumechili 1997) as explained in the last paragraph of Section 3.1. The *0* from the north-south EEJ current has actually been observed at Kodaikanal and Annamalainagar (Rastogi 1996).

3.4 On the solar control of magnitudes of variability

The inferred solar control of the magnitudes of day-to-day variability can be tested, in a quest for greater insight. The

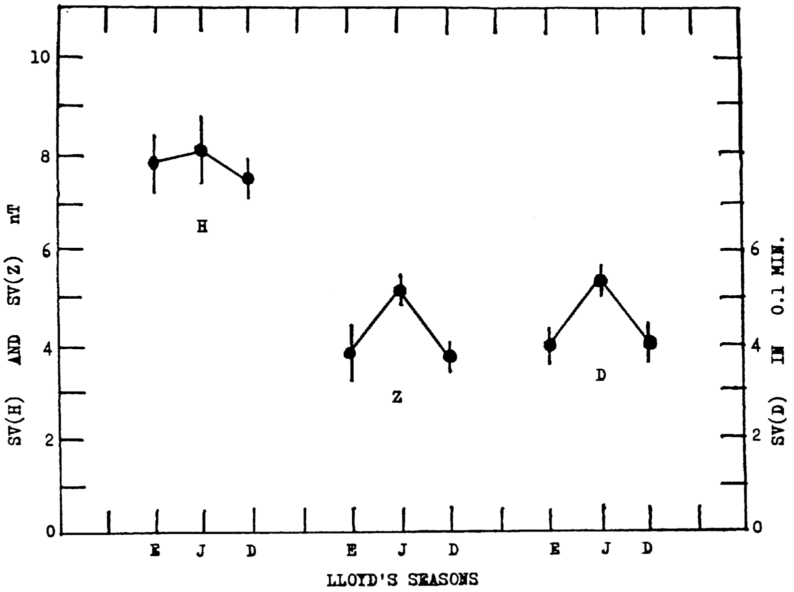

Figure 6. Seasonal variation of the magnitudes (SV) of day-to-day variabilities of the hourly amplitudes of $Sq(D)$, $Sq(H)$ and $Sq(Z)$ in 1962 at Muntinlupa. E, J and D are Lloyd seasons.

Table 4. Monthly means of the magnitude SV of day-to-day variability of hourly amplitudes of D, H and Z of Sq in June, October and December 1986 at Indian observatories. T – A = Trivandrum minus Alibag, K – A = Kodaikanal minus Alibag and M – A = Annamalainagar minus Alibag.

Station	June			October			December		
	D (0.1 min)	H (nT)	Z (nT)	D (0.1 min)	H (nT)	Z (nT)	D (0.1 min)	H (nT)	Z (nT)
Trivandrum	6.1	5.6	12.6	4.8	2.9	11.5	5.9	4.0	10.5
Kodaikanal	4.4	5.4	11.8	4.8	5.2	8.9	6.0	3.1	12.0
Annamalainagar	6.0	4.2	10.7	4.8	3.2	8.8	4.4	4.2	10.7
Mean	5.5	5.1	11.7	4.8	3.8	9.7	5.4	3.8	11.1
Standard deviation	1.0	0.8	1.0	0.0	1.3	1.5	0.9	0.6	0.8
Hyderabad	4.1	4.6	10.7	2.4	3.8	9.0	2.6	4.6	9.5
Alibag	4.4	4.6	10.1	3.0	3.4	7.4	2.6	4.7	10.2
Ujjain	3.2	4.5	—	2.0	3.4	7.5	1.9	3.9	10.3
Jaipur	3.2	5.4	10.3	1.8	3.5	7.6	1.7	5.0	10.5
Sabhawala	5.7	5.1	10.6	3.9	4.4	10.3	2.9	5.8	11.2
Mean	4.1	4.8	10.4	2.6	3.7	8.4	2.3	4.8	10.3
Standard deviation	1.0	0.4	0.3	0.8	0.4	1.3	0.5	0.7	0.6
T – A	6.8	4.3	8.3	5.5	3.1	6.9	5.6	3.5	5.1
K – A	6.5	4.6	7.3	5.3	4.1	6.1	5.0	5.0	9.3
M – A	6.0	4.8	6.4	5.5	2.6	3.6	4.4	3.2	4.0
Mean	6.4	4.6	7.3	5.4	3.3	5.5	5.0	3.9	6.1
Standard deviation	0.4	0.3	1.0	0.1	0.8	1.7	0.6	1.0	2.8

magnitude of Sq is solar-controlled. For each hour, we divide the magnitude SV of day-to-day variability by the corresponding magnitude of Sq for the same hour. From eqs (1) and (4) this ratio is

$$(SV/Sq)_t=\frac{1}{n}\sum_{i=1}^{n}\left[\,|(c_{t(i+1)}-c_{ti})|\bigg/\frac{1}{2}(c_{t(i+1)}+c_{ti})\right], \qquad (5)$$

where c_t stands for d_t, h_t or z_t. The factor of ionospheric current intensity cancels out if the variabilities and Sq are subject to the same solar control. The sequence of values of $(SV/Sq)_t$ for $t=1$ to 24 defines the diurnal variation of the ratio. We work with the more convenient percentage ratio $100\,SV/Sq$.

