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On latitudinal profile of Storm Sudden Commencement in *H*, *Y* and *Z* at Indian Geomagnetic Observatory chain

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The unique network of geomagnetic observatories along 145°E geomagnetic longitude extending from the magnetic equator to the north pole has enabled to study the latitudinal profiles of Storm Sudden Commencement (SSC) amplitudes in the three components H, Y and Z of the geomagnetic field separately for the daytime and nighttime events. An abnormally large positive impulse of Z is observed at the equatorial stations with maximum at Trivandrum during the daytime as well as the nighttime hours suggesting large induced current within the earth's crust south of Indian continent. The daytime enhancement of SSC (H) at the extended equatorial latitudes is undoubtedly due to the disturbed electric field generated by the magnetopause current communicated to the equator through polar latitudes. A prominent decrease of SSC (H) during night hours and the 'induction vector' at SSC frequencies at equatorial latitudes are indicative of the concentration of induced current from source fields extended in altitudes.

1. Introduction

SSC (Storm Sudden Commencement) is one of the important aspects in Solar Terrestrial Relationships involving solar wind, Interplanetary Magnetic Field (IMF), Magnetosphere, Ionosphere and Equatorial Electrojet. The pressure of solar plasma on the earth's magnetosphere under favourable conditions results in an increase of H field suddenly and simultaneously at all the ground magnetic observatories in the world. The association of SSC amplitudes in H with the equatorial electrojet currents has been earlier reported in the literature (Rastogi *et al.*, 1964; Rastogi, 1978 etc.). The latitudinal, longitudinal and solar cycle variations of SSC (H) at equatorial regions are reviewed by Rastogi (1993).

The geophysical association of the SSC amplitudes in the other two components of the geomagnetic field, viz., the vertical (Z) and the zonal component (Y) fields have drawn comparatively less attention (Obayashi and Jacobs, 1957; Forbush and Casavarde, 1961; Ivanov, 1964 etc.). According to the theoretical consideration of Parker (1962), the sign of Z amplitude in SSC is negative (positive) in the northern (southern) hemispheres. However, the spatial distribution of SSC (Z) has been observed to be fairly random, as the short period variations in the Z component are very sensitive to the local earth's electromagnetic induction effects.

Rastogi (1999) worked out the SSC amplitudes association in H, Y and Z employing the equatorial electrojet stations data around the world during IGY-C (1957–1959) interval. At Trivandrum in the Indian sector, comparable or at times larger magnitudes of SSC amplitudes in Z (ΔZ) when compared with those in H (ΔH) were reported. No such larger magnitudes of ΔZ or ΔZ to ΔH amplitude ratios were obtained either at Huancayo, Koror, Addis-Ababa or Jarvis. It was suggested that the abnormal behaviour at Trivandrum was due to the concentration of induced currents over a wide range of low latitudes north and south of the dip equator through the conducting graben in the sub-surface region between India and Sri Lanka, besides the channeling of induced ocean currents through Palk Strait.

Sekhar and Arora (1994) have dealt the problem of Geomagnetic Induction in South India by working out the response function ($\Delta Z/\Delta H$) for short period fluctuations during day and night hours separately. They attributed the reduction in the response function during daytime near the centre of electrojet axis to the weaking of the intensity of induced currents due to second and higher order spatial derivatives.

Under the geomagnetic meridian project (International Magnetospheric Studies, 1977–1979), number of new observatories were established in India and the former USSR countries along 145°E geomagnetic meridian. Utilising the extensive latitudinal coverage of the geomagnetic observatories, some of the complexities of the solar flare effects were reported by Rastogi *et al.* (1997) and Rastogi *et al.* (1999). SSC amplitudes behaviour under varying ionospheric conditions (during day and night hours), especially in the geomagnetic elements H and Z at the observatories influenced by the daytime equatorial electrojet in the Indian region are found to be enigmatic for a long time. This aspect is addressed in this communication by selecting few examples

Table 1. Coordinates and geomagnetic parameters at the Observatories whose data are utilised in this paper during June 1982.

