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Preliminary impulse of the geomagnetic storm sudden commencement of November 18, 1993

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Abstract. The characteristics of the geomagnetic sudden commencement (SC) that occurred at 1211:30 UT on November 18, 1993, following an interval of prolonged geomagnetic quietness are studied using high time resolution data of several magnetometer networks. We present the first results concerning the behavior of the preliminary reverse impulse (PRI) of the H component of the SC near the dip equator from simultaneous observations in different longitude (local time) sectors. It is found that the preliminary reverse impulse appeared only in the prenoon (0912 LT) sector very close to the magnetic equator (dip 0.6°). At locations farther away (dip 6.0°-7.2°) but on the same meridian, the preliminary reverse impulse diminished in amplitude and led to a delayed onset of the main impulse (MI) of the SC. The preliminary reverse impulse is not apparent at locations close to the magnetic equator (dip 1.2°-2.7°) in either the afternoon (1300 LT) or the near-dusk (1740 LT) sectors. What is seen instead here is an unambiguous reduction in the rate of increase of H component coincident with the preliminary reverse impulse in the forenoon sector. HF Doppler radar measurements of F layer vertical plasma drift close to the magnetic equator (dip 4.9°) near the dusk sector showed the SC-related disturbance to be a decrease in ambient upward drift with considerable temporal structure, which indicates the imposition of a westward electric field. The preliminary reverse impulse is seen in the subauroral to polar region (MLAT 56.8°-76°) on the afternoon side simultaneous with that near the prenoon dip equator and with a conspicuous increase in amplitude and duration with latitude over MLAT range 66°-76°. Theoretical calculations suggest that the global current system set up by a pair of field-aligned currents at 80° latitude and shifted to morningside (centers at 1300 and 0300 LT) could, in general, account for the observed behavior of the preliminary reverse impulse, except in the dip equatorial region near dusk.

1. Introduction

Geomagnetic storm sudden commencements (SCs) result from the interaction of interplanetary shocks /discontinuities with the Earth's magnetosphere. SCs have been extensively studied with ground level magnetic field measurements for many years and in recent times with spaceborne instrumentation as well (see review of *Araki* [1994, and references therein]) [*Petrinec et al.*, 1996; *Engebretson et al.*, 1999; *Takeuchi et al.*, 2000]. It is established that the SC waveform at the surface is quite complex with a strong dependence on latitude and local time. *Araki* [1977, 1994] synthesized the vast body of observational results and developed a physical model of SC, building on the original work of *Tamao* [1964]. According to the model, the SC waveform in the H component typically consists of two successive pulses of opposite polarity termed preliminary impulse (PI) and main impulse (MI), which result from three effects associated with sudden magnetospheric compression caused by the increase in solar wind dynamic pressure. The preliminary impulse (PI), the first effect, is due to a dusk-to-dawn electric field imposed on the polar ionosphere by a transverse Alfvén wave converted from the compressional hydromagnetic wavefront propagating in the dayside magnetosphere. This large-scale electric field excites a twin-vortex ionospheric current system in the polar region

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and penetrates instantaneously to the magnetic equator as an electromagnetic wave between the conducting Earth and ionosphere [*Kikuchi et al.,* 1978; *Kikuchi and Araki,* 1979]. This component of SC disturbance field of polar origin termed $DP_{\rm pi}$ manifests as a sharp negative (positive) impulse simultaneously at auroral latitudes on the afternoonside (morningside) and at the dayside dip equator. The second is the fundamental effect of the compressional hydromagnetic (HM) wave that induces a step-like increase in the H component of magnetic field which dominates at low latitudes, and this part of the SC disturbance field is referred to as *DL*. The third effect prevails if the ram pressure, after the tailward passage of the compressional wave, is kept high behind the interplanetary shock that caused the sudden compression, leading to enhanced magnetospheric convection and the associated dawn-to-dusk electric field. The outcome of this process is the same as for the preliminary impulse but of opposite polarity. This component termed $DP_{\rm mi}$ contributes to the large amplitude of the main impulse generally seen at auroral latitudes and at the dayside dip equator. The SC waveform in the ground level magnetic field is thus interpreted as being due to the superposition of *DP* and *DL* subfields that dominate at high and low latitudes, respectively. The preliminary impulse of the SC is exclusively due to electric fields and currents of polar origin $DP_{\rm pi}$, whereas the main impulse is due to the combined effects of magnetosphreic compression and electric fields/currents of polar origin (DL+$DP_{\rm mi}$).

The statistical study of *Yamada et al.* [1997] showed that the local time pattern of occurrence of preliminary impulse at middle and low latitudes on the same meridian is symmetric about noon, whereas the magnetic variation theoretically computed for a stationary current system driven by a pair of field-aligned currents (FAC) and ionospheric currents is asymmetric about noon with an intrusion of the dusk vortex into the morning sector. The disagreement between observations and theory, which is considered unlikely to be due to the models of field-aligned currents and ionospheric conductivity assumed, raised questions about the origin of the preliminary impulse at low latitudes, which has a direct bearing on the issue of electrical coupling of high-latitude and low-latitude ionospheres. In a very recent case study, *Engebretson et al.* [1999] found the preliminary impulse to propagate very rapidly and with considerable dispersion across both of the polar caps and not along the auroral oval as expected from current SC models reviewed by *Araki* [1994]. This behavior is argued to be consistent with a fast mode ionospheric propagation of a pulse created by the temporary imposition of a pair of field-aligned currents on the polar ionosphere antisymmetric about local noon. These studies indicate that the current understanding of SC in general and of its preliminary impulse in particular is far from complete. Continued studies are therefore required to improve our comprehension of the transient and complex current systems that develop in the magnetosphere-ionosphere domain as a result of sudden magnetospheric compression. As already mentioned, the PI appears as a negative H component impulse along the dayside dip equator [*Matsushita,* 1960] and is often called preliminary reverse impulse (PRI). The occurrence rate of equatorial PRI statistically studied from observations at individual stations shows diurnal variation with a maximum around noon [*Araki,* 1977; *Araki et al.,* 1985]. There is a glaring dearth of information, however, on the local time dependence of equatorial PRI from simultaneous observations at different longitudes because of the lack, till recently, of high time resolution magnetometers along the dip equator. The establishment of the equatorial network by the Japanese research group has made it possible to obtain geomagnetic data from several longitude sectors along the dip equator with high time resolution and sensitivity [*Yumoto et al.,* 1996].

It is against this background and with the stated perceptions that we conducted a study of the SC of November 18, 1993. In this paper, we shall present the salient characteristics of the equatorial preliminary reverse impulse from simultaneous observations at three longitudes on the dayside as well as of the preliminary impulse at high latitudes of this SC. We believe that these results are a significant addition to our empirical knowledge of the SC phenomenon. Study of the other aspects of the SC is in progress and will be reported separately.

