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Signatures of storm sudden commencements in geomagnetic H, Y and Z fields at Indian observatories during 1958–1992

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Abstract. The work describes an intensive study of storm sudden commencement (SSC) impulses in horizontal (H), eastward (Y) and vertical (Z) fields at four Indian geomagnetic observatories between 1958–1992. The midday maximum of ΔH has been shown to exist even at the low-latitude station Alibag which is outside the equatorial electrojet belt, suggesting that SSC is associated with an eastward electric field at equatorial and low latitudes. The impulses in Y field are shown to be linearly and inversely related to ΔH at Annamalainagar and Alibag. The average SC disturbance vector is shown to be about 10–20°W of the geomagnetic meridian. The local time variation of the angle is more westerly during dusk hours in summer and around dawn in the winter months. This clearly suggests an effect of the orientation of shock front plane of the solar plasma with respect to the geomagnetic meridian. The ΔZ at SSC have a positive impulse as in ΔH. The ratio of ΔZ/ΔH are abnormally large exceeding 1.0 in most of the cases at Trivandrum. The latitudinal variation of ΔZ shows a tendency towards a minimum over the equator during the nighttime hours. These effects are explained as (1) resulting from the electromagnetic induction effects due to the equatorial electrojet current in the subsurface conducting layers between India and Sri Lanka, due to channelling of ocean currents through the Palk Strait and (2) due to the concentration of induced currents over extended latitude zones towards the conducting graben between India and Sri Lanka just south of Trivandrum.

Key words. Interplanetary physics (interplanetary shocks) · Ionosphere (equatorial ionosphere) · Magnetospheric physics (storms and substorms)

Introduction

The occurrence of aurora in northern high latitudes during disturbed solar and geomagnetic conditions has attracted the attention of scientists for many centuries. These auroral displays were found to be associated with geomagnetic disturbances. No such apparent relationship between the solar and terrestrial disturbances are easily noticed at low and equatorial latitudes. It has been even suggested that the storms do not affect equatorial ionospheric currents (Chapman, 1951; Matsushita, 1953; Sugiura and Chapman, 1960). The Trivandrum observatory was the first one in the world to operate close to the magnetic equator. Broun (1874) observed systematic storm effects in the geomagnetic field at Trivandrum. Moos (1910) was the first to isolate the geomagnetic storm effects at a low-latitude station, at Alibag, India. India is the only country in the world where three equatorial standard magnetic observatories have been in operation for over four decades. The data continue to be published regularly and distributed for the world scientific community. Here an attempt has been made to study the first signatures of geomagnetic storm sudden commencement (SSC) phenomena on all three components of the geomagnetic field at Trivandrum (TRD), Kodaikanal (KOD) Annamalainagar (ANN) and Alibag (ABG) between 1958–1992.

Following the earlier work of Newton (1948), many investigations have been reported on the diurnal variations of the amplitude and the occurrence frequency of storm sudden commencements in horizontal field H, SSC-H, (Watson and McIntosh, 1950). The first global morphology of SSC was discussed by Jacobs and Obayashi (1956). Studies of SSC based on the rapid run magnetograms during the IGY have been reported by Sano (1963). Ferraro and Unthank (1951) was first to note the similarity between the solar daily variation of the mean amplitude of SSC(H) and that of ΔH itself. The maximum amplitude of SSC(H) at Huancayo, an equatorial electrojet station, occurred at noon and was considerably larger than the same at any other station. Similar daytime enhancement of SSC(H) at equatorial stations were reported by Sugiura (1953), Srinivasamurthy (1959), Maeda and Yamamoto (1960), Rastogi (1965) and Natarajan (1969).

Rastogi *et al.* (1964) showed that the latitudinal variation of the amplitude of SSC in H at equatorial stations was similar to that of the solar daily range of H itself. Further, the equatorial enhancement of the amplitude of SSC(H) was shown to be more pronounced in American than in Indian longitudes in a similar fashion to the equatorial enhancement of the amplitude of Sq(H) itself. Recently, Rastogi (1993) described a detailed study of latitudinal and longitudinal variations of the amplitude of SSC(H) in H at equatorial latitudes. The amplitude of SSC(H) over the magnetic equator was shown to vary with longitude inversely as the square of the mean magnetic field intensity.

During the IGY period, additional geomagnetic observatories were started in India at Trivandrum and Annamalainagar situated respectively at the centre and at the fringe of the equatorial electrojet belt, besides the already existing observatories at Alibag and Kodaikanal. Trivedi and Rastogi (1968) found that the latitudinal variation of SSC(H) showed a maximum value at Trivandrum during the daytime and at Annamalainagar during the nighttime hours. The amplitude of SSC in the vertical field, Z, showed a maximum at Trivandrum during the day as well as during the nighttime hours.

Obayashi and Jacobs (1957) described a detailed study of all the three components of geomagnetic field during storm sudden commencements and drew the current system due to SSC. They identified a part of SSC effect (*Dst* part) to be of extra terrestrial origin and another part, DS, due to atmospheric origin, and suggested an atmospheric dynamo theory for the SSC current system. Simultaneous changes in declination and horizontal fields during SSC were examined by Wilson and Sugiura (1961) and by Sano (1963) from the rapid run magnetograms during the IGY. Rastogi (1992) reported that the storm time (*Dst*) as well as the disturbance daily (SD) variations in H and westerly declination at equatorial electrojet station, Huancayo, were remarkably similar to each other. Chandra and Rastogi (1997) showed significant simultaneous effects in H and Y at Kodaikanal during SSC and subsequent storm periods. Rastogi (1998) has recently described the result of detailed study of the effect of storm sudden commencement in H, Y and Z fields at the equatorial electrojet station, Annamalainagar based on the data covering 1958–1991. The impulses due to SSC were found to be positive in H and Z but negative in Y. The increase of the Z field simultaneously with the increase of the H field at a northern electrojet station is itself anomalous. The mean amplitudes of SSC impulses were found to be amplified during the day time for H as well as Y components.

Fukushima (1994) showed that the direction of SSC disturbance vector defined as $\tan^{-1}(\Delta Y/\Delta H)$ at low latitude station can give an idea of the direction of the shock front of the solar plasma bubble causing the sudden commencement. The apparent abnormal ΔZ due to SSC at Annamalainagar cannot be explained in terms of temporary increase of the strength of the equatorial electrojet current. It was therefore felt necessary to study the effect of the equatorial electrojet on the SSC amplitude ΔH, ΔY and ΔZ at other equatorial stations. With the availability of an excellent set of SSC data from four Indian observatories Trivandrum, Kodaikanal, Annamalainagar and Alibag since IGY, an analysis was made of the effect of SSC in H, Y and Z components of the geomagnetic field at these stations and are described in this work. The coordinates and the geomagnetic field components are given in Table 1. It is to be noted that the station Trivandrum has been almost at the centre of the electrojet belt, Kodaikanal nearly half way and Annamalainagar near the fringe of the electrojet belt. Alibag seems to be outside the general effects of the equatorial electrojet current.

The amplitudes of the sudden commencement impulses ΔH, ΔD and ΔZ were measured from the predisturbed level of the field to the first main impulse. Any preliminary reversed impulses in H field and very rarely in Z or D fields were ignored. The ΔD values were converted in ΔY according to the formula ΔY (in nT) =

Table 1. Coordinates of geomagnetic data used in the analysis

Station codes	Trivandrum TRD	Kodaikanal KOD	Annamalainagar ANN	Alibag ABG
Geographic latitude	8.5°N	10.2°N	11.4°N	18.6°
Geographic longitude	77.0°E	77.5°E	79.7°E	72.9°
Dipole latitude	0.8°S	0.9°N	1.9°N	9.7°
Dipole longitude	148.5°	149.1°	151.4°	145.6°
Declination, D, 1958	2°40.4′W	2°35.1′W	2°35.1′W	0°48.3′
Declination, D, 1992	2°27.0′W	2°11.1′W	2°17′W	0°28.5′
Horizontal force H 1958	40062 nT	39524 nT	40397 nT	38668 nT
Horizontal force H 1992	39848 nT	39099 nT	40216 nT	38114 nT
Vertical force Z 1958	−423 nT	2323 nT	3853 nT	17738 nT
Vertical force Z 1992	404 nT	3406 nT	5027 nT	18084 nT
Inclination I 1958	−0°36.2′	3°21.8′	5°26.9′	24°38.5′
Inclination I 1992	+0°34.9′	4°58.7′	7°07.5′	25°22.9′
Dip latitude 1958	−0°18.1′	1°41.0′	2°43.8′	12°55.1′
Dip latitude 1992	0°17.4′	2°29.6′	3°34.6′	13°20.7′
Geomagnetic dipole declination ψ	−6.4°	−6.7°	−6.2°	−7.2°
Geomagnetic dipole declination ψ-D	−3.6°	−4.3°	−3.6°	−6.4°

(ΔD in minutes of arc) (H/3438) where H is the mean horizontal field at the station. The westerly declination is taken as negative and easterly as positive.