Observatory	Code	Latitude (°N)	Geog.	Longitude (°E)	H	D (°)	Z	I (°)
Trivandrum	TRD	8.5		77.0	39846	−2.8	−39	−0.6
Ettaiyapuram	ETT	9.2		78.0	39850	−3.0	978	2.2
Kodaikanal	KOD	10.2		77.5	39190	−2.4	2580	3.8
Annamalainagar	ANN	11.4		79.7	40230	−2.6	4414	6.3
Hyderabad	HYB	17.4		78.6	39624	−1.6	15347	21.1
Alibag	ABG	18.6		72.9	38190	−0.7	17700	24.4
Ujjain	UJJ	23.2		75.8	36969	−0.5	24441	33.5
Jaipur	JAI	26.9		75.8	35628	−0.8	29628	39.7
Shillong	SHL	25.6		91.8	37409	−0.8	27479	36.3
Sabhawala	SAB	30.4		77.6	33758	+0.4	34499	45.6
Gulmarg	GUL	34.1		74.6	31676	+1.6	38919	50.9
Tashkent	TKT	41.3		69.6	25670	+4.7	45400	60.1
Alma Ata	AAA	43.3		76.9	25270	+4.5	47920	62.2
Karaganda	KGD	49.8		73.1	20120	+1.8	52370	68.9
Novosibirsk	NVS	55.1		82.9	17130	+0.5	52570	71.9

and a statistical study. Some of the very intense SSC events occurring during the day and night hours have been selected to avoid the ambiguities of scaling and the results are presented. The proportionate 'induction vector ($\Delta Z/\Delta H$)' at the SSC frequencies are examined and the results of the day and nighttime profiles are discussed qualitatively with those available in the literature. Finally, the results on the mean of SSCs occurred during three years interval, 1980–1982, are presented statistically as a support for the latitudinal profiles on individual cases.

2. Observational Results

The list of observatories in India and former USSR whose data have been utilised, are given along with the abbreviations in Table 1 and their locations are indicated on a map shown at Fig. 1. Four of the observatories, TRD, ETT, KOD and ANN are within the equatorial electrojet belt, ABG and UJJ are far from the electrojet influence whereas GUL is an observatory close to the latitude of Sq focus. While all these are located south of the focal latitude, four observatories TKT, AAA, KGD and NVS are situated towards the north of the focus.

Two events (20 August 1991 and 30 March 1990) when the SSCs occurred during daylight hours and two similar events during nighttime (8 July 1991 and 10 May 1992) have been selected for presentation. The profile results are described in detailed below.

SSC at 1301 hrs (75°EMT) on 20 August 1991 was the largest event recorded at TRD since its commissioning in 1957. The amplitude of SSC in H was 214 nT and in Z it was 198 nT. In Fig. 2 are shown the tracings of magnetograms of H, Y and Z components at the equatorial electrojet stations, TRD and ANN, at ABG and at GUL. Referring to Fig. 2, at TRD a very short duration and abnormally large impulses in H and Z fields were recorded as the time was close to that of the daily peak of the electrojet current. Most of the

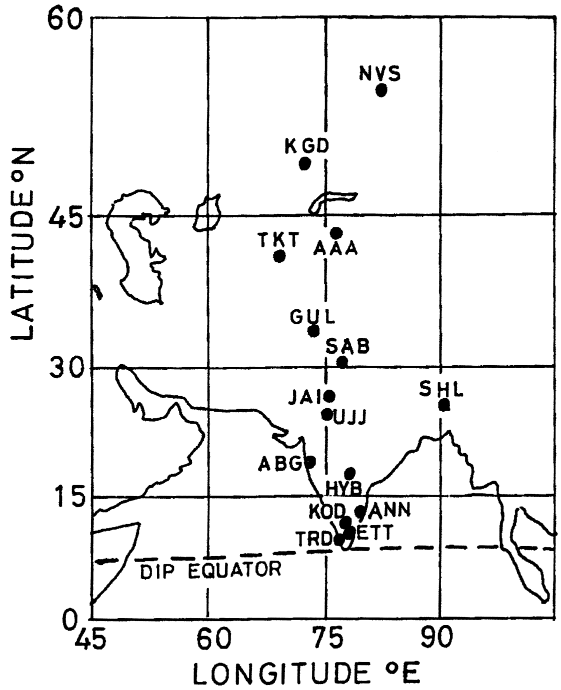

Fig. 1. The map showing the location of geomagnetic observatories whose data have been used.

impulses in H due to SSC were very faithfully reproduce with practically the same magnitude in Z. The impulse in Y was imperceptible in spite of the large amplitudes of ΔH and ΔZ. At ANN the impulse in H was slightly less than that at TRD but SSC (Z) was greatly reduced to a value of 30 nT only. SSC amplitude in H at ABG was only about 30 both ΔZ and ΔY amplitudes are negative at ABG. At GUL, a station close to Sq focus the SSC amplitude was 40