It is found that in the diurnal variation, the noontime peak of SV disappears from $100\,SV/Sq$. Indeed, it turns into a flat trough. Table 5 gives the mean values of $100\,SV/Sq$ for local times of 0900–1500 and 1600–0800. Outside the higher latitudes, rockets have failed to find ionospheric currents in the period of 1600–0800 local time (Onwumechili 1992d). In view of this result and for convenience here, we refer to the

Table 5. Comparison of the average values of $100\,SV/Sq$ for 0900–1500 and 1600–0800 local time.

Element	October 1962, Muntinlupa			
	Quiet days		Moderately disturbed days	
	0900–1500	Other hours	0900–1500	Other hours
D	74 ± 8	95 ± 6	91 ± 6	123 ± 6
H	60 ± 7	122 ± 6	69 ± 15	132 ± 5
Z	33 ± 4	115 ± 7	40 ± 5	104 ± 6
	March 1986, in India			
	Kodaikanal		Kodaikanal-Alibag	
	0900–1500	Other hours	0900–1500	Other hours
D	95 ± 17	169 ± 12	74 ± 6	159 ± 9
H	37 ± 6	115 ± 16	47 ± 9	113 ± 9
Z	54 ± 11	111 ± 17	70 ± 6	147 ± 15

period 0900–1500 local time as daytime and to 1600–0800 as night-time.

Table 5 shows that the slight difference between quiet periods and moderately disturbed periods is hardly significant. It is seen from this table that the daytime increase in SV indicated in Figs 4 and 5, caused by solar control, has been effectively removed from the EEJ field (Kodaikanal minus Alibag), the WSq field at Muntinlupa and their combined fields at Kodaikanal. This means that the effect of the daytime increase in ionospheric conductivity, peaking at about local noon, has at least been minimized. The effect of the daytime increase of the Sq global-dynamo electric field to a peak near local noon (Viswanathan, Vikramkumar & Reddy 1987) has also been minimized. With the trend removed, the problem now becomes a straightforward comparison of daytime and night-time values.

From Table 5 and results for other, similar months we see that in the night-time, the change at the hour t from one day to the next in eq. (2) is, on average, very slightly larger than the change from midnight to the same local time t in eq. (1). These night-time changes of the geomagnetic field have been reviewed in Onwumechili (1992d) and references therein. They are mostly due to non-ionospheric sources. We also see that in the daytime, the change at the hour t from one day to the next is, on average, less than the change from midnight to the same local time t. In the WSq zone the ratio $100\,SV/Sq$ appears largest for D and least for Z, but in the EEJ zone the ratio seems largest for D and least for H. The dominant cause of the changes of $100\,SV/Sq$ in the daytime is likely to be local and regional winds.

3.5 On the contrary phases of EEJ and *WSq* variabilities

In Sections 3.1 and 3.3 we found evidence that led to the inference that the phases of the EEJ and WSq currents could sometimes be contrary. This is now examined further, in a quest for greater insight. Onwumechili (1995) compared the monthly mean $Sq(H)$ with $Sq(H)$ on 10 selected quiet days ($Ap \leq 5$) using the 1986 data of the eight Indian stations in Table 1. The monthly mean Sq is based on the five internationally quietest days of each month. Corrections are made for storm time variation, Dst, and non-cyclic variation. The hourly amplitude h_t on a sample day is compared with the hourly h_t of the monthly mean of Sq in terms of the superposed horizontal magnetic field (SPMF), defined as follows:

$$h_t(\mathrm{SPMF}) = h_t(\mathrm{sample}) - h_t(\mathrm{mean}\ Sq)\,. \tag{6}$$

Therefore, h_t(SPMF) determines the hour-to-hour changes in the amplitude of $Sq(H)$ on a sample day relative to the monthly mean $Sq(H)$ amplitude.

It is found that on most days the diurnal pattern of h_t(SPMF) inside the EEJ zone is different from the pattern outside the EEJ zone. Therefore, the h_t(SPMF) inside the EEJ zone is attributed to dominance by the EEJ, and outside the EEJ zone to dominance by WSq. This demonstrates contrasting changes in the intensities and phases of the EEJ and WSq currents. Thus, when h_t(SPMF) at a given station on a given sample day is generally enhanced at the noon period relative to the monthly mean h_t, it is denoted by EEJE or WSqE according to whether the station is in the EEJ zone or outside it. Quantitatively, an enhanced, mean or reduced amplitude is judged according to

$$h_{10} + h_{11} + h_{12} + h_{13} \gtreqless h_{01} + h_{02} + h_{23} + h_{24}\,, \tag{7}$$

where h_{10}, etc., are the values of h_t(SPMF). When the amplitude is reduced relative to monthly mean $Sq(H)$, it is denoted by EEJR or WSqR; when it is neither enhanced nor reduced relative to monthly mean $Sq(H)$, it is denoted by EEJM or WSqM, where M indicates ‘mean’, E indicates ‘enhanced’ and R indicates ‘reduced’.

We now illustrate cases of contrary changes of the EEJ and WSq in the noon period of the same day, which is our main point of interest here. Fig. 7 shows that in the noon period on 7 August 1986 ($Ap = 4$), the SPMF was enhanced in the EEJ zone but reduced in the WSq zone relative to the monthly mean Sq. However, on 11 January 1986 ($Ap = 4$), Fig. 8 shows that the SPMF was reduced in the EEJ zone but enhanced in the WSq zone. Indeed, Fig. 9, for 23 July 1986 ($Ap = 5$), illustrates how opposing changes of the EEJ and WSq fields can reduce the amplitude of hourly changes where they combine in the EEJ zone. In Fig. 9, the EEJ is enhanced but WSq is reduced relative to the same monthly mean Sq.