Observations

Before describing the characteristics of SSC at these observatories, the yearly mean solar daily variations of H, Y and Z as well as the latitudinal variations of the solar daily ranges of H, Y and Z are shown in Fig. 1 for the typical years 1958 and 1992 which are the beginning and end years of the epoch studied.

During the low sunspot year 1992, the H field at any of the stations was almost constant during midnight to sunrise, increased rapidly with the rising of the Sun reaching a peak around 11 00 LT, after which it decreased relatively slowly reaching the base midnight value shortly after sunset. The amplitude of daily range of H decreased with increasing distance of the station from the equator. During the high sunspot year, 1958, a negative value of ΔH was observed at TRD and KOD for couple of hours before sunrise. The decrease of ΔH after the midday peak continued well after the sunset, almost till midnight. The daily range of H at any of the stations was larger in 1958 than for 1992 because there were sunspots in 1958 than in 1992. These observations are similar to those observed at other equatorial electrojet stations described by Rastogi and Iyer (1976).

The eastward field, Y during 1992 or 1958 showed minor maximum around 09 00 LT and a major minimum around 12 00 LT at the equatorial stations TRD, KOD and ANN. The magnitude of the minimum was largest at ANN. At ABG the magnitude of forenoon maximum and noon minimum were of the same order.

The vertical field Z, at KOD and ANN showed primarily a minimum around noon as expected at an equatorial station close to the northern fringe of the electrojet belt. At ABG the ΔZ showed comparatively smaller minimum around noon. At the station close to the magnetic equator the ΔZ should be almost zero. However, at TRD a significant positive peak of ΔZ was observed around 09 00–10 00 LT and a comparatively smaller minimum in the evening hours. Fukushima (1993) noticed similar features in the Z field at Koror and has attributed it to induction by the ocean currents.

Thus, the important features to remember in interpreting observations of SSC in H, Y and Z are (1) a large midday peak of ΔH at the centre of the electrojet, Trivandrum; (2) largest midday minimum of ΔY at Annamalainagar; (3) a large forenoon peak of Z at Trivandrum.

In Fig. 2 are reproduced the H, D and Z magnetograms following a nighttime SSC at 21 38 h on July 17, 1959 at Indian stations TRD, KOD and ANN and ABG. The traces have been so arranged that an upward shift of the trace indicates a increase of ΔH, ΔDw westerly declination as well as ΔZ for any of the stations, but the sensitivity of traces are different for different stations and are indicated in the diagram.

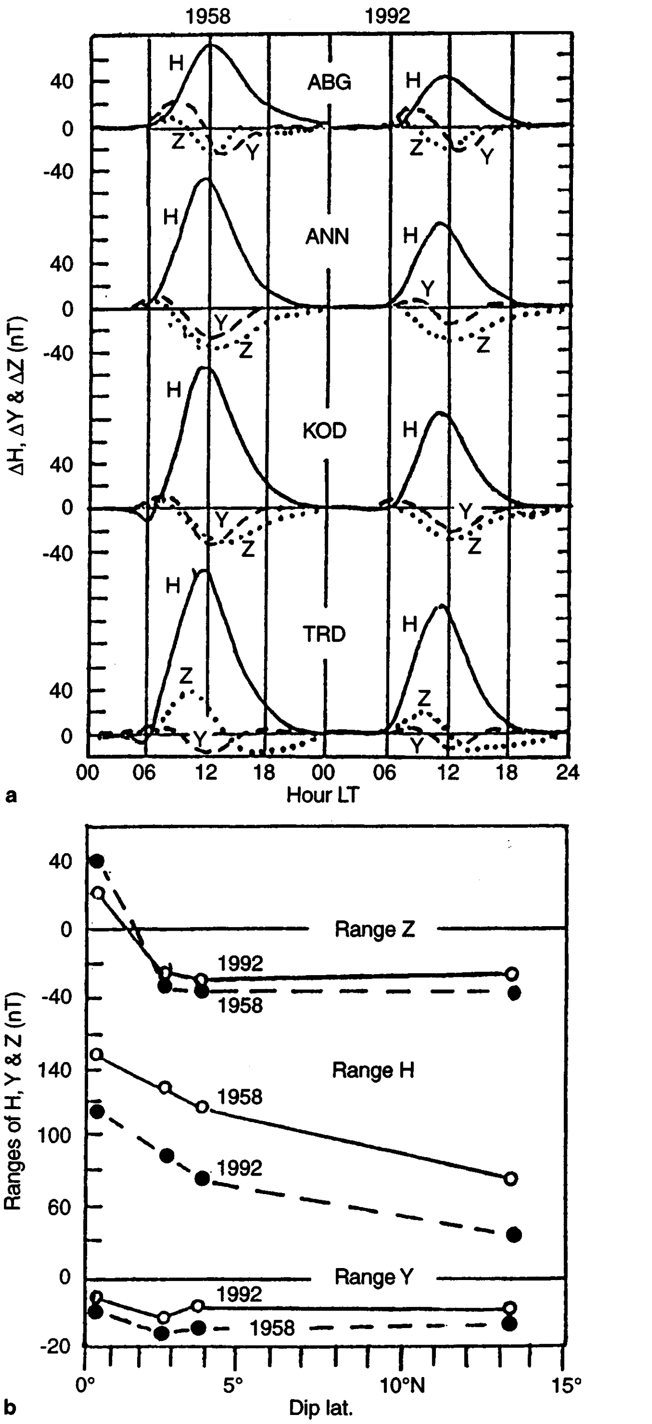

Fig. 1. Annual mean solar daily variations of the three components of the geomagnetic field, horizontal (H), eastward (Y) and vertical (Z) for the years 1958 and 1992 at the four observatories in India. Trivandrum (*TRD*), Kodaikanal (*KOD*), Annamalainagar (*ANN*), and Alibag (*ABG*)

It is to be noted that the impulse of SSC in H indicates a positive change at any of the stations. It is 131 nT at TRD, 150 nT at KOD, 160 nT at ANN and 149 nT at ABG showing significant decrease of ΔH near the magnetic equator.