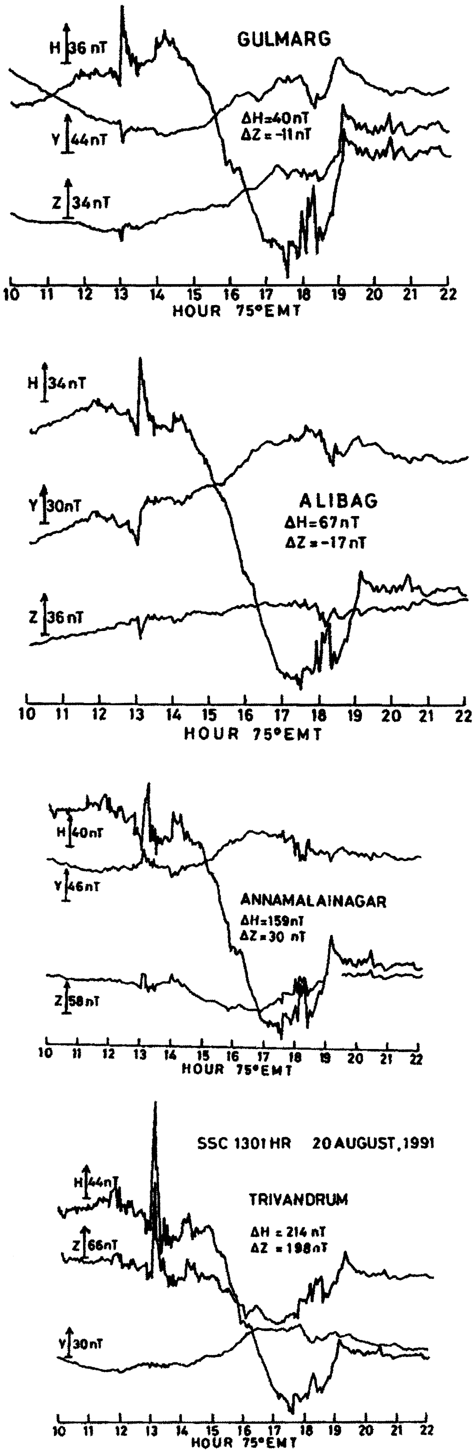

Fig. 2. Tracings of the H, Y and Z magnetograms at some of the Indian observatories during the daytime SSC at 1301 hr 75°EMT on 20 August 1991. The amplitudes of SSC and the scale values are indicates at the respective station tracings.

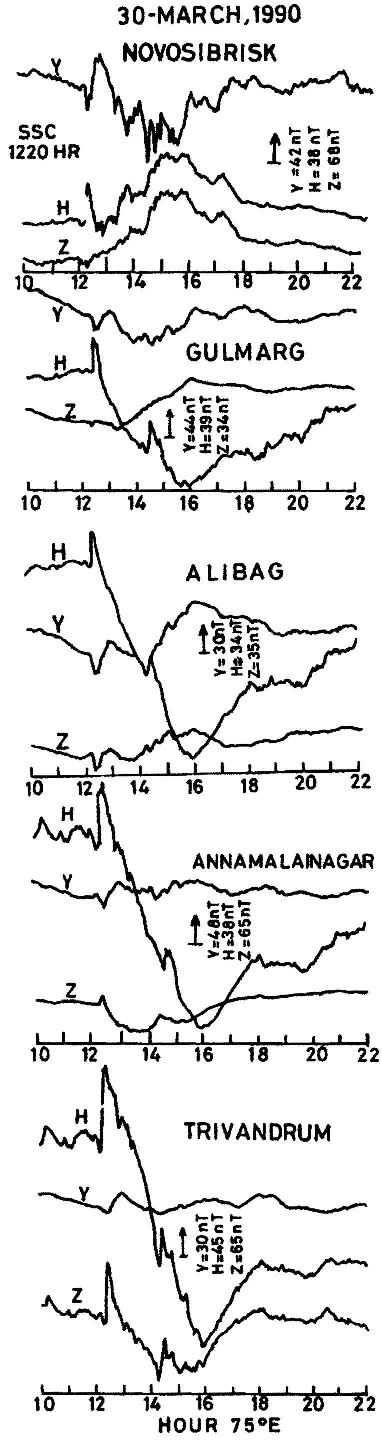

Fig. 3. Tracings of the H, Y and Z magnetograms at Trivandrum, an equatorial station, at Gulmarg a station close to the Sq focus and at Novosibirsk a station well north of the Sq focus during the daytime SSC at 1220 hr (75°EMT) on 30 March 1990. The respective scale values at each of the stations are also indicated.