It is seen from Fig. 9 that the large decrease in WSq from 09 to 13 hr, conspicuous at Hyderabad and Alibag, depresses the enhanced EEJ at Trivandrum and Kodaikanal from 09 to 13 hr. Indeed, it completely reverses the EEJ enhancement at the border station of Annamalainagar, where the EEJ field is smaller than at Trivandrum and Kodaikanal. This demonstrates the destructive interference inferred in Section 3.3, arising from contrary phases of the EEJ and WSq fields as they combine in the EEJ zone.

It should be noted that the contrasting phases are not limited to the case of complete antiphase. Cases of (1) EEJE with WSqE, (2) EEJE with WSqM, (3) EEJE with WSqR, (4) EEJR with WSqE, (5) EEJR with WSqM and (6) EEJR with WSqR have all been found from the relatively small amount of data so far analysed in this way.

4 CORRELATIONS OF DAY-TO-DAY VARIABILITIES OF HOURLY AMPLITUDES

The correlation coefficients $R(DH)$, $R(HZ)$ and $R(ZD)$ of the magnitudes SV of the day-to-day variability of two different

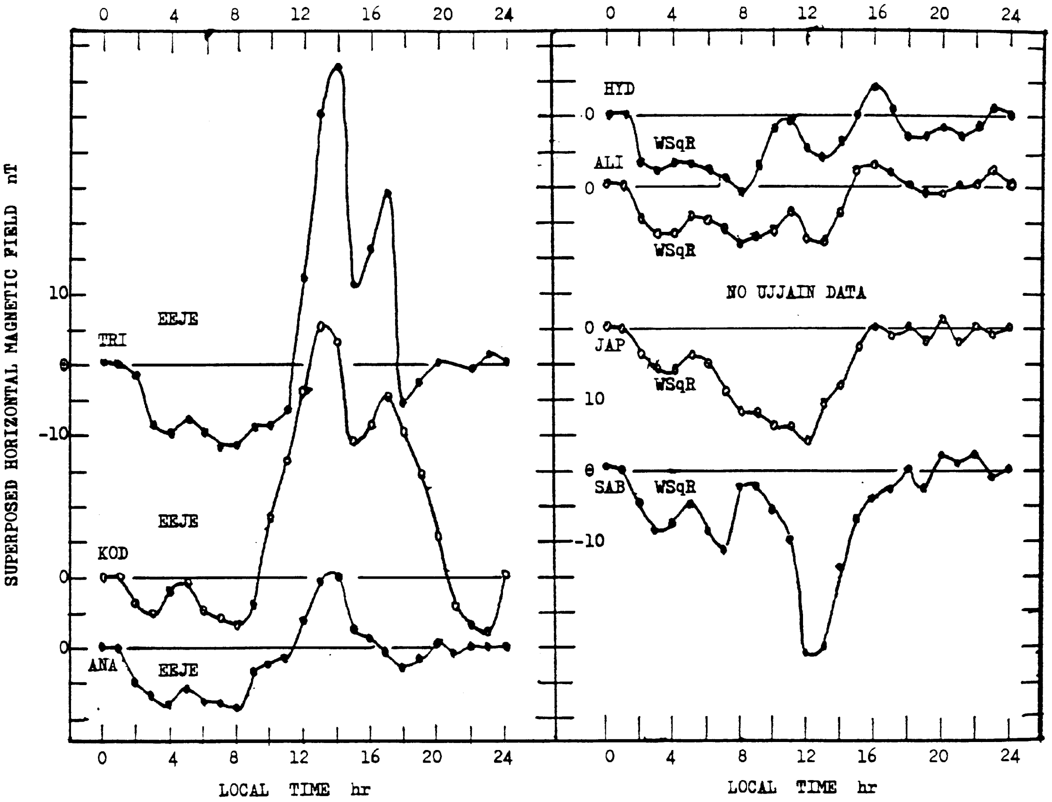

Figure 7. Diurnal variation of the horizontal magnetic field (SPMF) superposed on the monthly mean *Sq*(*H*) on 7 August 1986 at Trivandrum (TRI), Kodaikanal (KOD), Annamalainagar (ANA), Hyderabad (HYD), Alibag (ALI), Jaipur (JAP) and Sabhawala (SAB). All curves are at the same scale as that marked with ⊙ as zero. See text for other symbols.

elements at the same station have been computed for each month of 1986 for each of the eight Indian stations listed in Table 1, as well as for T − A, K − A and M − A. All the correlation coefficients are very high. They range from 0.75 to 0.98. There is therefore no point in presenting their tables.

The correlation coefficients *R*(*DD*), *R*(*HH*) and *R*(*ZZ*) of the magnitudes *SV* of the day-to-day variability of the same element at two stations have also been computed for the 11 station codes for each month of 1986. This is illustrated in Table 6, which gives 100 *R* for the January 1986 results. For all three elements, Table 6 shows (1) high correlations of the EEJ fields at two stations in the EEJ zone, (2) high correlations of the *WSq* fields at two stations in the *WSq* zone, (3) high correlations of the *WSq* field plus the EEJ field at two stations in the EEJ zone, and (4) high correlations of the *WSq* field at a station in the *WSq* zone with the EEJ field plus the *WSq* field at a station in the EEJ zone; but (5) low correlation of the EEJ field at a station in the EEJ zone with the *WSq* field at a station in the *WSq* zone and (6) low correlation of the EEJ field at a station in the EEJ zone with the *WSq* field plus the EEJ field at any station also in the EEJ zone.