The ΔZ due to SSC was positive at all electrojet stations, the value at TRD was abnormally large being

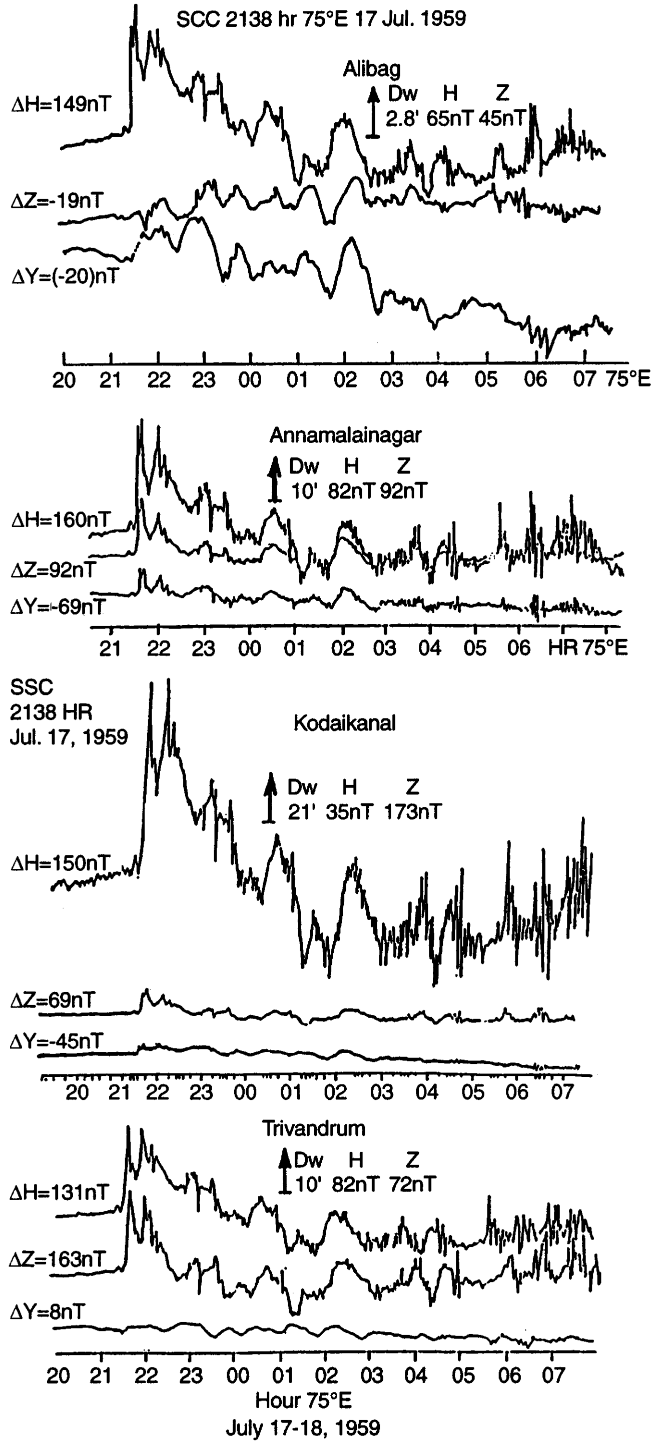

Fig. 2. Tracings of H, Y and Z magnetograms at Trivandrum, Kodaikanal and Annamalainagar during SSC at 2138 LT (night-time) on July 17, 1959

more than corresponding ΔH at TRD, ΔZ at ABG was small and negative.

The ΔY due to SSC was small and positive at TRD and negative at other stations. The value of ΔY was largest at ANN.

To obtain a consistent idea of the impulses the whole period of study was divided into a daytime period (09 00–13 00 LT) and nighttime period (22 00–02 00 LT). In Fig. 3a, b and c respectively are shown the histograms of the amplitude of impulse in H, Y and Z fields at each of the stations for the nighttime and daytime periods separately. In Fig. 3d are shown the latitudinal variations of the SSC impulses ΔH, ΔY and ΔZ for the daytime and for the nighttime hours.

Referring to Fig. 3a relating to the distribution of SSC(ΔH) the individual values during the daytime ranged from 0 nT to more than 150 nT at TRD, KOD and ANN and between 0 nT and 70 nT at ABG. During the night, the ranges of distribution of ΔH were smaller compared to those during the daytime at TRD, KOD and ANN. At ABG the scatter of individual values of ΔH was larger during the night than during the day. The latitudinal variation of ΔH during the daytime showed a consistent increase towards the magnetic equator. During the nighttime ΔH showed instead a minimum at the magnetic equator.

The distributions of ΔY at TRD is very different from those at KOD, ANN or ABG. The amplitudes of ΔY at TRD are too low and more are positive than negative. The impulses at KOD, ANN or ABG were always negative, the mean value were largest at ANN, a station near the fringe region of the electrojet belt. The latitudinal variation of ΔY during the day or the nighttime shows a negative peak at ANN. The values of ΔZ are positive at electrojet stations TRD, KOD and ANN and negative at ABG. A very anomalous observation, is that ΔZ shows a very significant maximum at the magnetic equator during the day as well as nighttime hours. Thus, this anomaly in SSC(Z) is despite the electrojet and is probably due to induction effects by a distant and uniform source field in the magnetospheric regions.

In Fig. 3d are shown latitudinal variations of SSC impulses in H, Y and Z during a few daytime and nighttime events. The impulses in H field during the daytime have a general tendency to increase towards the magnetic equator but on 30 November, 1988 event ΔH at (ANN) was slightly larger than ΔH (KOD) and on 24 October, 1988 ΔH (KOD) was larger than ΔH (TRD). Whether it is significant may be confirmed by a detailed analysis of the magnetograms of all these observatories. The impulse in Z field showed a rather narrower peak over the magnetic equator. The impulse in Y field consistently showed largest value at ANN. During the nighttime there was always a minimum of ΔH at TRD and maximum at ANN. This is most probably a bite out of the usual peak of ΔH at the equator during the daytime. The ΔZ showed a maximum over the magnetic equator such that at TRD ΔZ was larger than ΔH. The impulse on Y field consistently showed the largest value at ANN. Thus the features seen in the mean latitudinal variations are consistent with the same during individual SSC events.

In Fig. 4a, b and c the daily variations of the H, Y and Z components respectively at each of the stations are shown. It may be noticed that the amplitude of SSC(H) at any of the stations was at a minimum during dawn and dusk periods and there is a major maximum around noon and a minor one at midnight. The daytime