2. Database

The present study is based on high time resolution digital data of the equatorial magnetometer network (time resolution 3 s) of Kyushu University, Japan, the International Monitor for Auroral Geomagnetic Effects (IMAGE) network (10 s) in Scandinavia, and the Greenland magnetometer chain (20 s). The details of instrumentation of the various networks are given by *Yumoto et al.* [1996], *Luehr et al.* [1998], and *Stauning* [1994]. The locations of the stations of the networks are shown in Figure 1. The geographic and geomagnetic dipole coordinate and magnetic local time (MLT) at 1212 UT are summarized in Table 1. It is to be noted that for stations of the equatorial network, the dip angle calculated using the International Geomagnetic Reference Field (IGRF) model is given instead of magnetic latitude (MLAT). The equatorial magnetometer data are complemented by HF Doppler radar measurements at Kodaikanal (10.2°N, 77.5°E geographic; dip 4.9°), India. The radar, which is operated at 4 MHz in the normal incidence mode, provides data on the time rate of change of phase path (in units of a wavelength of the probing radio waves) or Doppler velocity $V_{\rm d}$ of ionospheric F region reflections with a time resolution of 6 s. The F region vertical plasma drift V_z is calculated from the Doppler velocity V_z=$V_{\rm d}/2$). This is appropri-

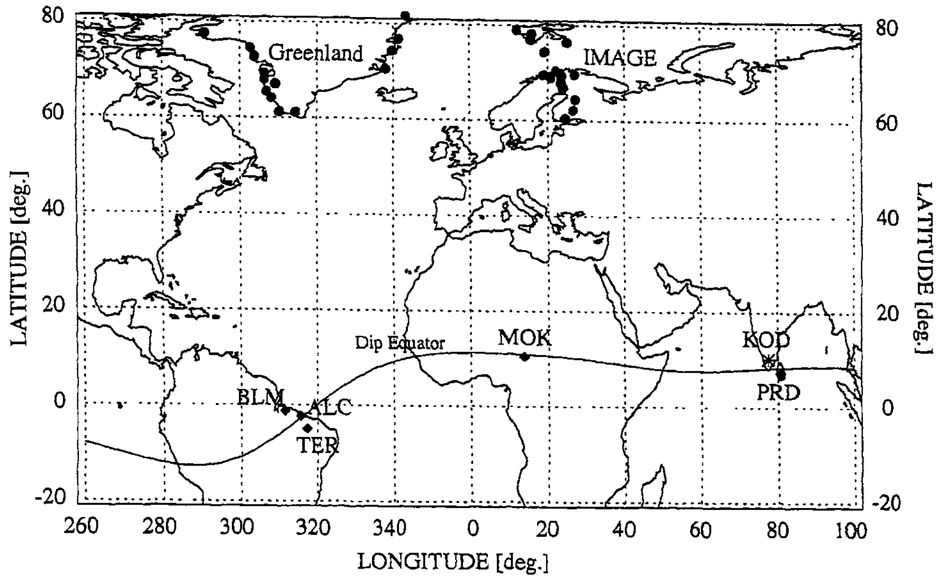

Figure 1. Locations of magnetometer stations of the equatorial magnetometer network (EMN), International Monitor for Auroral Geomagnetic Effects (IMAGE), and Greenland chains (see Table 1 for details of station coordinates). The location of the dip equator computed with the International Geomagnetic Reference Field (IGRF) for 1993 is also shown for reference.

ate because (1) vertical plasma motions near the reflection level are very effective in producing changes in phase path of ionospheric echoes at normal incidence [e.g., *Georges*, 1967] and such a vertical plasma motion commonly prevails in the vicinity of the magnetic equator driven by the zonal electric fields [see *Fejer*, 1991, and references therein] and (2) during the evening-night period the Doppler velocity of F region echoes represents the vertical plasma motion due to the zonal electric field with a minor positive contribution from the chemical loss effect, depending on the height of the ionospheric reflections [see *Sastri et al.*, 1993, and references therein]. The technical details of the radar system were published elsewhere [*Sastri et al.*, 1985]. The HF Doppler technique is a useful tool for the detection and study of transient ionospheric vertical plasma motions and electric fields associated with geophysical phenomena like SC and *DP* 2 events [e.g., *Kikuchi et al.*, 1985; *Kikuchi*, 1986; *Sastri et al.*, 1993, 1995; *Abdu et al.*, 1998].

3. Observations

3.1. Background Conditions

The geomagnetic sudden commencement studied here occurred at 1211:30 UT on November 18, 1993, following prolonged geomagnetic quietness. The quiet ambient conditions can be seen from the time histories of the auroral electrojet indices (AU/AL) and the midlatitude symmetric disturbance index (SYM-H) plotted in Figure 2. The SYM-H index is essentially the same as the hourly equatorial *Dst* index but with a time resolution of 1 min [*Iyemori and Rao*, 1996]. AU/AL remained quite low (<130 nT) for more than 12 hours prior to the SC, and SYM-H was not less than -11 nT. It is therefore not unreasonable to assume that the SC corresponds to northward interplanetary magnetic field (IMF) conditions although direct IMF data are not available to verify the inference (IMP 8 satellite was in the magnetosphere at the time of the SC). The SC is considered to be free of substorm effects because Pi2 pulsations indicative of substorm onset [*Rostoker et al.*, 1980] were recorded at midlatitude stations Memambetsu (34.9° MLAT) and Kanoya (21.4° MLAT) on the nightside at 1345 UT, much later than the SC. The occurrence of substorm activity well removed from the SC can also be seen from the time variations of AU/AL indices in Figure 2.

3.2. SC Waveform

3.2.1. Geostationary orbit. Magnetometers aboard GOES 6 (78.5°W) and GOES 7 (112°W) satellites duly recorded the SC at 1211:30 UT, as may be seen from the data plotted in the bottom panel of Figure 2. Both of the satellites were in the morning sector (GOES 6, 0700 LT; GOES 7, 0445 LT) at the time of the SC. The SC is seen as a stepwise increase in H_p component (parallel to the Earth's rotation axis) with a rise time of 7 min at both of the satellite locations and an amplitude of 19 nT and 11.2 nT at GOES 6 and GOES 7, respectively. The magnitude of the asymptotic response in H_p (change in level prior to and after the stepwise increase) at GOES 6 and GOES 7 is 23 nT and 12.8 nT, respectively. Note that the preliminary impulse is not apparent at the geostationary orbit, which suggests that the main source of the preliminary impulse is an