We have also computed the correlation coefficients *R*(*DH*), *R*(*HZ*) and *R*(*ZD*) of the percentage ratio $100\,SV/Sq$ of the magnitude of day-to-day variability to *Sq* for different elements at the same station, for each month at the 11 station codes. This is illustrated with results from August 1986 in Table 7. There is generally low correlation among the elements. Occasionally, somewhat high correlations occur but they have neither pattern nor consistency. We therefore regard them as fortuitous.

Similarly, the correlation coefficients *R*(*DD*), *R*(*HH*) and *R*(*ZZ*) of the percentage ratio $100\,SV/Sq$ for the same element at two stations were also computed for the 11 station codes for every month. The results are illustrated by 100 *R* for October 1986 in Table 8. The situation is similar to the case of Table 7. For each element, the few correlations that are somewhat high appear to occur randomly. In addition, the negligibly small negative correlations are more than double the number of somewhat high correlations. We conclude that there is no consistent correlation.

5 GENERAL DISCUSSION

Each of the subsections of Section 3 has been discussed to some extent along with the presentation of the results, but the discussion of Section 4 has been deferred to this section. Here we start with the necessary background information that enables us to provide natural explanations for the results of Section 4 and to elucidate the discussions in Section 3 where necessary. There is no doubt that the day-to-day variabilities of *Sq* arise from the corresponding day-to-day variabilities of the ionospheric currents that generate *Sq*. It is therefore necessary to outline the structure of the ionospheric currents.

Rockets have observed two current layers in the EEJ zone. The lower current layer peaks at about 106 ± 1 km altitude and the upper current layer at about 136 ± 8 km altitude.

Table 6. Correlation coefficients $R(DD)$, $R(HH)$ and $R(ZZ)$ of the monthly means of the magnitude of day-to-day variability of the same element at two stations in India in January 1986, multiplied by 100. The station codes are 1, T, Trivandrum; 2, K, Kodaikanal; 3, M, Annamalainagar; 4, H, Hyderabad; 5, A, Alibag; 6, U, Ujjain; 7, J, Jaipur; 8, S, Sabhawala; 9, T – A, Trivandrum minus Alibag; 10, K – A, Kodaikanal minus Alibag; 11, M – A, Annamalainagar minus Alibag.

100R(DD)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	89	100									
3	M	87	80	100								
4	H	96	94	86	100							
5	A	88	75	96	86	100						
6	U	93	83	86	92	88	100					
7	J	86	93	74	93	72	78	100				
8	S	86	93	69	93	68	83	94	100			
9	T - A	11	15	16	10	5	4	11	3	100		
10	K - A	9	13	10	9	3	2	14	8	87	100	
11	M - A	-1	2	2	-1	-5	-6	1	-4	86	96	100

100R(HH)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	80	100									
3	M	82	74	100								
4	H	90	92	89	100							
5	A	87	70	88	88	100						
6	U	92	79	91	95	96	100					
7	J	85	82	86	88	79	87	100				
8	S	90	91	87	96	82	90	89	100			
9	T - A	9	11	27	13	15	10	24	27	100		
10	K - A	8	11	17	8	7	3	29	20	87	100	
11	M - A	-4	-1	0.3	-3	-4	-7	7	10	88	86	100

100R(ZZ)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	82	100									
3	M	97	93	100								
4	H	95	94	99	100							
5	A	91	57	81	78	100						
6	U	92	59	82	79	97	100					
7	J	88	81	90	89	83	77	100				
8	S	95	85	95	95	85	86	91	100			
9	T - A	10	4	10	10	15	8	28	26	100		
10	K - A	8	2	7	8	13	6	25	24	99	100	
11	M - A	10	8	12	15	12	8	20	23	78	81	100

Table 7. Correlation coefficients $R(DH)$, $R(HZ)$ and $R(ZD)$ of the percentage ratio $100\,SV/Sq$ of the magnitude of day-to-day variability to Sq for different elements at the same station in India in August 1986.

Station	$R(DH)$	$R(HZ)$	$R(ZD)$
1 Trivandrum (T)	0.12	0.52	0.34
2 Kodaikanal (K)	0.77	0.80	0.35
3 Annamalainagar (M)	0.07	−0.02	0.07
4 Hyderabad (H)	0.28	0.24	0.29
5 Alibag (A)	−0.07	0.38	0.27
6 Ujjain (U)	0.79	0.004	0.16
7 Jaipur (J)	0.49	0.60	0.01
8 Sabhawala (S)	0.67	0.06	0.09
9 T – A	0.28	0.23	0.29
10 K – A	0.05	−0.02	0.04
11 M – A	−0.07	0.34	0.24

The altitude of the peak current density of the upper current layer decreases with latitude from about 136 ± 8 km at the dip equator to about 120 km outside the EEJ zone. From their characteristics, the lower current layer is associated with the EEJ and the upper current layer is associated with the *WSq* (Onwumechili 1992a,b). The *WSq* is mainly a Pedersen current driven by the zonal component E_y of the global *Sq* dynamo polarization electric field E. The EEJ is mainly a Hall current driven by the vertical Hall polarization electric field E_z. The measurement of the vertical profile of E_z near local noon, close to the dip equator, by Sartiel (1977) strongly supports the assertion that the lower current layer is the EEJ.