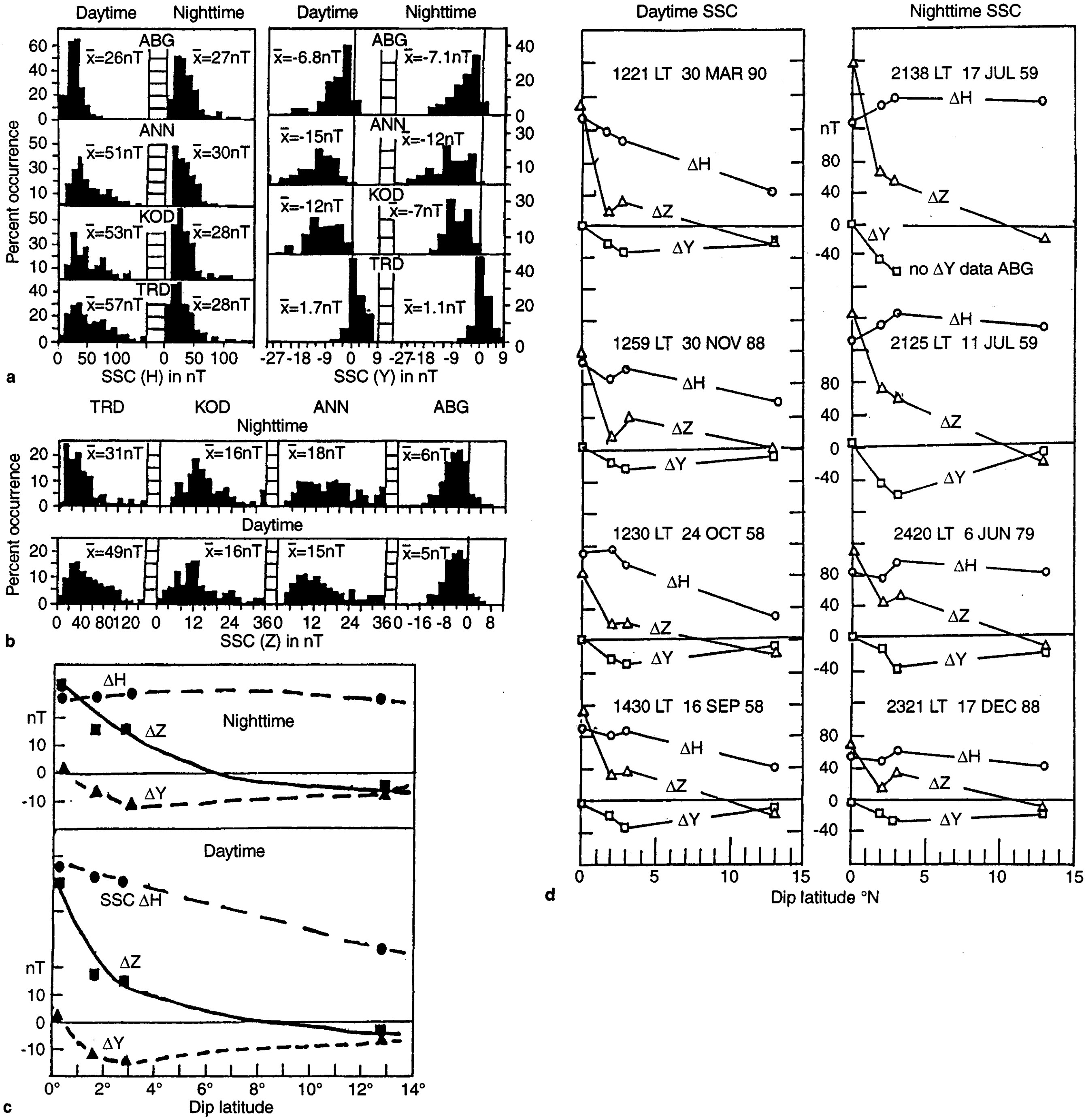

Fig. 3a–d. Histograms of the amplitudes of sudden commencements in **a** horizontal field H and Y and **b** vertical field, Z occurring during midday hours (09 00–13 00 LT) and during night time hours (20 00–02 00 LT) at Indian observatories *TRD*, *ANN*, *KOD* and *ABG* averaged for 1958–1992, **c** Latitudinal variations of mean ΔH, ΔY, and ΔZ due to SSC occurring during daytime and nighttime. **d** Latitudinal variations of ΔH, ΔY, and ΔZ during individual SSC events of daytime and nighttime

enhancement of SSC(H) was most pronounced at TRD, a station closest to the magnetic equator, but is definitely clear even at ABG a station accepted to be on the outside of the belt of equatorial electrojet effects. Thus, the amplitude of SSC(H) at low latitude is closely related to the conductivity of the ionosphere which reaches its maximum value at midday. In other words the SSC(H) at low latitudes is associated with an eastward electric field in addition to the compression of the magnetosphere during the impact of solar plasma on the magnetosphere. The amplitude of SSC(Y) at TRD does not show any significant change with time of the day. At KOD and ANN and to a lesser degree at ABG, the SSC(Y) impulse is negative in sense and larger in magnitude around the midday hours. Thus, a large positive ΔH is associated with a larger negative ΔY

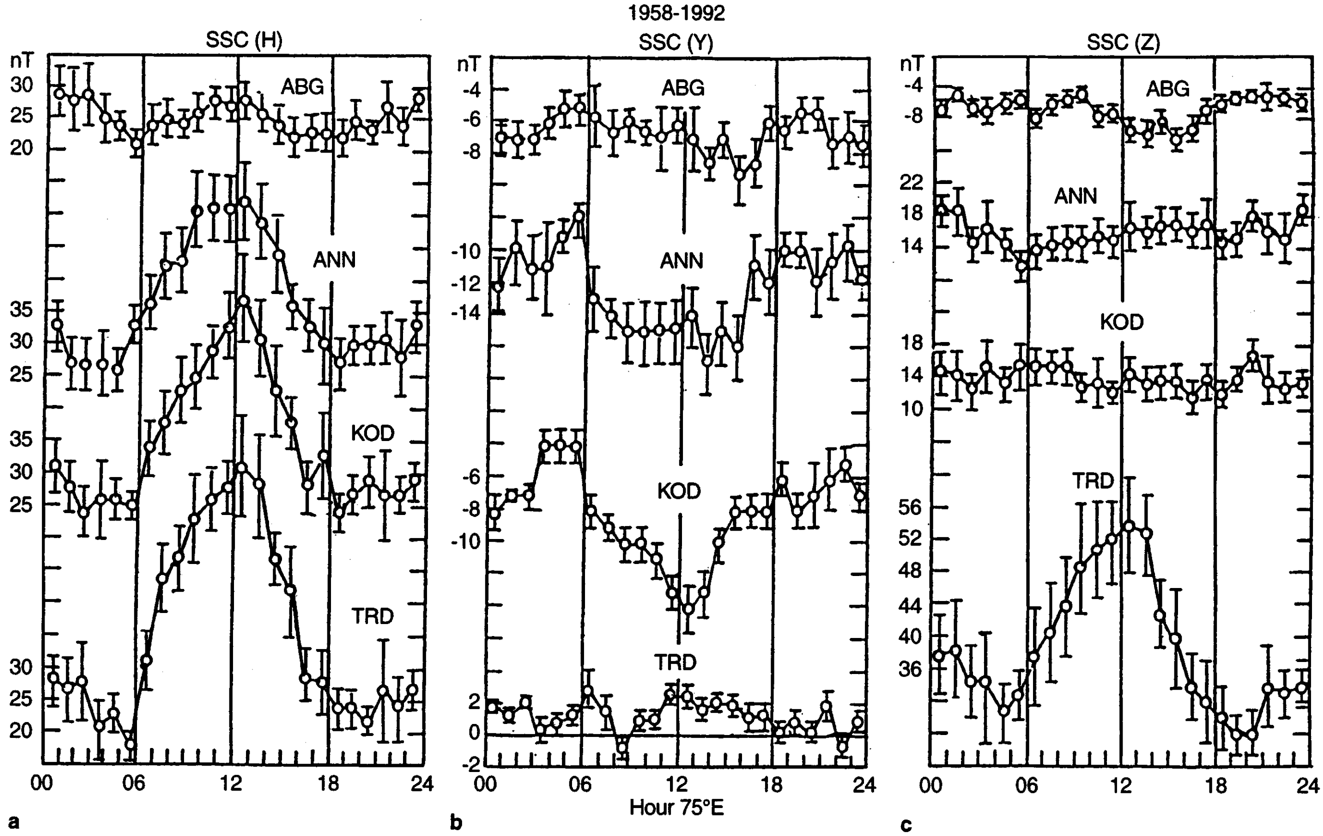

Fig. 4a–c. Solar daily variations of the amplitudes of SSC in **a** horizontal field, H; **b** eastward field, Y and **c** vertical field, Z averaged over 1958–1992 at *TRD*, *KOD*, *ANN* and *ABG*

around noon hours at low-latitude stations. The diurnal changes in the amplitude of SSC(Z) do not seem to be significant at KOD, ANN or ABG. However, SSC(Z) at TRD shows a very large diurnal change with a maximum around midday hours, the magnitude of which is comparable to the corresponding SSC(H) at the same station.

Figure 5 shows the diurnal variations of the ratios $|\Delta Y/\Delta H|$ and $|\Delta Z/\Delta H|$ at each of the stations averaged over the entire period of study. The ratio $|\Delta Y/\Delta H|$ seems to have minor maxima at sunrise and sunset hours and a minimum around 10 00 LT. The value of $|\Delta Y/\Delta H|$ averaged over all hours of the day was 0.07 for TRD, 0.23 for KOD, 0.36 for ANN and 0.25 for ABG. It is to be noted that the ratio of $|\Delta Y/\Delta H|$ is largest at Annamalainagar. The ratio $|\Delta Z/\Delta H|$ showed a minimum before midday hours at all the equatorial stations TRD, KOD and ANN while at ABG a small maximum was seen in the afternoon hours. It is important to note that $|\Delta Z/\Delta H|$ at TRD was more than 1.0 at any hour of day. Further the value was larger during nighttime hours than during the day. The whole day mean value of $|\Delta Z/\Delta H|$ was 1.23 for TRD, 0.42 for KOD, 0.45 for ANN and 0.26 for ABG.

The relationship between individual impulses in ΔH due to SSC at pairs of stations for the nighttime and daytime events is examined separately. Mass plots of SSC(H) at pairs of stations TRD/ABG, KOD/ABG and ANN/ABG are shown in Fig. 6. During the daytime events the average ratio of ΔH was 2.5 for TRD/ABG, 2.2 for KOD/ABG and 1.2 for ANN/ABG. This just confirms the equatorial enhancement of SSC(H) at low latitudes. During the nighttime events of SSC the average ratios of ΔH was 0.90 for TRD/ABG, 0.93 for KOD/ABG and 1.20 for ANN/ABG. Thus, on average the impulses of H during the nighttime events decreased towards the magnetic equator suggesting a reversal of the daytime enhancement of the ΔH due to SSC.