Table 1. Stations Used in the Analysis

Station Name	Abbreviated Code	Geographic Latitude	Geographic Longitude	Geomagnetic Dipole Latitude	Geomagnetic Dipole Longitude	MLT (at 1212 UT)
		International Monitor for Auroral Geomagnetic Effects (IMAGE) (10 s)				
Ny Alesund	NAL	78.92	11.95	76.07	112.25	16.5
Longyearbyen	LYR	78.20	15.82	75.12	113.00	16.5
Hornsund	HOR	77.00	15.60	74.02	110.48	16.3
Hopen Island	HOP	76.51	25.01	72.93	115.91	16.6
Bear Island	BJN	74.50	19.20	71.33	108.73	16.1
Soroya	SOR	70.54	22.22	67.24	106.71	15.8
Kevo	KEV	69.76	27.01	66.21	109.73	16.0
Tromso	TRO	69.66	18.94	66.54	103.44	15.6
Masi	MAS	69.46	23.70	66.07	106.92	15.8
Kilpisjarvi	KIL	69.02	20.79	65.78	104.31	15.6
Muonio	MUO	68.02	23.53	64.62	105.70	15.7
Pello	PEL	66.90	24.08	63.46	105.38	15.6
Oulujarvi	OUJ	64.52	27.23	60.89	106.54	15.6
Hankasalmi	HAN	62.30	26.65	58.62	104.99	15.5
Nurmijarvi	NUR	60.50	24.65	56.81	102.54	15.3
		Greenland Network (20 s)				
Qaanaaq	THL	77.48	290.83	88.46	14.10	9.1
Kullorsuaq	KUV	74.57	302.82	84.61	42.26	10.8
Upernavik	UPN	72.78	303.85	82.88	37.44	10.4
Qeqertarsuaq	GDH	69.25	306.47	79.27	34.63	10.1
Attu	ATU	67.93	306.43	78.01	32.61	10.0
Kangerlussuaq	STF	67.02	309.28	76.83	36.25	10.2
Maniitsoq	SKT	65.42	307.10	75.52	30.94	9.8
Nuuk	GHB	64.17	308.27	74.19	31.68	9.9
Paamiut	FHB	62.00	310.32	71.86	33.09	9.9
Narsarsuaq	NAQ	61.18	314.57	70.59	38.60	10.3
Nord	NRD	81.60	343.33	80.88	131.60	16.6
Danmarkshavn	DMH	76.77	341.37	79.20	105.02	14.8
Daneborg	DNB	74.30	339.78	77.88	94.29	14.1
Ittoqqortoormiit	SCO	70.48	338.03	75.26	82.02	13.3
		Equatorial Magnetometer Network (EMN) (3 s)				
Balem	BLM	-1.22	311.47	7.20[a]	22.6	9.2
Alcantara	ALC	-2.34	315.59	0.60[a]	26.6	9.5
Teresina	TER	-5.03	317.17	-6.09[a]	28.0	9.6
Mokolo	MOK	10.44	13.48	-1.24[a]	86.4	13.5
Peradenia	PRD	7.28	80.64	-2.72[a]	151.7	17.8
		HF Doppler (6 s)				
Kodaikanal	KOD	10.23	77.47	4.90[a]	149.4	17.6

[a]Dip angle (degrees).

ionospheric current. The role of ionospheric currents in the preliminary impulse had, in fact, been established from simultaneous observations above and well below the ionosphere [*Araki et al.*, 1982, 1984]. The sudden decrease in the H_p component around 1600 UT and the subsequent increase at 1720 UT indicate magnetopause crossings [*Rufenach et al.*, 1989], presumably due to an enhanced solar wind pressure and a prolonged southward interplanetary magnetic field. Worth noting is the strong southward magnetic field of 100 nT just outside the magnetosphere, which can be regarded as the cause for the high magnetic activity as indicated by the AU/AL and SYM-H variations shown in Figure 2.

3.2.2. Auroral and polar regions. Figure 3 displays the SC waveform in the X and Y component at the IMAGE network stations spanning the auroral-polar region in the afternoon sector (see Table 1 for coordinates of the stations). In the X component the positive main impulse (MI), which is the most readily identifiable aspect of the SC, is preceded by a negative preliminary reverse impulse (PRI) at all of the stations from Nurmijarvi (NUR) to Ny Alesund (NAL). The presence of a distinct preliminary reverse impulse at the subauroral to polar region in the afternoon sector is consistent with the physical model of *Araki* [1977, 1994]. The noteworthy feature of the preliminary re-

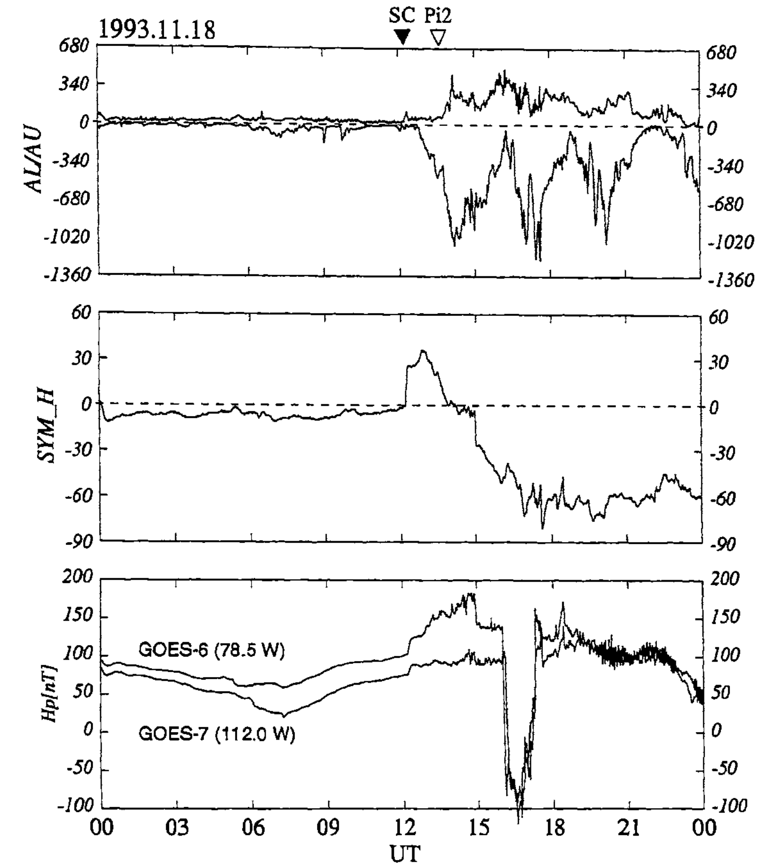

Figure 2. Time variation of AU/AL and SYM-H indices and H_p (northward) component obtained by GOES 6 (78.5°W) and GOES 7 (112°W) on November 18, 1993. The times of the sudden commencement (SC) and Pi2 are indicated. Note the prolonged quiet condition that preceded the onset of SC and the occurrence of Pi2 and substorm activity far removed from SC.

verse impulse is not its presence but the difference in its manifestation from auroral to polar stations (Masi to Ny Alesund) of the IMAGE network. This can clearly be seen from the SC waveform shown on an expanded scale in Figure 4. Note that the X component traces are folded in Figure 4 when they exceed the set range in each panel. It is quite evident from Figure 4 that the nominal peak amplitude and duration (and hence nominal peak time) of the preliminary reverse impulse show a more or less linear increase over the MLAT range 66°-76° (see right-hand-side panels of Figure 4). At Ny Alesund (NAL) the peak time of PRI occurred 3 min later than at Masi (MAS) and with an amplitude higher by a factor 3. At locations lower than 66° MLAT, the nominal peak time is almost the same at all of the stations with a progressive reduction in amplitude such that at Nurmijarvi (NUR), the southernmost station of the IMAGE network, the peak amplitude of the preliminary reverse impulse is 3 nT. A similar latitudinal variation of nominal peak amplitude and peak time across the IMAGE network has very recently been found by *Takeuchi et al.* [2000] for the preliminary impulse (PI) of the negative sudden impulse (SI^-) that occurred at 1154 UT on May 13, 1995.