Onwumechili (1997) has obtained the current vortices of the EEJ and *WSq* from the 1986 observational data of the Indian stations. He gave the electric fields that drive the various components of the EEJ vortex. In particular, the meridional electric field E_p, which drives the meridional current component that closes the EEJ vortex is presented by Singh & Cole (1988). He also showed that both the EEJ and *WSq* current vortices are in agreement with results from other sources. In particular, his *WSq* current vortex agrees with that of Matsushita (1968). It is important to note that rockets have observed the eastward component of the EEJ vortex at the dip equator, and its westward component at about 5° dip latitude, where it is largest. Also, Rastogi (1996) has given observational evidence of the north–south component of the EEJ vortex.

Taking the ratio $100\,SV/Sq$ constitutes a normalization that removes or at least minimizes the solar-control trends of the

Table 8. Correlation coefficients $R(DD)$, $R(HH)$ and $R(ZZ)$ of the percentage ratio $100\,SV/Sq$ of the magnitude of day-to-day variability to the Sq amplitude for different pairs of stations in India in October 1986, multiplied by 100. The station codes are 1, T, Trivandrum; 2, K, Kodaikanal; 3, M, Annamalainagar; 4, H, Hyderabad; 5, A, Alibag; 6, U, Ujjain; 7, J, Jaipur; 8, S, Sabhawala; 9, T − A, Trivandrum minus Alibag; 10, K − A, Kodaikanal minus Alibag; 11, M − A, Annamalainagar minus Alibag..

100R(DD)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	4	100									
3	M	6	42	100								
4	H	11	39	19	100							
5	A	-5	2	-6	-6	100						
6	U	-1	12	-4	45	-5	100					
7	J	49	8	-6	2	-6	4	100				
8	S	23	14	4	11	-4	7	31	100			
9	T - A	-8	1	-5	-9	-5	7	33	43	100		
10	K - A	-5	-3	11	14	6	-2	-9	18	19	100	
11	M - A	6	1	15	-1	0	1	-4	9	-6	-6	100

100R(HH)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	19	100									
3	M	3	58	100								
4	H	12	28	26	100							
5	A	47	25	36	8	100						
6	U	26	58	6	3	20	100					
7	J	37	46	13	10	9	51	100				
8	S	-5	1	-4	-8	1	24	15	100			
9	T - A	65	4	1	-4	63	6	10	11	100		
10	K - A	7	17	7	-6	12	20	11	8	26	100	
11	M - A	-12	12	-1	3	-0.3	7	19	16	8	35	100

100R(ZZ)		1	2	3	4	5	6	7	8	9	10	11
		T	K	M	H	A	U	J	S	T-A	K-A	M-A
1	T	100										
2	K	26	100									
3	M	3	3	100								
4	H	14	19	-4	100							
5	A	31	6	35	37	100						
6	U	56	71	-2	13	8	100					
7	J	28	23	2	15	11	20	100				
8	S	39	49	17	62	56	34	41	100			
9	T - A	-8	-7	-5	-7	-8	-7	12	-1	100		
10	K - A	25	-2	-3	31	47	-4	6	22	-5	100	
11	M - A	3	-4	-4	-11	-6	-9	18	14	37	35	100

ionospheric conductivity σ through the zenith angle factor χ, and of the global Sq dynamo polarization electric field E evidenced by its diurnal variation (Balsley 1973; Fejer *et al.* 1979, 1991). The total electric field $\mathbf{E}'$ that drives Sq is given by

$$\mathbf{E}' = \mathbf{E} + \mathbf{W} \times \mathbf{B}\,, \tag{8}$$

where $\mathbf{B}$ is the ambient magnetic field, $\mathbf{W}$ is the wind velocity and $\mathbf{W} \times \mathbf{B}$ is the locally induced emf which ensures that the Sq current flow is divergence-free. We infer that when the diurnal effects of the magnitudes of σ and E are suppressed, the random variation of $100\,SV/Sq$ which is seen from its correlations arises from $\mathbf{W} \times \mathbf{B}$. We therefore expect that the randomness is due to the random variations of local and regional winds. It is likely that this is the random component of day-to-day variability considered by MacDougall (1979a) and the regional component found by Schlapp *et al.* (1988).

Our correlation results for SV are in full agreement with previous results mostly based on the day-to-day variability of the daily ranges of $Sq(H)$. It remains to discuss their physical mechanism and sources. Reddy, Somayajulu & Davasia (1979) found that most of the bay-like disturbances in the surface geomagnetic field, with typical durations of 20–50 min, result from corresponding fluctuations of the overhead currents in the ionospheric dynamo region. They went on to show that during a magnetic disturbance two electric field perturbations δE measured with VHF backscatter radar at Thumba, India, caused global perturbations δH. Their result was confirmed by Gonzales *et al.* (1979, 1983) even for perturbations several hours in duration. This is relevant to our night-time day-to-day variabilities of hourly amplitudes.

Vikramkumar *et al.* (1987) used VHF backscatter radar measurements of the electric field at Thumba and calculated the corresponding conductivity and current in order to calculate the corresponding horizontal magnetic field H. For the daytime period 0800–1600 local time, their calculations were in good agreement with the locally observed diurnal profile of ΔH on quiet days and the perturbations δH lasting about 1–4 hr on disturbed days. This is relevant to our daytime day-to-day variability of hourly amplitudes in quiet periods. We therefore infer that our day-to-day variabilities are caused by corresponding day-to-day variabilities of the electric field supported by the ionospheric conductivity in the dynamo environment.