nT (more or less the same as that of ABG) suggesting that the proximity of the Sq current vortex has no effect on the SSC amplitude at stations outside the electrojet belt. Also, the noteworthy point is that the SSC amplitudes in Z at all the equatorial electrojet influenced stations are systematically positive although the daily variations in Z are of opposite phase to that of H. The SSC amplitudes in H at all the Indian observatories are very coherent with each other, suggesting a far distant current source's association.

In Fig. 3 are shown the tracings of H, Y and Z magnetograms at TRD, ANN, ABG, GUL and NVS, a station well north of the Sq focus, for 30 March 1990, with SSC at 1220 hr (75°EMT). At TRD the SSC impulse was 140 nT for H and 149 nT for Z fields. The short period fluctuations in H

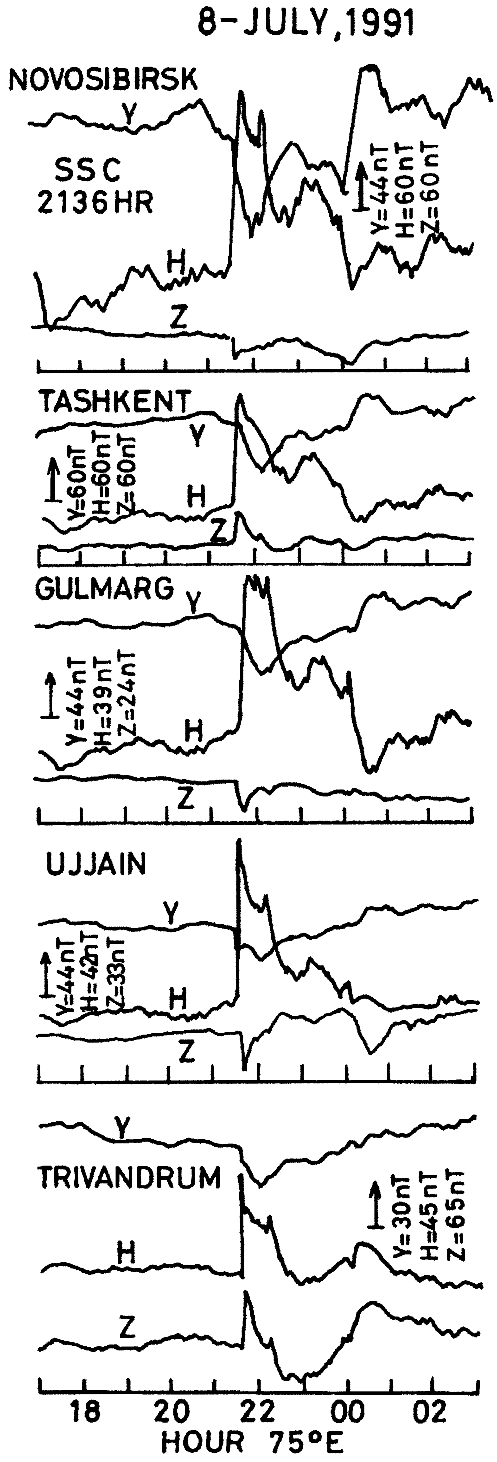

Fig. 4. Tracings of the H, Y and Z magnetograms at some of the observatories in Indo-USSR chain during the nighttime SSC at 2136 hr (75°EMT) on 8 July 1991. The respective scale values at each of the stations are indicated.

and Z fields during the main phase of the storm were coherent to each other and comparable in amplitude at TRD. At ANN, SSC (H) was slightly smaller than that at TRD but SSC (Z) was positive and much smaller than that at TRD. At ABG, SSC (H) was considerably reduced and SSC (Z) was negative as expected at a northern low latitude station. At GUL, ΔZ was significantly small. At NVS too, ΔZ was