Figure 7 compares the impulse in Y with respect to corresponding impulse in H for individual events at Trivandrum, Annamalainagar and Alibag. The values of ΔY at TRD were always too small to show any definite relationship. The mass plots of ΔY and ΔH at ANN show a clear linear relationship, the magnitudes of $-\Delta Y$ increasing with increasing ΔH. The average ratio of $\Delta Y/\Delta H$ was -0.37. It is to be noted that large impulses in Y field were occasionally noted at ANN, number of SSC(Y) exceeds the value of -50 nT. Some of the largest SSC events recorded at Annamalainagar are indicated in the diagram. The amplitude of $-\Delta Y$ at ABG also increased with corresponding ΔH, the average ratio was 0.25 (see Fig. 7).

The relationship between individual values of ΔZ versus ΔH for each of the stations TRD, ANN and ABG were studied separately for the nighttime and for the daytime events. Figure 8 shows the mass plots of the individual amplitudes of ΔZ and ΔH. The amplitude of ΔZ increased linearly with increase of ΔH. Thus it is

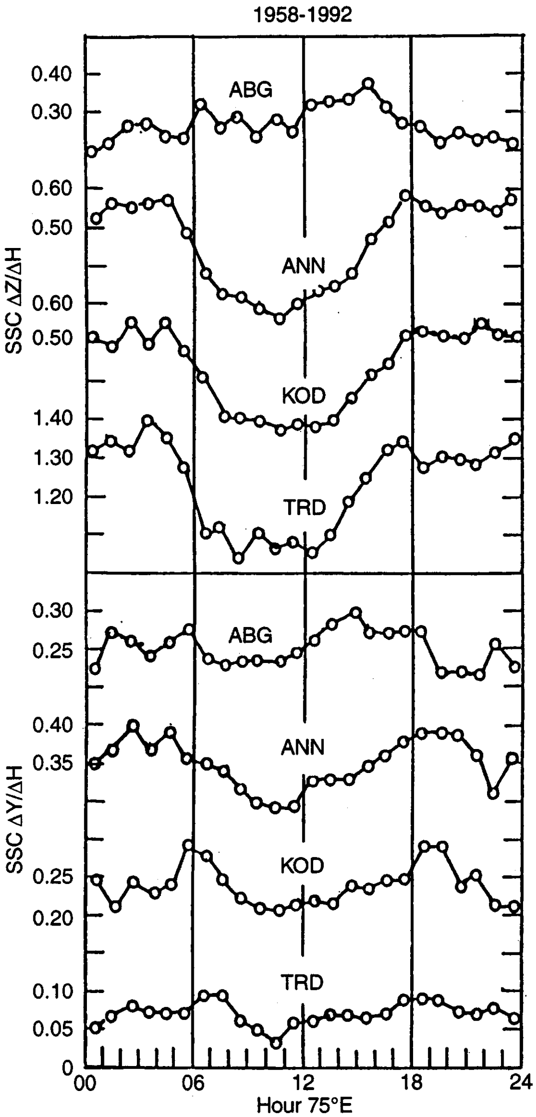

Fig. 5. Solar daily variations of the ratios of SSC amplitudes $|\Delta Y/\Delta H|$ and $|\Delta Z/\Delta H|$ averaged over 1958–1992 at *TRD*, *KOD*, *ANN* and *ABG*

seen that greater the intensity of storm, the greater were the impulses in the vertical component too. The ratio of $\Delta Z/\Delta H$ at TRD was 1.3 for the nighttime and 1.1 for the daytime. The corresponding ratio $\Delta Z/\Delta H$ at ANN was 0.52 during the nighttime and 0.33 during the daytime. At ABG the ratio of $\Delta Z/\Delta H$ was 0.17 during the nighttime and 0.29 during the daytime. It is seen that the ratio of $\Delta Z/\Delta H$ is smaller during the daytime than during the nighttime at equatorial electrojet stations only.

To test whether the individual values of the SSC(Y) at two stations have any relationship, Fig. 9 shows the mass plot of individual values of SSC(Y) at ANN and ABG. Clearly the impulses in the Y field were always larger at ANN than at ABG. The average ratio of ΔY ANN/ΔY ABG was about 2.0. There were more than dozen cases during the period under study when ΔY at ANN was larger than 40 nT. The largest impulse in SSC (ΔY) was −70 h at 17 14 IT on 30 April, 1960. The next two largest SSC (Y) were on 8 July, 1991 and 20 August, 1991.

The change in the eastward field Y during the sudden commencement is supposed to be due to the alignment of magnetic field due to SSC towards the direction of the geomagnetic dipole meridian.

The ratio of $\Delta Y/\Delta H$ can be estimated to give the direction of the SSC disturbance vector in the horizontal plane equal to $\sin^{-1}(\Delta Y/\Delta H)$ in degrees east of north (magnetic). Figure 10 shows the histograms of the percent occurrence of different values of the direction of SSC disturbance vectors at Trivandrum, Kodaikanal, Annamalainagar and Alibag. The SSC vector angles is low and 2°E of north of magnetic north or practically due geographic north. At Kodaikanal the median value of SSC vector is 12°W of magnetic or 12°W of geographic north. At Annamalainagar the median vector is 20°W of magnetic or geographic north. At Alibag the SSC vector is 16°W of geographic as well as magnetic north. Thus the derivation of SSC vector is again largest at Annamalainagar. This suggests an additional westward deviation of the field besides the effect due to the orientation of the disturbance vector with respect to the axis of earths magnetic field.

Fukushima (1966) noted that at Kakioka, Japan, the average magnetic declination was 6.5°W and the geomagnetic dipole meridian deviates 6.3° eastward from the geographic meridian. Therefore, the geomagnetic north deviates about 13° eastward from the local magnetic meridian. Fukushima (1966) showed that the main impulse of SSC at Kakioka, as expected, showed an eastward declination change in most of the SSCs. The deviation angle ranged from 10° to 50° with an average value of 18.2° eastward from the local magnetic meridian. Rastogi (1998) had shown that for Annamalainagar the geomagnetic dipole meridian was 3.6°W of the true magnetic meridian. The SSC disturbance vector at Annamalainagar ranged from 10°W to 40°W with a mean value of 20°W. The present study shows that the mean deviation of the SSC disturbance vector is 12°W at Kodaikanal and 16°W at Alibag and only 2°E at Trivandrum. Thus, the direction of disturbance vector follows the direction suggested by Fukushima (1966). There seem to be local irregularities due to the electrojet at Indian equatorial stations superposed over the global component of the disturbances.

To identify whether the individual values of the direction of SSC vector at ANN and ABG are arbitrary or have any relationship between themselves, in Fig. 11 are shown the mass plots of the direction of SSC vector at ANN against the same at ABG. In spite of a rather large scatter of points, a linear relation between the directions of vector at the two places is very evident. This suggests that besides the intensity of individual SSC magnitudes, there is another parameter possibly the direction of impact of the solar plasma at the magnetosphere at the time of SSC. This needs the study of the direction of the SSC vector with respect to the longitude (θ) of the interplanetary Magnetic Field during the SSC.

The yearly magnetic data bulletins of Quetta (QUE) are available at the University of Sydney, Australia.