With mass plots of the observed diurnal variations of the eastward component E_y of the global Sq dynamo polarization

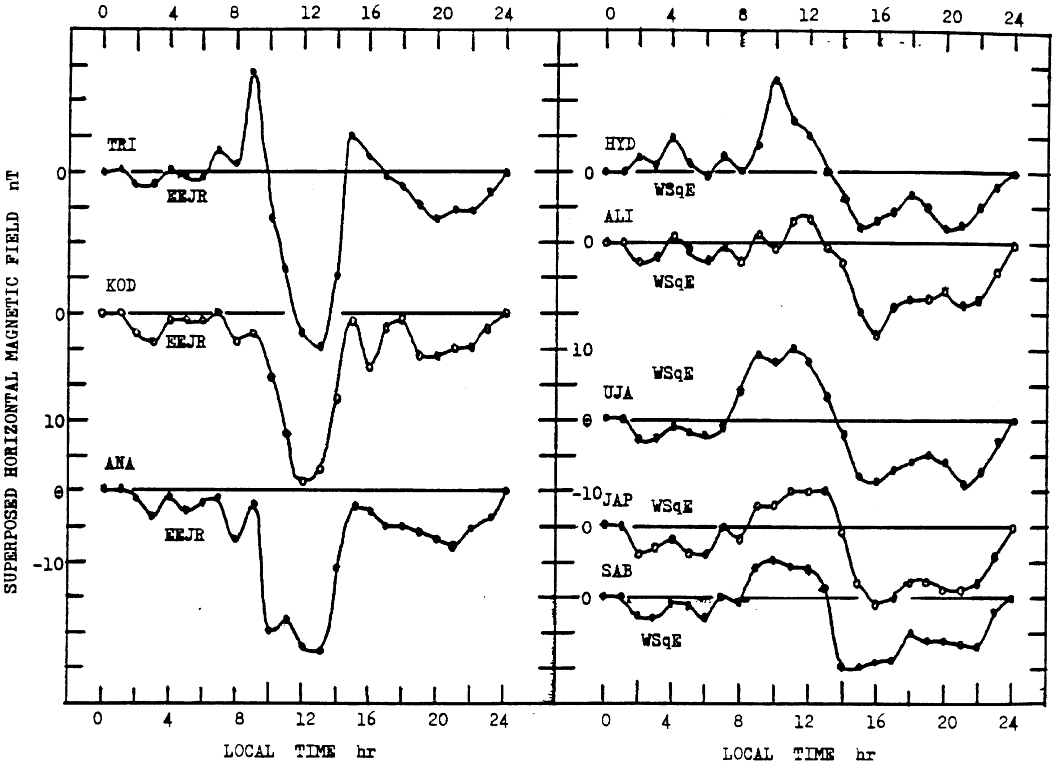

Figure 8. Diurnal variation of the horizontal magnetic field (SPMF) superposed on the monthly mean *Sq*(*H*) on 11 January 1986 at Trivandrum (TRI), Kodaikanal (KOD), Annamalainagar (ANA), Hyderabad (HYD), Alibag (ALI), Ujjain (UJA), Jaipur (JAP) and Sabhawala (SAB). All curves are at the same scale as that marked with ⊙ as zero. See text for other symbols.

electric field, Balsley (1973) clearly showed that it has conspicuous day-to-day variabilities and short-period perturbations lasting from a few minutes to several hours. This is in accord with the results of Woodman (1970), Earle & Kelly (1987), Viswanathan *et al.* (1987) and Viswanathan, Nair & Rao (1993). Also with a composite plot, Fejer (1991) clearly demonstrated that the vertical component of the electric field E_z, deduced from observations with VHF backscatter radar at Jicamarca, exhibits day-to-day variabilities and short-period perturbations.

It should be noted that part of E_z in the EEJ zone is generated by E_y, but not all of it. It has been shown by Richmond (1973), Reddy & Devasia (1981) and Raghavarao & Anandarao (1987) that local zonal winds also produce considerable E_z. For this reason and also because the EEJ and *WSq* current layers flow at different heights, the variabilities of *WSq* current intensity, driven mainly by E_y, and the variabilities of EEJ current intensity, driven mainly by E_z, are not necessarily always correlated. This explains the contrasting phases of the EEJ and *WSq* diurnal variabilities and the observation that they are sometimes in antiphase. Consequently, their observed day-to-day variabilities of hourly amplitudes do not correlate.

Our very high correlations for the same element at different stations for the EEJ fields derived from the T − A, K − A and M − A data, for the *WSq* fields at the Hyderabad, Alibag, Ujjain, Jaipur and Sabwahala stations, and for the combined fields at Trivandrum, Kodaikanal and Annamalainagar involve some new results. They validate the implication of the recent EEJ vortex produced by Onwumechili (1997) that the EEJ is not only an eastward current but also has a meridional return component. For this reason, the very high correlations of different elements at the same station found for the EEJ field from the T − A, K − A and M − A data, for the *WSq* field at stations in the *WSq* zone and for the combined fields at stations in the EEJ zone are particularly important. They show that the same meridional component of the EEJ current intensity that correlates highly at different latitudes in the EEJ zone also correlates very highly with the eastward component of the EEJ at the dip equator. This agrees with the current vortex of Onwumechili (1997) for the EEJ.