Figure 5 shows the SC waveform in the H and D component at the Greenland chain. At stations of the Greenland west coast chain (left-hand side of Figure 5) which was in the prenoon sector, a sharp preliminary reverse impulse is apparent in the H component from Kangerlussuaq (STF) to Qeqertarsuaq (GDH) (MLAT 76.8°-79.3°), while at lower-latitude stations, Paamiut (FHB, MLAT 71.9°) and Narsarsuaq (NAQ, MLAT 70.6°), the preliminary reverse impulse became broader and the main impulse became smaller in amplitude. At higher-latitude stations Upernavik (UPN) to Qaanaaq (THL) (MLAT 82.9°-88.5°) the two-pulse structure of the SC with an opposite polarity sequence, namely, a positive pulse followed by a negative pulse, is seen. These observations imply that the focus of the current vortex responsible for the preliminary impulse is located around 80° MLAT in the prenoon sector. Stations of the Greenland east coast chain (right-hand side of Figure 5) are suitable poleward extensions of the IMAGE network (see Table 1). A preliminary reverse impulse can be seen at Ittoqqortoormiit (SCO, MLAT 75.26°) and Daneborg (DNB, MLAT 77.9°), and a positive preliminary impulse can be seen at Nord (NRD, MLAT 80.9°). The focus of the current vortex of the prelimi-

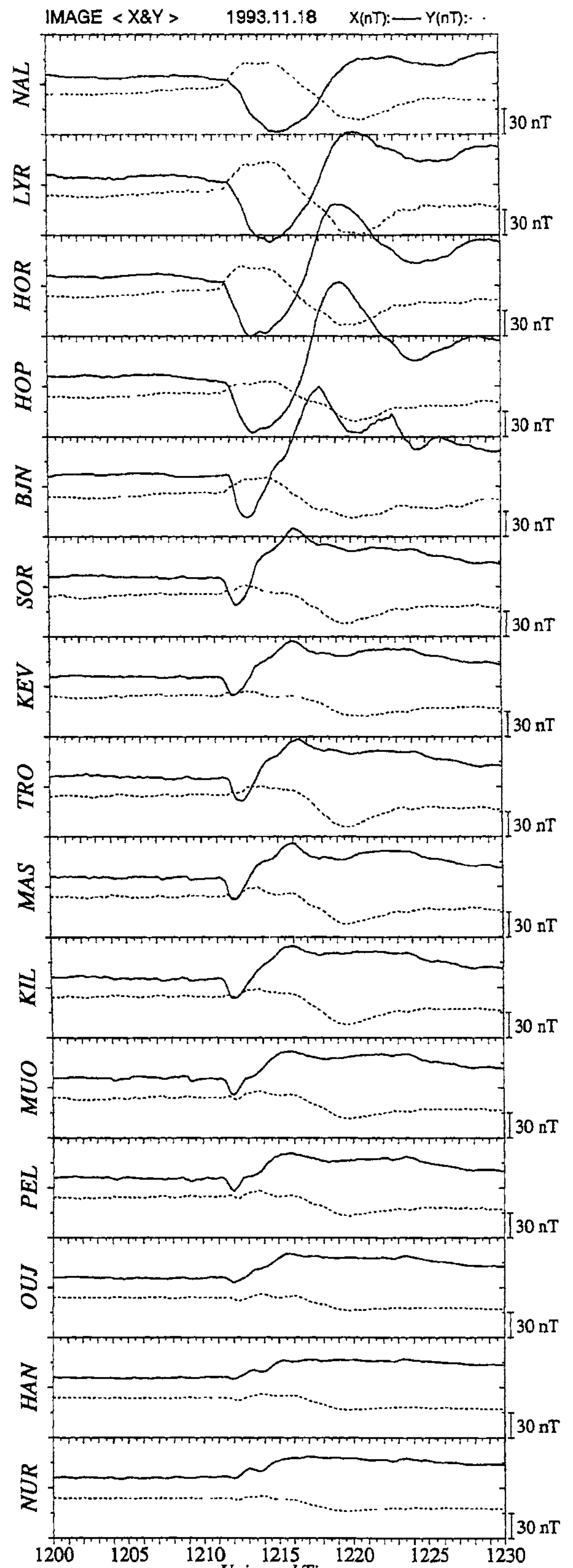

Figure 3. The SC waveform in the X (solid line) and Y (dashed line) components at the IMAGE network stations.

nary impulse is therefore between Nord and Daneborg, namely, around 80° MLAT along the IMAGE chain.

Psc, which represent damped geomagnetic pulsations excited by the SC, are prominently seen superposed on the MI at the stations from Qeqertarsuaq (GDH) to Maniitsoq (SKT) (MLAT 79.3°-75.5°) of the Greenland west coast but only at Bear Island (BJN, MLAT 71.3°) of IMAGE network. The characteristics of the preliminary impulse (positive or negative) of primary interest here are not affected by Psc because the X and H components at most of the stations of both IMAGE and Greenland networks are practically free of Psc prior to the onset of SC, as may be seen from Figures 3 and 5.

3.2.3. Dip equatorial region. We have examined the 3 s resolution data of the equatorial magnetometer network stations to assess the longitudinal (local time) pattern in the dip equatorial appearance of PRI. For the SC studied, the stations covered the local time interval from forenoon (Brazil) to near-dusk (India/Sri Lanka). It is pertinent to highlight here that all of the earlier statistical studies of equatorial preliminary reverse impulse (as well as main impulse) pertain to individual stations spread over many SC events [see *Araki*, 1977; *Araki et al.*, 1985; *Rastogi*, 1993 and references therein]. This is the first time that the characteristics of equatorial PRI have been studied for the same event in different longitude sectors. The SC waveforms at the equatorial network stations displayed in Figure 6 exhibit several noteworthy features.