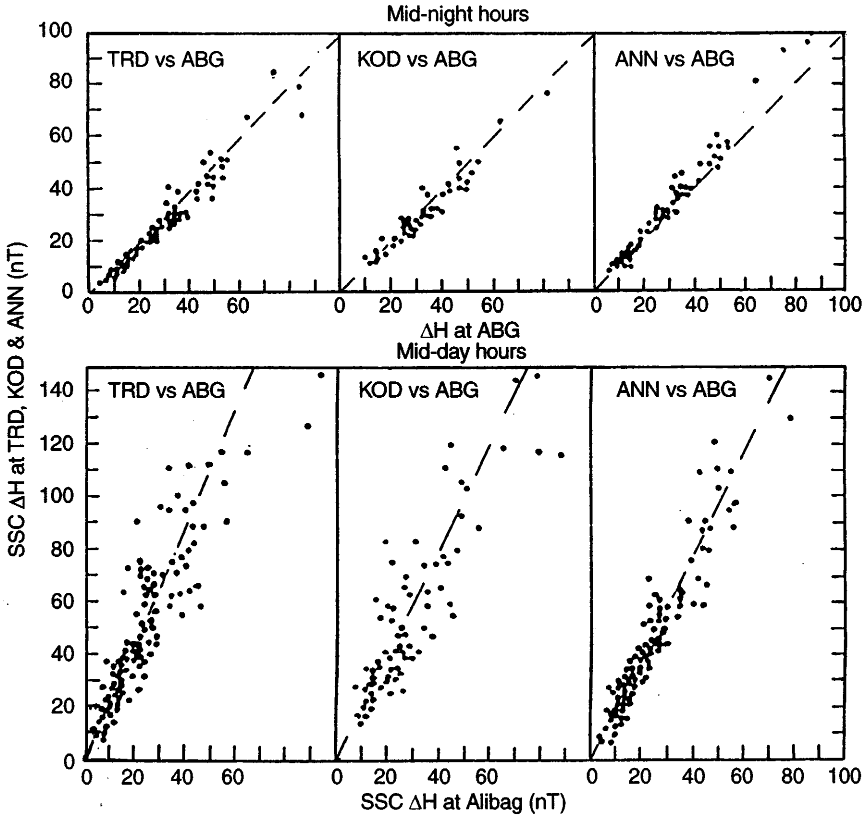

Fig. 6. Relationship between amplitudes in horizontal field H, at *TRD*, *KOD*, *ANN* and *ABG* of daytime and nighttime SSCs

Using the Quetta data of SSC (67.0°E, 30.2°N) and at Alibag (72.9°E, 18.6°N), relationship between individual values of ΔY, ΔH and $\sin^{-1}$ (ΔY/ΔH) were computed at the two stations for the simultaneously available data during 1959–1968). The mass plots of ΔY, ΔH and of the direction of disturbance vector for each event at ABG and QUE are shown in Fig. 12.

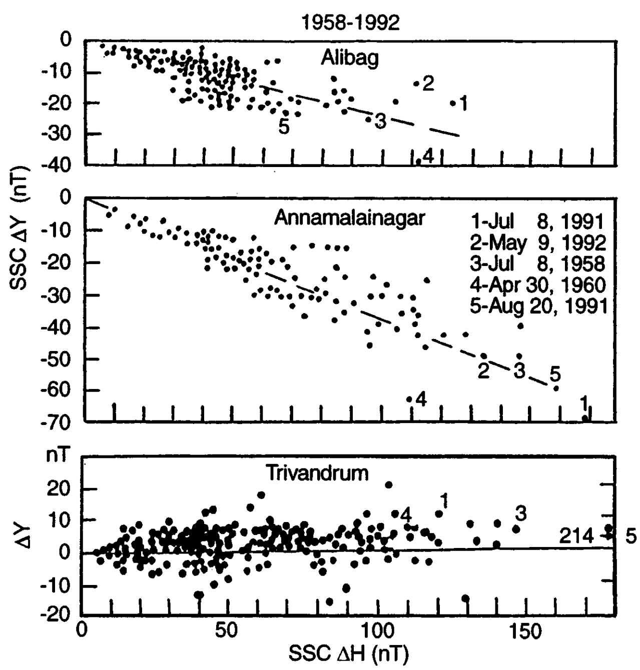

Fig. 7. Relationship between amplitudes of SSC ΔY and ΔH at the stations Annamalainagar (*ANN*) Trivandrum (*TRD*) and Alibag (*ABG*) of SSCs for 1958–1992

Clearly the amplitudes of the SSC(ΔH) were almost the same at ABG and QUE. The magnitudes of SSC(Y) at ABG seemed to be smaller than those of QUE, the ratio of ΔY(ABG)/ΔY(QUE) being about 0.7. Correspondingly the deviation of the disturbance vector westward from the magnetic north is slightly smaller at ABG than at QUE. The declination at Alibag is 0.8°W and at Quetta it is 1.3°E. Thus, when correction due to this effect is made, the deviation of the disturbance vector from the geographical north may be taken as practically the same at Alibag and Quetta. Thus we may presume that the scatter of individual values of $\sin^{-1}$ΔY/ΔH at Alibag were primarily due to the varying direction of the solar disturbance front with respect to the Earth's polar axis and not due to any random or experimental errors.

On the advice of the referee, I have computed the local time variation of the direction of the SSC disturbance vector during the different seasons of the year for each of the four Indian stations. The summer season is represented by J months (May, June, July and August), the E months consist of March, April, September and October, and D months (winter season) consist of November, December, January and February months. The resultant plots are shown in Fig. 13. The diurnal variation of disturbance vector at Alibag during summer months so clearly shows easterly deflection in the dawn hours and westerly deflection during dusk hours. It is further remarkable that during the winter months the tendency is reversed with westerly deflection

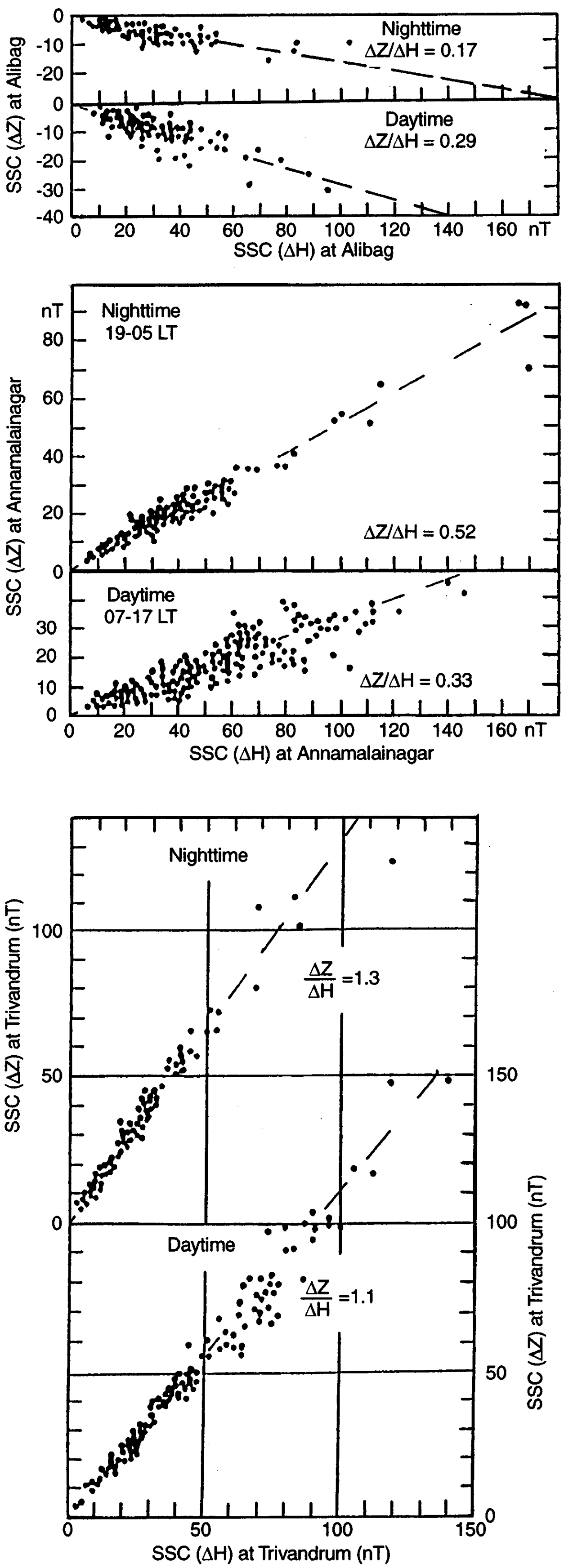

Fig. 8. Relationship between the individual amplitudes of ΔZ and ΔH due to SSC during daytime and nighttime for *TRD*, *ANN* and *ABG* for 1958–1992