With the observed data from the Indian stations, Rastogi (1996) found evidence of the meridional component of the EEJ current vortex and illuminated this phenomenon. In particular, he found (1) evidence of two current layers and inferred that the lower layer is the EEJ and the upper layer is the global *Sq*; (2) on comparing stations in the EEJ zone, that the meridional component is largest at Annamalainagar, but outside the EEJ zone it is completely absent at Hyderabad, Alibag and higher latitudes; (3) changes in the EEJ zonal current are linearly related to corresponding changes in the meridional current; and (4) that the meridional current reverses at the same time as when the EEJ reverses into the counter-electrojet. He inferred that the two components are integral parts of each other. These are all in full agreement with the current vortex of the EEJ and with our results here. We must confess that we were not able to explain the *D* aspect of our results since 1993 until we saw Rastogi (1996).

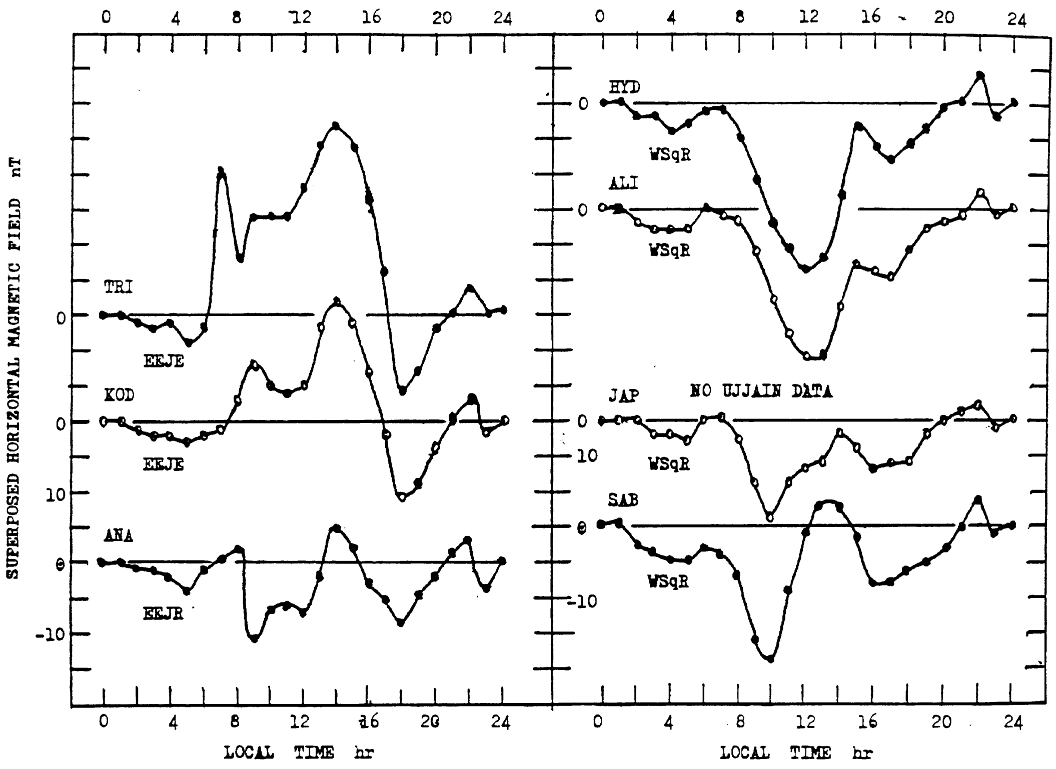

Figure 9. Diurnal variation of the horizontal magnetic field (SPMF) superposed on the monthly mean *Sq*(*H*) on 23 July 1986 at Trivandrum (TRI), Kodaikanal (KOD), Annamalainagar (ANA), Hyderabad (HYD), Alibag (ALI), Jaipur (JAP) and Sabhawala (SAB). All curves are at the same scale as that marked with ⊙ as zero. See text for other symbols.

It remains to probe the sources of the variabilities of the electric field. Earle & Kelley (1987) studied the sources of electric-field variabilities and developed criteria for resolving them. When the disturbance index, $Kp > 3$ they are of magnetospheric origin but when $Kp < 3$ they are of atmospheric origin.

Gonzales *et al.* (1983) calculated the cross-correlation of the zonal electric fields measured at Jicmarca (19.95°S, 76.86°W) and Arecibo (18.3°N, 66.75°W) on 11, 16 and 23 October 1980. They found very high correlation and simultaneity for the fluctuations on the disturbed days of 11 and 23 October but very low correlation on the quiet day of 16 October. This suggests that the fluctuations of the electric field are global, simultaneous and of magnetospheric origin on disturbed days, but on quiet days the fluctuations at two distant stations are not necessarily related and are of atmospheric origin.

For variabilities of electric fields in the period range 1–10 hr, Earle & Kelley (1987) attribute those dominated by atmospheric winds to atmospheric gravity waves. Following Earle & Kelley (1987), we consider that the day-to-day variabilities of hourly amplitudes in the daytime on quiet days ultimately arise from variabilities in atmospheric winds. In particular, the random components of the variabilities are likely to be dominated by atmospheric winds of gravity wave origin.

In the light of all these results, it is almost a paradox that a direct correlation of wind and magnetic field perturbations is yet to be demonstrated. A comprehensive study by Phillips & Briggs (1991) found no correlation whatsoever. Stening, Meek & Manson (1996) attempted to link the counter-equatorial electrojet (CEJ) to changes in observed winds. They stated 'It is the authors' belief that the CEJs are driven by a global tide, probably semidiurnal, which has amplitude and/or phase which differs from the normal during CEJ. The data presented have not proven this'. What is the missing link?