1. At Mokolo (MOK, dip -1.24°) near the magnetic equator in the postnoon (1300 LT) sector, the SC primarily consists of the positive main impulse (MI), and there is no evidence of a sharp preliminary reverse impulse preceding it. The absence of the preliminary reverse impulse is rather unusual because the previous statistical studies consistently showed that the occurrence of equatorial preliminary reverse impulse is a maximum in the postnoon hours at 1300-1400 LT [see *Araki*, 1977; *Araki et al.*, 1985, and references therein]. As already presented, the preliminary reverse impulse is clearly seen at Nurmijarvi, the southernmost station of the IMAGE network, though with a small amplitude of 3 nT. Taken together, these observations suggest a marked reduction in amplitude of the preliminary reverse impulse from subauroral latitudes right down to the dip equator in the afternoon sector, in contrast to the usual pattern of a dip equatorial enhancement. The absence of the preliminary reverse impulse also prevailed at Peradenia (PRD, dip -2.72°) close to dusk (1740 LT) in the Indian zone, where only the positive main impulse is apparent with an amplitude (27 nT) lower than that at Mokolo (42 nT) in the postnoon sector.

2. The preliminary reverse impulse is conspicuous in its appearance very close to the dip equator in the prenoon sector (Brazil), in contrast to the situation obtained in the postnoon and near-dusk sectors. This can clearly be seen from the SC waveform at Alcantara

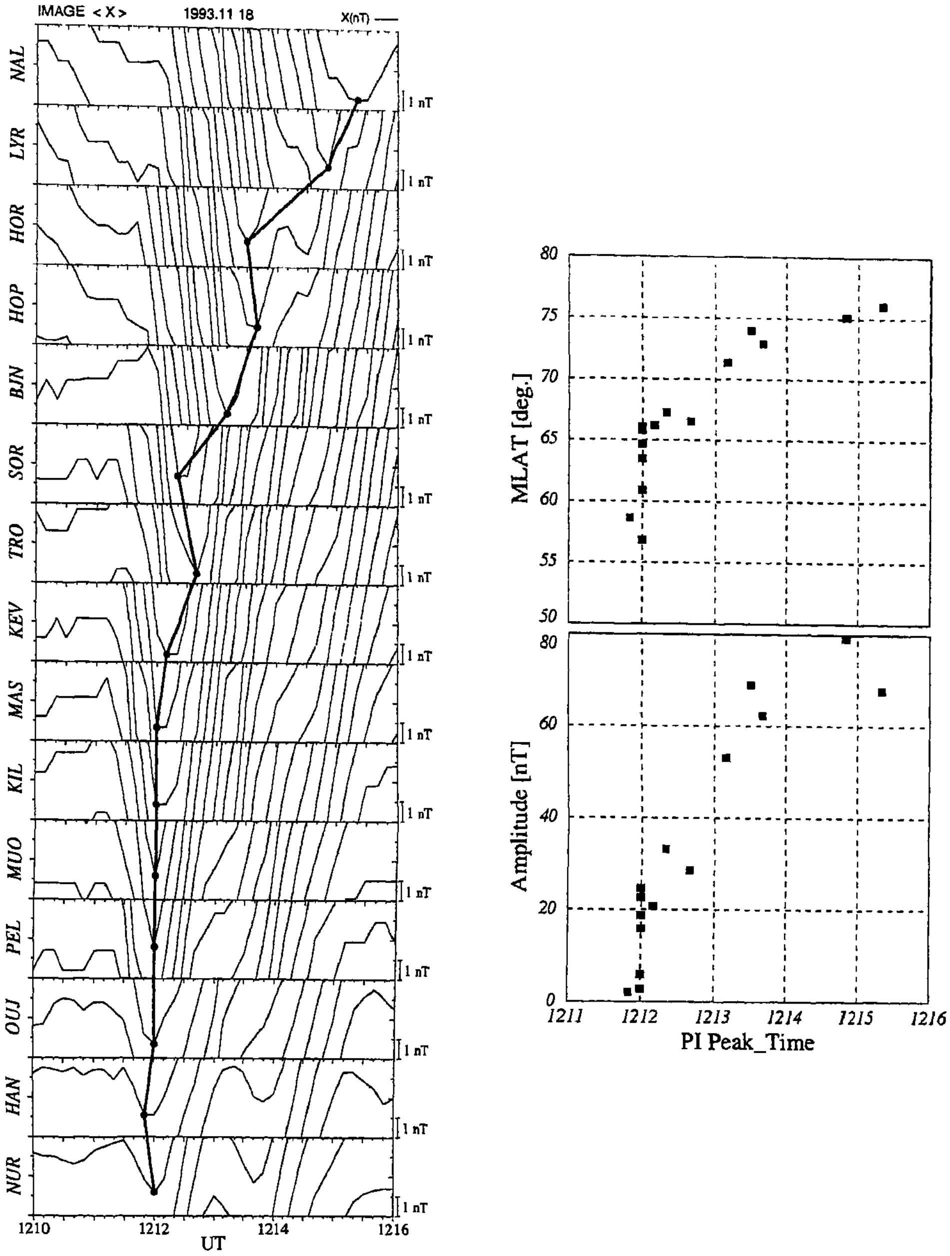

Figure 4. (left panel) Enlarged plot of SC waveform at IMAGE network stations showing the delayed occurrence of the nominal peak of the preliminary reverse impulse (PRI) with increasing latitude over the MLAT range 66°-76°. The data are folded once they exceed the maximum plotting range in the y direction. (right panel) The variation with latitude of the PRI nominal peak time and PRI amplitude with peak time.

(ALC, dip 0.6°). The amplitude of the preliminary reverse impulse (marked by the two vertical dashed lines in Figure 6) is 9 nT at Alcantara. The preliminary reverse impulse in the Brazil sector also exhibited the well-known dip equator enhancement in that it is not seen at Belem (BLM) and Teresina (TER) more or less on the same meridian but away from the magnetic equator with a dip angle in the range 6°-7°. The structure of the SC waveform at these two stations (particularly in comparison to that at Alcantara) suggests that a preliminary reverse impulse may, in fact, be present here but of only a small amplitude to delay the onset of the positive main impulse. The well-known increase of the amplitude of the main impulse close to the dip equator is also apparent in the Brazil sector. The amplitude of the main impulse at Alcantara is higher than that at Belem (Teresina) by a factor of 2.0 (1.7). The dip angle variation of the size of both the preliminary reverse impulse and the main impulse in the Brazil sector is in conformity with earlier studies which showed the rate of equatorial enhancement of the preliminary reverse impulse amplitude to be larger and the latitudinal extent to be narrower when compared to those of MI [see *Araki*, 1977, 1994 and references therein].

3. Though the preliminary reverse impulse did not appear at Mokolo and Peradenia, the time profile of the SC waveform at these locations shows a distinct reduction in the rate of increase of H component coincident with the preliminary reverse impulse at Alcantara in the prenoon sector. This feature suggests that a very weak DP_{pi} field could also be present at Mokolo and Peradenia but is overtaken by the DL field to start with. It is only after the DP_{pi} field intensified that it could oppose the DL field appreciably and inhibit temporarily the development of the main impulse. The inflection or step is better defined at Peradenia than at Mokolo. A schematic picture that explains the inflection feature is shown at the bottom of Figure 6.