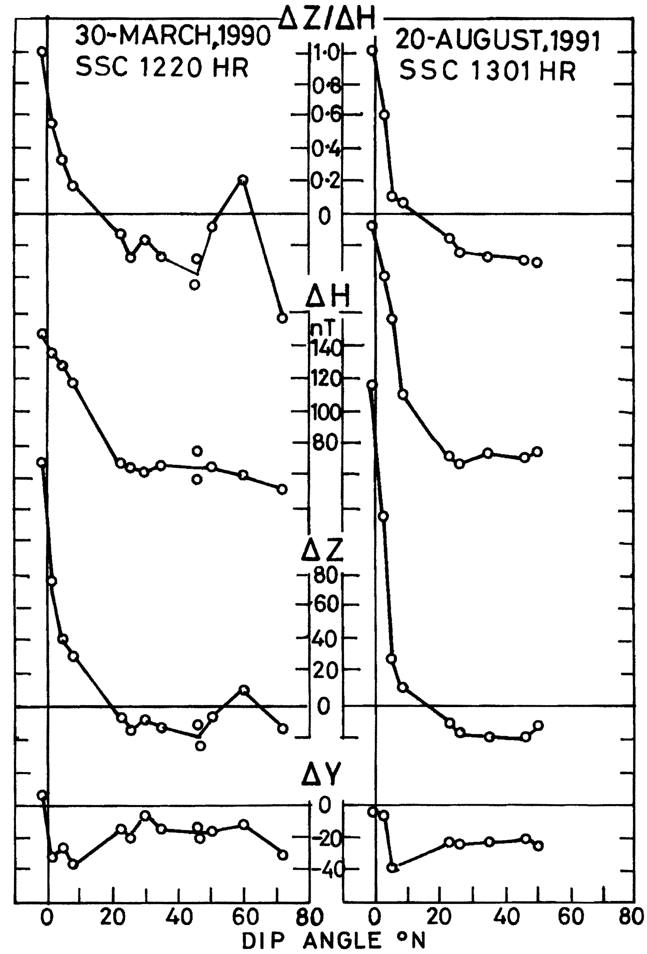

Fig. 5. The latitudinal profiles of ΔH, ΔY, ΔZ and $\Delta Z/\Delta H$ during daytime SSC at 1220 hr on 30 March 1990 and 1301 hr on 20 August 1991.

small and negative.

In Fig. 4 are shown the tracings of a nighttime SSC that occurred at 2136 hr (75°EMT) on 8 July 1991. This was the second largest nighttime SSC at TRD, with $\Delta H = 120$ nT, the largest being at 2138 hr on 17 July 1959 with $\Delta H = 131$ nT. At TRD, both ΔH and ΔZ were larger in magnitude. ΔY was also large but its signature did not duplicate that of ΔH. At UJJ station, well outside the electrojet region, ΔZ was negative and ΔH was higher in magnitude than that at TRD. It is to be noted that ΔH during nighttime has not decreased at stations north of electrojet as in the case of daytime SSC described above.

The SSC amplitudes in H, Z and Y for the four selected storms at TRD, ANN, ABG and UJJ are given in Table 2 for the completeness of the comparison of their relative magnitudes. The magnitudes of the impulses in H, Y and Z traces were scaled from the copies of magnetograms at all the interesting stations in the Indo-USSR chain. Care was taken to measure the magnitudes between identical points in the various station traces. However, few discrepancies were noticed between published values and the presently scaled values and the later are considered to be more accurate.

Figure 5 shows the latitudinal variation of the amplitude of SSCs in H, Y and Z as well as ($\Delta Z/\Delta H$) for the day-

Table 2. Amplitude (in nT) of SSCs in H, Z and Y at four stations for the selected storms.

Date	Time	TRD			ANN			ABG			UJJ		
	(75°EMT)	ΔH	ΔZ	ΔY	ΔH	ΔZ	ΔY	ΔH	ΔZ	ΔY	ΔH	ΔZ	ΔY
30-3-90	1220	140	149	−1	111	32	−34	44	−21	−20	51	−13	−18
20-8-91	1301	214	198	−5	159	30	−57	67	−29	−23	78	−19	−23
8-7-91	2136	120	114	−9	120	91	−68	123	−25	−20	155	−30	−21
10-5-92	0056	100	141	−5	134	75	−50	111	−17	−14	138	−26	−15