6 CONCLUSIONS

A survey of the many studies of the variabilities of geomagnetic solar daily variation showed that the day-to-day variability of hourly amplitudes had not yet been studied. Our study was designed to fill this gap. The study recognizes three fields: (a) the worldwide part of the *Sq* (*WSq*) field observed at stations in the *WSq* zone outside the influence of the equatorial electrojet; (b) the combined field (EEJ field + *WSq* field), observed at stations in the EEJ zone; and (c) the EEJ field at stations in the EEJ zone, customarily obtained as the difference between observations at a station in the EEJ zone and a nearby station in the *WSq* zone (Rastogi 1989).

The amplitude and sign of the day-to-day variability of the hourly amplitudes of *D*, *H* and *Z* change virtually randomly in such a way that the mean for a good number of days is practically zero for each of the three fields (a), (b) and (c) above. The randomness probably arises ultimately from a wind origin.

The variability of the *D* component of the EEJ field at certain stations in the EEJ zone implies that the EEJ current system has not only an east–west but also a north–south component. This is supported by two recent publications (Rastogi 1996; Onwumechili 1997).

The study has shown that day-to-day variability occurs at all hours of the day. It is remarkable that the magnitudes of the day-to-day variabilities of all three elements D, H and Z of each of the three fields have similar diurnal variations, which peak at about noon like $Sq(H)$ in low latitudes. This indicates their solar control.

The ionospheric conductivity mainly controls the magnitude, while the electric field and ultimately winds mainly control the phase and the randomness of the day-to-day variability of the hourly amplitudes of Sq.

In geomagnetically quiet periods, the magnitude of the day-to-day variability of the hourly amplitudes of Sq in all three elements has a seasonal variation with a weak maximum at the June solstice (local summer).

The ratio of the magnitude of the variability SV at the hour t to the magnitude of Sq at the same hour minimizes the solar-control trend of the diurnal variation of SV. In the night-time, the magnitude of the variability at a fixed local-time hour t from one day to the next is, on average, only slightly larger than the change in Sq from midnight to the hour t. But in the daytime, the magnitude of the variability is, on average, less than the magnitude of Sq at the same hour t.

It has been demonstrated with observational data that the changes in the current intensity of the EEJ and WSq current layers have contrasting phases and can sometimes be in antiphase. This is because (1) the variabilities of the WSq current system are mainly driven by the variabilities of the eastward component E_y of the global Sq dynamo polarization electric field (Balsley 1973), but the variabilities of the EEJ current system are mainly driven by the variabilities of the vertical component E_z of the electric field (Fejer 1991), which arise partly from E_y and partly from local winds (Raghavarao and Anandarao 1987); and (2) the EEJ and WSq current layers flow at different altitudes, where the effective conductivities, electric fields and winds are normally different.

The magnitudes SV of the day-to-day variabilities of the hourly amplitudes of the three magnetic fields (a) the EEJ field, (b) the WSq field and (c) the combined field (EEJ field + WSq field) correlate as follows. Any two of the elements D, H and Z of the same field at the same station correlate very highly and positively. Any one of the elements D, H and Z at two stations shows

(1) high positive correlation of the EEJ field at two stations in the EEJ zone;

(2) high positive correlation of the WSq field at two stations in the WSq zone;

(3) high positive correlation of the combined EEJ and WSq fields at two stations in the EEJ zone;

(4) high positive correlation of the WSq field at a station in the WSq zone with the combined EEJ + WSq field at a station in the EEJ zone;

(5) no significant correlation of the EEJ field at a station in the EEJ zone with the WSq field at a station in the WSq zone;

(6) no significant correlation of the EEJ field at a station in the EEJ zone with the combined field at any station in the EEJ zone.

These results imply that the variabilities of the current intensities of the EEJ and WSq current layers are mostly independent.

The correlations of the variabilities of the D component of the EEJ field have crucial implications. The very high correlation coefficients $R(DH)$ at Trivandrum, Kodaikanal and Annamalainagar show that changes in the east–west and north–south components of the EEJ current intensity are positively and very highly correlated over the areas surrounding each of the stations. The very high, positive correlation coefficients $R(DD)$ and $R(HH)$ for any two of the three stations show that changes in the east–west EEJ current intensity at the dip equator and changes in the north–south EEJ current intensity at Kodaikanal and Annamalainagar are positively and very highly correlated. The above results imply that the meridional component of the EEJ current intensity that correlates highly at different latitudes in the EEJ zone also correlates very highly with the east–west component of the EEJ current intensity at the dip equator. This supports the conclusions of Rastogi (1996) that these meridional and zonal components are integral parts of each other and that both belong to the EEJ lower current layer. It also validates the EEJ current vortex of Onwumechili (1997).

The detrended magnitudes ($100\,SV/Sq$) of the day-to-day variabilities of the hourly amplitudes of the three fields (a), (b) and (c) above correlate as follows. There is no consistent correlation either (1) between any two of the elements D, H and Z of the same field at the same station, or (2) between the same element of any one or two of the three fields at any two stations. The randomness and lack of consistency of $100\,SV/Sq$ imply local and/or regional wind origin. In particular, the random changes of hourly means are in the period range for which Earle & Kelley (1987) suggest winds of gravity wave origin.

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