Figure 7 shows the temporal variation of F region vertical plasma drift V_z around the time of the SC at Kodaikanal (dip 4.9°) in the near-dusk sector, derived from HF Doppler measurements. It is quite evident that the SC is accompanied by a transient plasma drift disturbance at Kodaikanal. The shaded regions in Figure 7 indicate the intervals prior to and after the SC-related perturbation, while the horizontal lines represent the average values of the upward vertical drift and their standard deviations over the two intervals. The ubiquitous high-frequency fluctuations (period ~1 min) in the vertical plasma drift are a common feature of V_z near the magnetic equator during the evening-night period, though their origin remains unexplored [e.g., *Nair et al.*, 1992; *Sastri*, 1995]. It is well known from incoherent scatter radar measurements at Jicamarca,

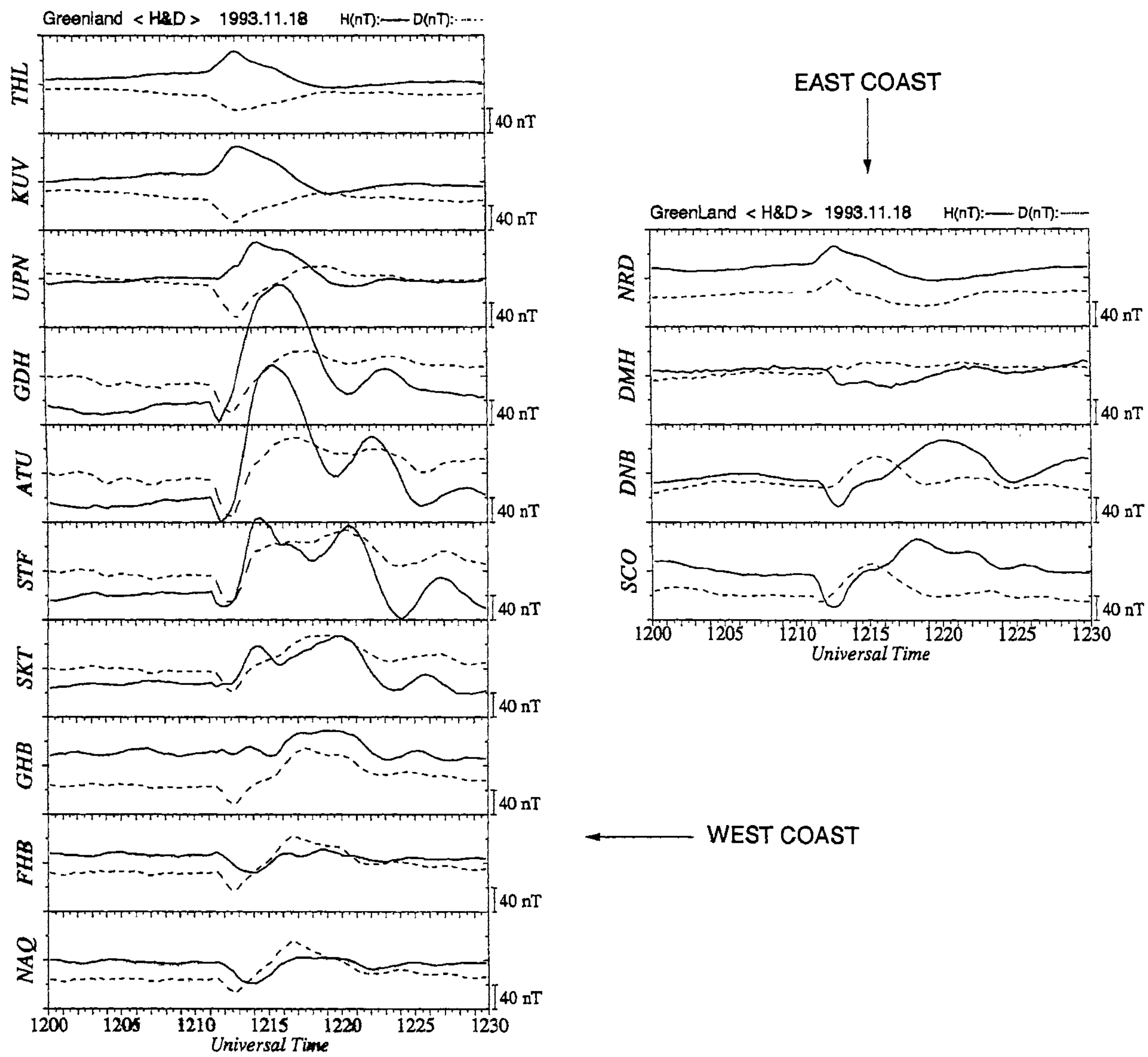

Figure 5. The SC waveform in H (solid line) and D (dashed line) components at stations of the Greenland network.

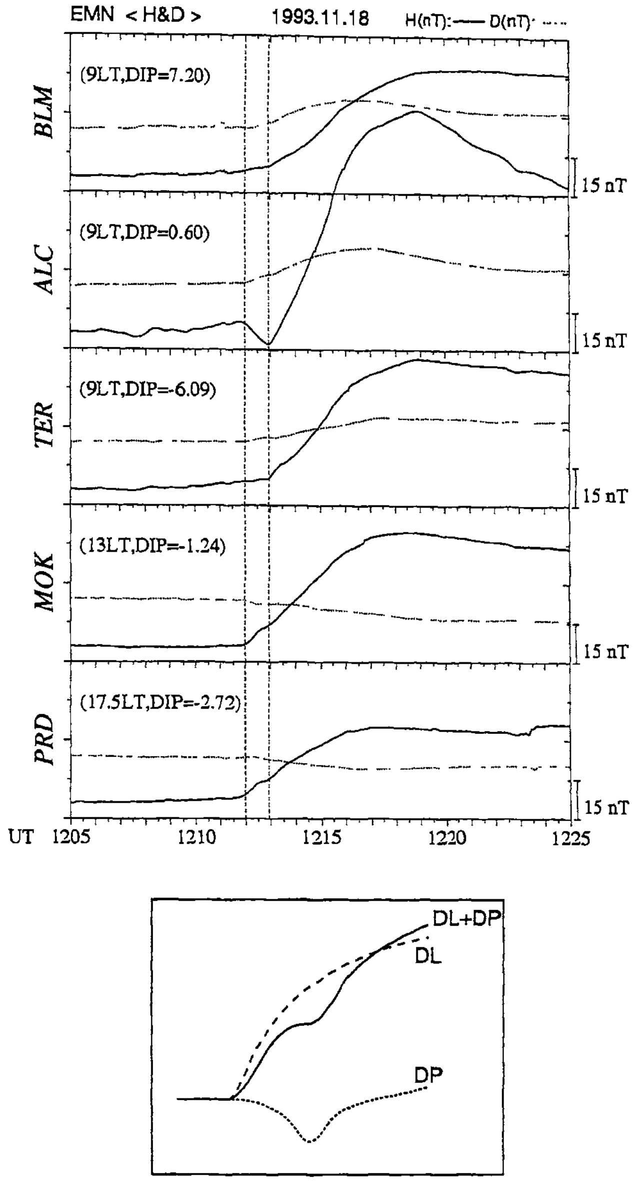

Figure 6. SC waveform at stations of the equatorial magnetometer network (EMN) extending from Brazil to India. The vertical dashed lines mark the preliminary reverse impulse (PRI) of the SC, which is prominently seen only at ALC. A schematic picture at the bottom shows how the inflection at MOK and PRD is produced.