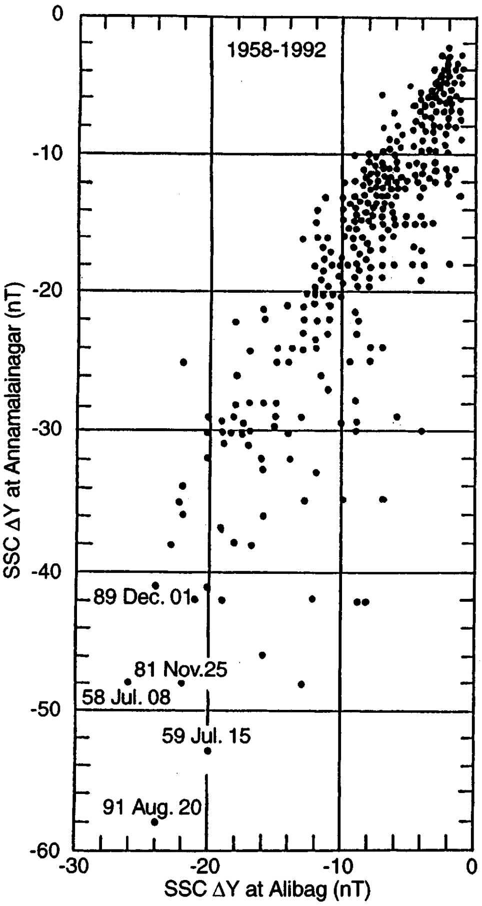

Fig. 9. Relationship between the individual amplitudes of H due to SSC at *ABG*, and *ANN* during daytime and nighttime for 1958–1992

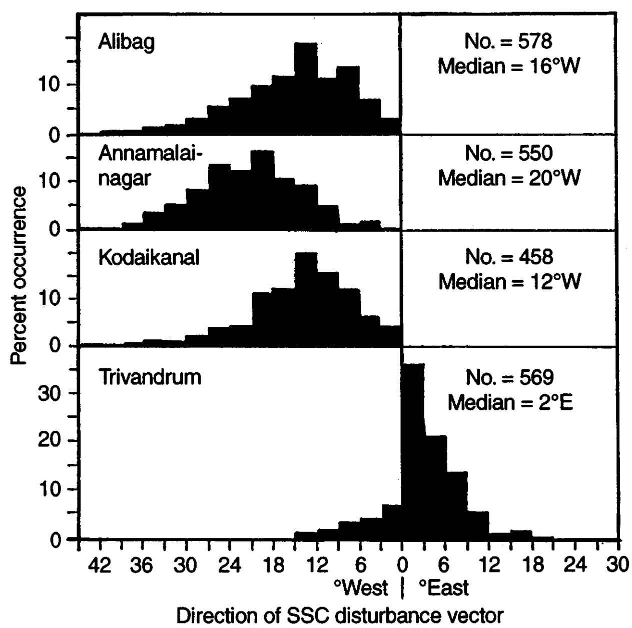

Fig. 10. Histograms for the direction of SSC disturbance vector $\sin^{-1}$ (ΔY/ΔH) at *TRD*, *KOD*, *ANN* and *ABG*

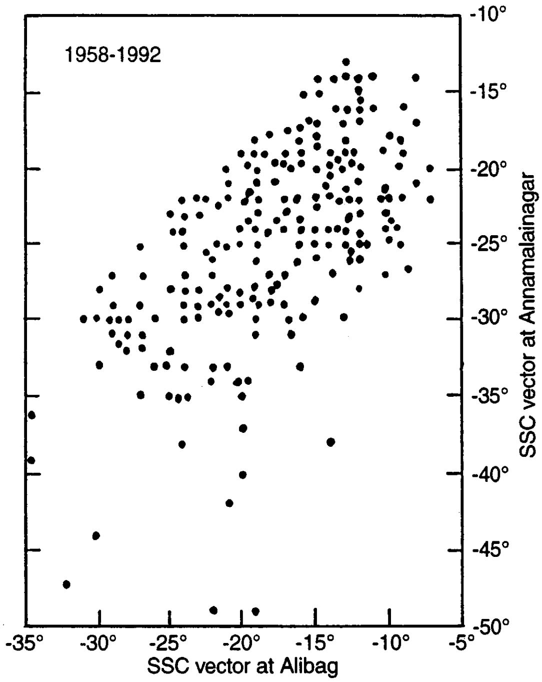

Fig. 11. Mass plot of the direction of SSC disturbance vector at Annamalainagar versus that at Alibag for 1958–1992

at dawn and easterly deflection during dusk hours. During equinoxes westerly deflections are evident at both pre-dawn and post sunset hours. Similar variations are seen at the other equatorial stations Annamalainagar and Kodaikanal. The deflections of vectors at Trivandrum are small and rather random. These results are a strong confirmation of Fukushima's (1966) suggestion for the seasonal dependence of the deviation angle of SSC vector from the geomagnetic meridian around dawn and dusk hours.

Discussion

The geomagnetic sudden commencement is a clear global phenomenon with its onset almost simultaneously everywhere on Earth. The source of SSCs are undoubtly the interplanetary shocks and discontinuities. Gold (1955) postulated the existence of an interplanetary shock at the leading edge of the plasma cloud ejected from a solar flare. The sudden increase in the solar wind dynamic pressure at an interplanetary shock and discontinuities generate the sudden rise of the H field observed at geomagnetic observatories round the world.

Rastogi and Patel (1975) showed that a sudden change in the vertical Z component of the Interplanetary Magnetic Field (*Bz*) is viewed as additional $-v \times Bz$ electric field by the Earth, v being the velocity of the solar wind. This field is transmitted almost instantaneously to the ground magnetic observatories.

Because of high electrical conductivity of the equatorial ionosphere, this sudden change of magnetopause electric field causes a sudden impulse in the magneto-

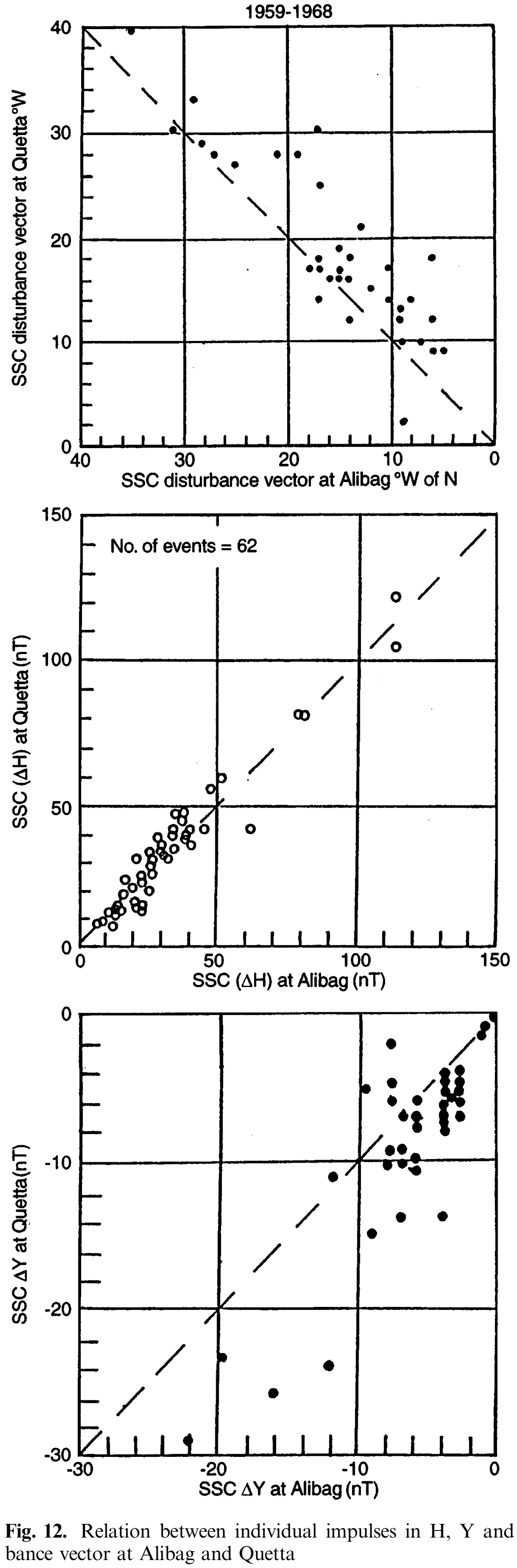

Fig. 12. Relation between individual impulses in H, Y and disturbance vector at Alibag and Quetta