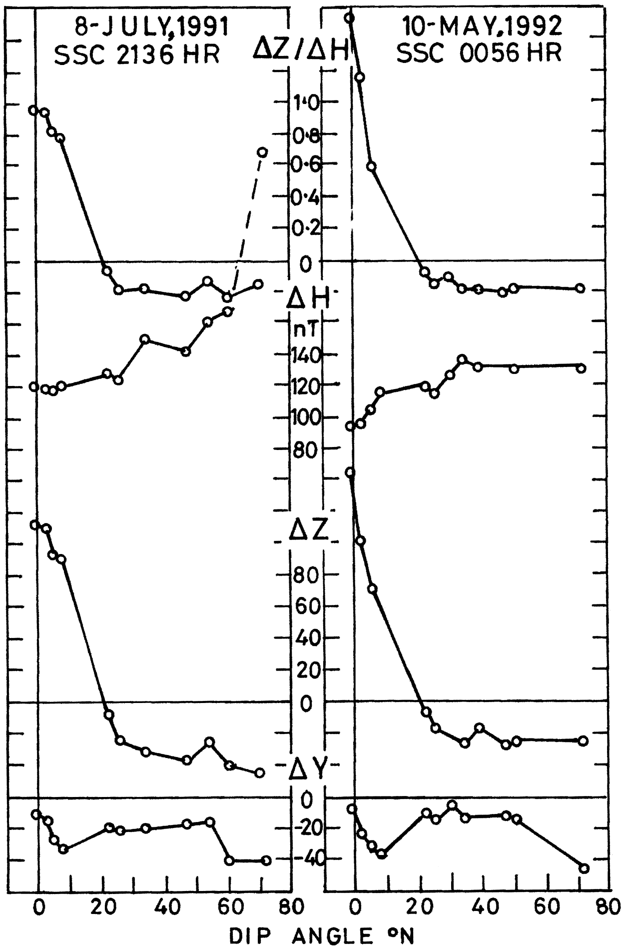

Fig. 6. The latitudinal profiles of ΔH, ΔY, ΔZ and $\Delta Z/\Delta H$ during nighttime SSC at 2136 hr on 8 July 1991 and 0056 hr on 10 May 1992.

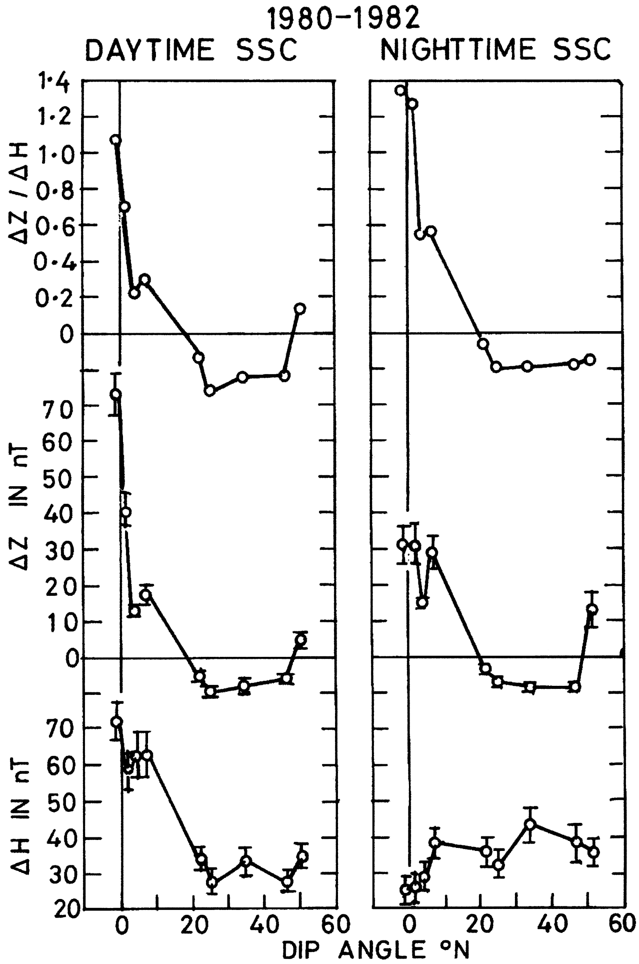

Fig. 7. The mean latitudinal profiles of ΔH, ΔY, ΔZ and $\Delta Z/\Delta H$ during day and night times SSCs during the years 1980 to 1982 at the Indian sector.

time storms on 30 March 1990 and 20 August 1991. As is expected, the amplitude of daytime SSC in H has shown a pronounced equatorial enhancement over the magnetic equator. The SSC in Z is noticed to be positive at all equatorial stations TRD, ETT, KOD and ANN. It is surprising to note that SSC in Z field shows even stronger enhancement over the equator. On 20 August 1991, ΔH is found to be 214 nT at TRD and 159 nT at ANN, a reduction to only 74 reduction of about 85 enhancement over the equator. The positive values of ΔZ at ANN (dip lat. 3.5°N) indicate that the effects are not directly due to the ionospheric currents but are due to the superposed effects of the currents induced within the earth as well.