Peru, that the equatorial F region drifts upward in the evening hours because of the eastward electric field of ionospheric dynamo action [see *Fejer,* 1991, and references therein]. The average values of upward V_z before (14.2 m/s) and after (15.9 m/s) the SC thus reflect the normal behavior of F region plasma dynamics in the evening period.

The SC-related drift disturbance is characterized by a decrease in the ambient upward vertical drift (i.e., imposition of a westward electric field) with considerable temporal structure. It is interesting that the sharp reduction in upward vertical plasma drift (segment between the dashed lines marked a and b in Figure 7) occurred in excellent temporal coincidence with the preliminary reverse impulse at Alcantara in the prenoon sector and the step-like inflection in the main impulse at Mokolo and Peradenia in the postnoon and near-dusk sectors, respectively (see Figure 6). On the other hand, a marginally reduced upward drift (relative to pre-SC and post-SC levels) prevailed at Kodaikanal during the main impulse of the SC at the dip equatorial stations. We consider the first component of the drift perturbation (segment ab) to be representative of the combined effects of the westward electric field due to DP_{pri} and DL, while the weaker component that immediately followed (segment bc) is essentially of DL field. Assessment of the relative contributions of DL and DP_{pri} to the first component is difficult because both of the fields are of the same polarity. It should be noted that the data of F region vertical plasma drift presented in Figure 7 refer to a reflection height of 277.5 km. The amplitude of SC-related drift disturbance could have been influenced by the chemical loss effect which comes into play at reflection heights <300 km. The apparent upward vertical drift due to the chemical loss ($= \beta L$, where β is loss coefficient and L is the electron density scale length) masks the decrease in upward drift (segment ab) and aids the increase that immediately followed (segment bc) in the SC-related drift disturbance. Model-dependent corrections for the chemical loss are not made for vertical drift data displayed in Figure 7 because it is essentially a *dc* effect and is unlikely to influence the basic nature of fluctuations with periods <40 min [*Sastri,* 1995] and hence the polarity pattern of the SC-associated perturbation in vertical plasma drift.

There is no indication of the presence of a DP_{mi} field at Kodaikanal because, if it were there, the upward vertical drift would have been much higher during the SC when compared to its pre-SC level. This feature is in line with the prevailing view that the dip equatorial enhancement of the main impulse is generally not as prominent in the evening hours as around midday. We have further checked this point with published data of the Indian magnetometer network that extends over the dip equatorial region and low latitudes. The SC amplitude at Trivandrum (dipole lattitude -0.8°), Hyderabad (dipole latitude 7.6°), Alibag (dipole latitude 9.7°) and Ujjain (dipole latitude 14°) is 24, 28, 26 and 30 nT, respectively (Prompt Reports, Solar-Geophysical Data, World Data Center A (WDC-A), NOAA, Boulder, Colorado). It should be recalled here that the amplitude of the main impulse at Peradenia (dip -2.72°) just south of Trivandrum (see Figure 1 and Table 1) in the Indian zone is 27 nT. These numerical data confirm the absence of a dip equatorial enhancement of the main impulse near the dusk sector, as inferred from the HF Doppler measurements at Kodaikanal. There does not seem to be any significant dip equator enhancement of the main impulse in the postnoon sector as well. The amplitude of the main impulse at Bangui (dipole lati-

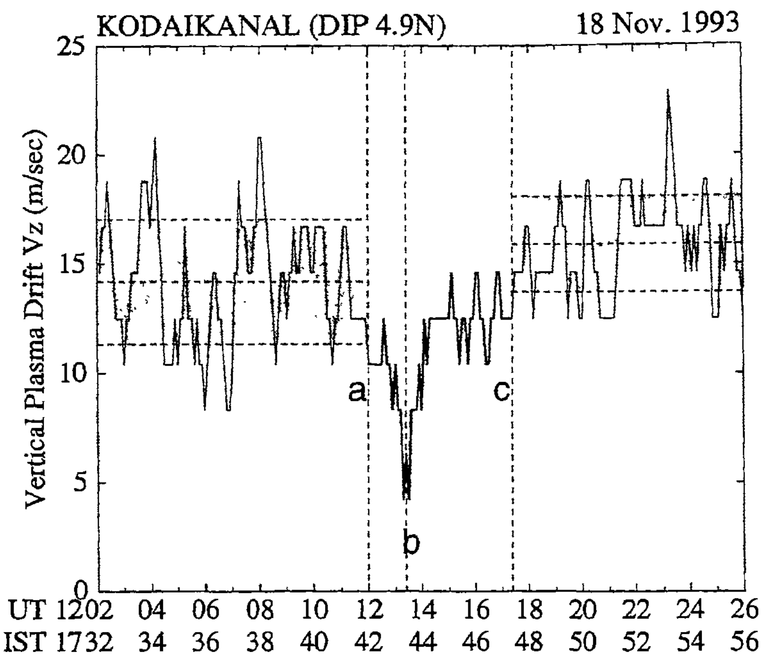

Figure 7. Time variation of F region vertical plasma drift V_z at Kodaikanal (dip 4.9°) in the Indian zone. The vertical lines mark the different segments of the short-lived disturbance in V_z associated with the SC. The average values of V_z and their standard deviations in the intervals prior to and after the disturbance (shaded regions) are indicated by horizontal lines.

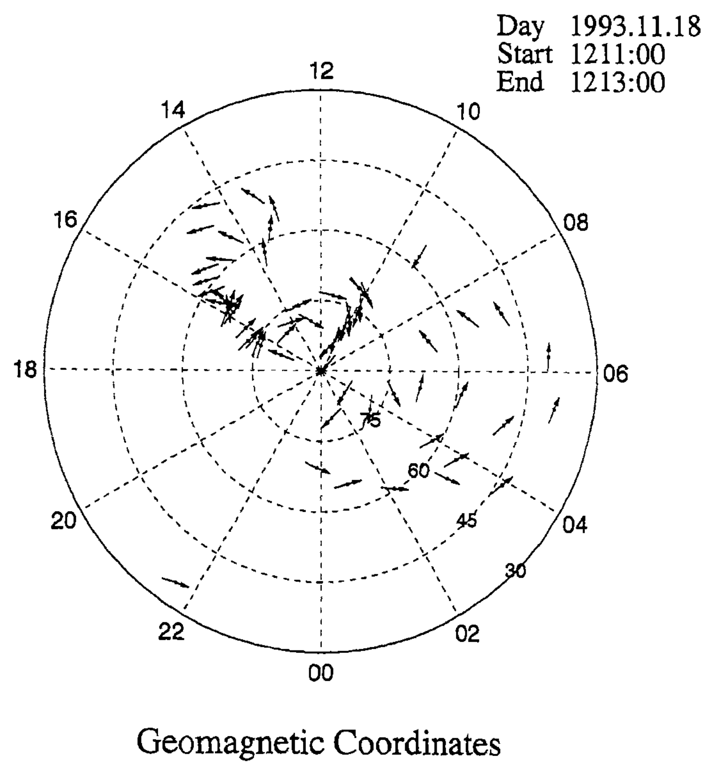

Figure 8. Equivalent current vectors for the preliminary impuse (PI) of the SC on November 18, 1993. Arrows are drawn at the same length to clearly show the high-latitude current vortices.

tude 4.5°) and Tamanrasset (dipole latitude 25.1°) is 34 and 30 nT, respectively, while that at Mokolo near the magnetic equator, more or less on the same meridian, is 42 nT.