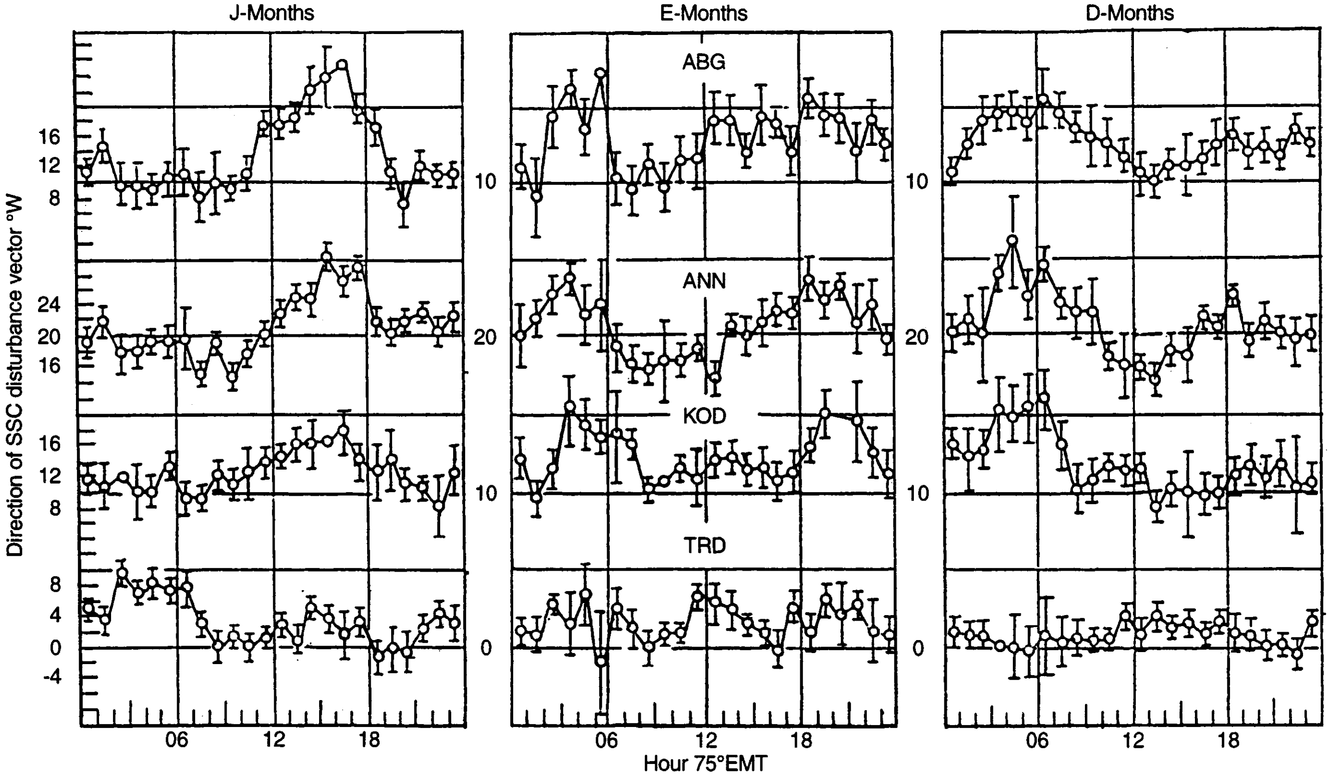

Fig. 13. Local time variations of the direction of SSC disturbance vector during different seasons of the year at each of the four Indian magnetic observatories

grams and Doppler shift records at an equatorial electrojet station. A sudden change of *Bz* from southward to northward direction would result to an increase of ΔH at the equatorial station. On the other hand a sudden change of *Bz* from northward to southward direction would produce a negative impulse in ΔH at ground level. Later Rastogi (1978) showed that whenever SSC(H) in equatorial regions has a preliminary negative impulse preceding the main positive excursion, the solar plasma cloud causing the magnetospheric compression is associated with a northward turning of the IMF near the magnetopause. Later, Rastogi (1980) discussed the signatures of SSC on the magnetograms at equatorial stations Huancayo (HUA), Addis A bab (AAE) and noca (TTB) in relation to the changes in IMF obtained from satellites Explorer 33, 34 and 35.

Araki (1977) made a comprehensive study of SSCs using rapid run magnetograms from eight American zone stations. He identified two components of SSC (1) a DL part caused by the compression of the magnetosphere and (2) a DP part is caused by the ionospheric currents generated by the polar ionospheric electric field. The polar electric field was shown to propagate to the equatorial ionosphere as a zeroth order TM (transverse magnetic) wave guide mode (Kikuchi *et al.*, 1978).

Thus, the effects of sudden commencement on the equatorial station consists of, first, the primary source current in the magnetosphere and the inherent electric field transmitted to the low latitudes from the magnetosphere via high latitudes. During the nighttime the electric field does not produce any ionospheric current due to low conductivity of the equatorial ionosphere. During the daytime the electric field from the magnetosphere produces additional current at equatorial ionosphere modifying the signature on the magnetograms. The latitudinal variations of these two source currents would be different as that in the magnetosphere is a distant and practically uniform source while that in the ionosphere is much closer with a large latitudinal variation in it.

The next step would be the electromagnetic inductions in the Earth's crust due to these current sources. The induction effects would include the effects due to regional anomalies of the conductivity structures of the underlying Earth crust.

Srivastava and Sankar Narayan (1967) pointed out the large value of ΔZ/ΔH due to SSC at Trivandrum. This anomaly was interpreted by Srivastava and Sankar Narayan (1970) in terms of ocean effects and electrical conductivity anomalies in the upper mantle at depths of 200–800 km. Srivastava and Abbas (1978) studied the induction arrows (Wiese vectors) for the nighttime SSCs. They found unusually large induction arrows at Trivandrum indicative of very strong induced current concentrations near and along the coast and the continental shelf and flow from north to south along the east coast. These currents concentrate further as they pass through the narrow Palk Strait and the Gulf of Mannar between India and Sri Lanka on to Kanyakumari and the Trivandrum coasts. They turn northward along the west coast due to obstructions provided by the volcanic ridge of Lakshadweep, Minicoy and Amindini

Island lying some 300 km west of Trivandrum. A similar suggestion of the concentration of induced current in the Palk Strait was given by Takeda and Maeda (1978). A model calculation based on a thin flat layer in which only contrasts of conductivity due to the distribution of land and depth of sea is taken into account was shown to explain the anomalous distribution of SSCs in South Indian region during the nighttime (Takeda and Maeda, 1979). The anomalous behaviour of Z at equatorial stations in India has been interpreted by invoking the concept of currents through a conductor in the upper mantle or lower trust between India and Sri Lanka (Nityananda *et al*., 1977; Rajaram *et al*., 1979). Rajaram *et al*. (1979) argued that the coastal effects or any other induction process based on the skin depth relationship cannot explain anomalous Z behaviour at Trivandrum for short period events like SSCs and long period events like Sq and *Dst*.

The present author feels that simple induction effects due to any kind of conductor cannot explain the observed anomalies of SSC signatures in H, Y and Z fields at Indian equatorial electrojet stations. Maeda *et al*. (1964) attributed the SC field observed on the Earth's surface to the magnetic field of an image dipole placed inside the intensified solar wind plasma approaching the Earth, assuming that the boundary of the approaching solar wind plasma is simply a flat plane. It would be extremely useful to study the SC disturbance vectors in relation with the solar wind plasma magnetic field and pre-shock Interplanetary Magnetic Field. The data from Indian sector are probably the most useful ones because of the relative absence of local irregularities of the Earth's magnetic field and because of the availability of new about a dozen of stations in this longitude sector for a period of about two decades.

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