In Fig. 6, are shown the latitudinal variations of SSC amplitudes in H, Y and Z fields during the nighttime events on 8 July 1991 and 10 May 1992. The latitudinal variation of ΔY is very similar to that for daytime SSCs reported earlier. There are clear indications of minimum amplitudes at latitudes near ANN. The amplitude of SSC in Z field shows positive signature at equatorial stations and intensification over the dip equator. The amplitude of ΔH due to SSC shows a minimum at the dip equator contrary to that during the daytime SSCs behaviour. The decrease in the amplitude of ΔH is a significant result of noteworthy. The ratios $\Delta Z/\Delta H$ show prominent maximum over the dip equator, the value being as large as 1.52 for the SSC on 10 May 1992.

In order to test the statistical significance of these latitudinal variations of SSC effects on the geomagnetic field observed at these individual cases, the amplitudes of SSC in H and Z fields at all Indian stations were scaled for storms during 1980, 1981 and 1982. Figure 7 shows the latitudinal variations of the mean amplitude of SSC in ΔH and ΔZ separately for the daytime (23 events) and nighttime (16 events). During the daytime, ΔH shows a large enhancement over the equatorial zone while during the nighttime the amplitude has decreased monotonously from mid latitudes to the dip equator, corroborating again the case study results. The amplitudes in Z field during the day and night hours are quite similar, however, the equatorial enhancement is much larger during the daytime than during the night hours. The ratio $\Delta Z/\Delta H$ has shown similar enhancement over the dip equator during the day as well as night hours.

3. Discussion

The present analysis has brought out clearly the following two aspects. The latitudinal profile of SSC (H) amplitude during nighttime reveals a minimum of amplitudes around the dip equator and $\Delta Z/\Delta H$ ratios are enhanced considerably again in the vicinity of the dip equator irrespective of the time of the day.

Onwumechilli and Ogbuhei (1962) have reported enhancement of nighttime geomagnetic fluctuations in the African and American zones. Chapman and Rajarao (1965) have shown the ratio of SSC (H) at equatorial to that at non-equatorial station during IGY period to be close to 1.0 during night hours but the same ratio is shown to exceed significantly from 1.0 during the day. Kane (1978) has described the results of an extensive study of SSC (H) at TRD, ANN and ABG in the Indian sector for the period 1958–1969. He has shown that the equatorial enhancement fluctuates over a very wide range and is not always commensurate with the electrojet strength. The mass plot of SSC (H) at TRD versus similar SSC magnitude at ABG for 00 hr LT by him has indicated lesser amplitudes at TRD than at ABG, suggesting an inhibition effect near the dip equator. He indicated that the data from the equatorial region may be affected by peculiar earth and/or ocean currents conductivity anomaly.

Kikuchi *et al.* (1978) and Kikuchi and Araki (1979) have extensively probed the physical nature of SSCs. They have shown that the high latitude electric field can penetrate to low latitudes as the zeroth order transverse magnetic wave-guide mode. Further, Araki (1977) has decomposed the disturbance field of SSC into two components. One of the components, the DL field is the main impulse originating as an abrupt increase of the magnetopause current and the other, DP is due to a polar electric field transmitted along the lines of force from the magnetosphere.

Analysing magnetic field data from the 210° meridian chain of stations, Yumoto *et al.* (1996), presented in their figure 5 the equatorial enhancement of SSC's (SC) and SI's main impulse amplitudes at the equatorward station, Yap ($\Delta = 0.3°$) to that at Guam ($\Delta = 4.6°$) during the daytime. Also, the enhancement is shown by them to be much stronger during local summer due to enhanced ionospheric conductivities in the summer hemisphere, as the electric currents flowing in the ionosphere play an important role in the energy transfer of SC and SI disturbances from high latitudes to the magnetic equator. Yumoto *et al.* (1996) have suggested that the polar electric fields (DP) of SC and SI magnetic variations predominate over the Chapman–Ferraro current on the magnetopause (DL) at low and middle latitudes and thus this dayside enhancement must be caused by the nearly instantaneous transmission of DP fields to the magnetic equator.

In our Fig. 7, where latitudinal variations during night and daytimes of mean SSC amplitudes in H and Z as well as $\Delta Z/\Delta H$ are shown, there were 23 events in the daytime and 16 events in the night hours for the years 1980–1982. The mean amplitude ratios for day to nighttime in SSC (H) at the stations, TRD, ETT, KOD and ANN are 2.9, 2.3, 2.2 and 1.7 respectively whereas for stations at higher latitudes from HYB to GUL, the ratios are all around 1.0 and slightly lower than 1.0. From this, we believe, because of the Cowling conductivity effect during the day light hours, the instantaneous transmission of DP fields will not only be confined to the station closest to the axis of the electrojet current but extends further to the northern latitudes, at least upto the station ANN.

It is not the aim here to model the earth's electromagnetic induction effects at this short period variation. The $\Delta Z/\Delta H$ ratios during the night and day times have been worked out separately to show that abnormality in SSC (Z) persists at the Indian equatorial observatories. The enhanced $\Delta Z/\Delta H$ at both the times at these observatories indicate that the effect is definitely associated with the 'induction'.

The increase in the ratio of $\Delta Z/\Delta H$ in the equatorial region during nighttime may be due to the decrease in the nighttime SSC amplitudes in H which are not proportional to the corresponding changes in the Z component. In other words, the Z amplitudes may be enhanced both during day and nighttime in the equatorial region due to the complex distribution of electrical conductivity at the southern tip of India whereas the H amplitude decreases when uniform source currents in the nighttime are present.

Various investigators have invoked major sub-surface electrical conductivity structures in the region for accounting the abnormal short-period geomagnetic variations (in the Z-component). Thakur *et al.* (1986) have indicated the presence of a deep-seated conductor of crustal origin across the Comorin Ridge and the thickening of sediments. Numerical model studies (Takeda and Maeda, 1979; Ramaswamy *et al.*, 1985; Mareschal *et al.*, 1987) and analogue model studies (Papamastorakis and Haerendel, 1983) have shown the importance of the sub-surface conductor in the Palk Strait region. Agarwal and Weaver (1989) were successful in numerically modelling the regional electromagnetic induction around the Indian peninsula and Sri Lanka by taking account three sub-surface conductors, besides the conductive regions representing the land and sea in the southern peninsular region. The three sub-surface conductors were (1) The Indo-Ceylon Graben and Pondicherry failed arm together with thick sediments (2) Crustal alteration and mantle uprise with thick sediments underneath or near the Comorin Ridge and (3) West coast rift owing to injection of mantle material or mantle uprise and sediments.

Sekhar and Arora (1994), while studying the latitudinal variation of short period fluctuations (not SSC frequencies) in H and Z fields, have identified two zones of significant differences between day and nighttime ratios of $\Delta Z/\Delta H$, one near the central axis and the other close to the periphery of the equatorial electrojet. They have explained the decrease in daytime ratios at the central axis of the electrojet as due to the second order spatial derivatives of the source field. However, their figure 3(b) in which they have shown latitudinal variation of ΔH from about 9° dip latitude to the equator during nighttime indicates a decrease in ΔH towards the equator. The progressive decrease of SSC amplitudes in H from a wider latitudinal range shown here coupled with the results of Sekhar and Arora (1994), can be explained if one assumes the source current is far off and uniform during the night hours thereby the induced currents, over a large latitudinal extent, may extend to the north and south sides of the axis of the electrojet. These induced currents may deviate towards the highly conducting narrow belt, just south of Trivandrum resulting the broad decrease of H field in shorter wavelengths. During daytime, this decrease is perhaps over compensated by the currents induced by the electrojet, which are non-uniform.

Viljanen *et al.* (1993) attempted to eliminate the distortion due to source effects at auroral and equatorial latitudes by taking averages over several events. For this, they considered three dimensional electrojet and two dimensional earth models and estimated $-Bz/Bx$ ratio which was called the 'induction vector', besides apparent resistivity and the impedance phase. Apart from other important conclusions, it was shown by them that the induction vector is sensitive to distant sources, even about 1000 km (altitude) away from the observation point. Also, the source effect was shown to change remarkably the amplitude of the vector between the anomaly and the source region. There exists an anomaly in the southern tip of the Indian peninsula and not only the ionospheric currents in the equatorial electrojet region but also the far distant currents in the ring current and beyond are expected to produce complex induction effects during the day and nighttime. This aspect has to be further quantified to account for the enhanced $\Delta Z/\Delta H$ ratios both during day and night hours.

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