3.3. Equivalent Current System of PI

Figure 8 shows the equivalent current vectors corresponding to the preliminary impulse of the SC. The current vectors are derived from the magnetic field variations between 1211 and 1213 UT at the different magnetometer networks, supplemented by 1 min data of standard magnetic observatories archived at WDC for Geomagnetism, Kyoto University. Note that the current vectors are intentionally made equal in length so as to bring out clearly the high-latitude current vortices. The presence of a dominant clockwise vortex at high latitudes on the afternoonside is quite evident in Figure 8. The vortex which extends over 8 hours in magnetic local time (MLT) is centered around 80° MLAT, 1400 MLT. The counterclockwise vortex on the morningside is centered around 70° MLAT, between 0300 and 0500 MLT. The boundaries between the two vortices are around 0900 MLT and 1700-2200 MLT. A clockwise vortex is associated with downward field-aligned currents, and a counterclockwise vortex is associated with upward currents. The field-aligned currents linked to the polar ionosphere are associated with a transverse hydromagnetic wave converted from the compressional mode wave [*Tamao,* 1964; *Araki,* 1977, 1994]. Positive charges accumulate at the center of the clockwise vortex, and negative charges accumulate at the center of the counterclockwise vortex. The electric field resulting from this charge separation is the cause of the preliminary impulse. The complex pattern of the current vectors below 65° MLAT in the afternoon is not unusual because the equivalent current vectors at the low-latitude and midlatitude contain the DL effect, a simple increase in the H component. What is unusual here is the extraordinary swelling of afternoon side vortex and of the high-latitude current source. The location of the focus in the polar region may be due to the abnormally quiet geomagnetic conditions that prevailed prior to the SC and the consequent contraction of polar cap. In the next section, we will present theoretical results bearing on this equivalent current pattern.

4. Discussion and Conclusions

The present study of the SC of November 18, 1993, revealed that the manifestation of the preliminary impulse (PI) of an SC in ground level magnetic field in the dayside dip equatorial region can deviate significantly from the pattern established by earlier statistical studies and currently available models of SC. We have shown that for the SC studied here, the preliminary reverse impulse (PRI) did not appear near the magnetic equator in the postnoon and near-dusk sectors, while it is distinctly seen in the prenoon sector simultaneous with that at high latitudes on the afternoon side. We consider this finding to be an important addition to the empirical knowledge base of SC, because it contrasts with earlier statistical analyses which show the diurnal variation of occurrence frequency of the preliminary reverse impulse to be a maximum around noon.

A number of researchers have calculated the characteristics of the steady state global current system for specific models of source currents at high latitudes and ionospheric conductivity distribution for comparison with ground level observations of SC, especially at low and equatorial latitudes [e.g., *Tsunomura and Araki,* 1984; *Yamada et al.,* 1997; *Tsunomura,* 1998, 1999]. On the basis of the SC model proposed by *Araki* [1977], *Osada* [1992] calculated the DP variation on the ground produced by a pair of time-varying field-aligned currents (symmetric about noon) flowing into and out of the polar ionosphere and synthesized the H component variation of SC by adding to it the stepwise increase due to the DL field. The result, which is referred to in Figure 15 of *Araki* [1994], shows that an equatorial preliminary reverse impulse appears clearly at 1000 LT, but the total H field shows almost monotonic increase at other local times along the equator. This local time dependence of the SC waveform along the magnetic equator, which is assessed as being due to the combined effect of the field-aligned currents (FAC) and the ionospheric current produced by the FAC, is broadly consistent with the observations of the SC of November 18, 1993, described here. We have, nevertheless, done similar theoretical calculations to examine in general the effect of an azimuthal shift to the morningside of the high-latitude current sources (see Figure 8 for the equivalent current system of the preliminary impulse) on the ground level magnetic fields at high and low latitudes. It is appropriate to emphasize here that the theoretical calculations are not event-specific, although we do assess whether the theoretical simulations would be able to explain some, if not all, of the characteristics of the SC of November 18, 1993. The computational procedure is the same as that described by *Tsunomura* [1999], including the modification of ionospheric conductivity in the vicinity of the dip equator due to the meridional current system driven by the zonal component of the external electric field. Calculations are done for a pair of field-aligned currents at 80° latitude with centers at 1300 and 0300 LT. Other model inputs are the same as those of *Tsunomura* [1999]. The calculation is repeated for field-aligned currents at 75° latitude to ascertain the effect of the latitudinal shift of the high-latitude current source on the global ionospheric current distribution. Here, the comparison is made by setting the maximum current density of the field-aligned currents equal for both of the calculations. This means that the term j_0 in the functional form of the field-aligned currents as given in equation (8) of *Tsunomura* [1999] is kept constant, while the center colatitude θ_0 is changed from 10 to 15. Earth induction effects are not considered.

Figure 9 shows the local time (LT) variation of the H component and the eastward component of the electric field (E_y) at 76° and 66° and the magnetic equator. The LT variations of the parameters are shown separately for source currents at 80° and 75°. It can be seen that at locations equatorward of the current source, the amplitude of the negative H field perturbation during daytime is lower for the source at 80° than at 75°. For example, at the magnetic equator the amplitude is reduced by about 50% at 0900 LT when the source is shifted from 75° to 80°. The LT pattern of the H field, however, remains more or less the same. This indicates that the amplitude of the preliminary reverse impulse in the H component near the dayside dip equator is sensitive to the latitudinal position of the causative field-aligned currents in the polar region. For the current source at 80°, which is appropriate for the SC event studied here (see Figure 8), the H field decrease at the magnetic equator is highly asymmetric about noon with a sharp maximum around 0900 LT, and the perturbation assumes positive values from 1500 LT onward. A similar pattern is seen in E_y. At high latitudes the H field decrease during the daytime (till 1500 LT) increases in general from subauroral to polar latitudes. This trend can be seen in the local time variation of H field perturbation at 76° and 66° shown in Figure 9.

Let us now compare the theoretical simulations with the SC observations, keeping in mind that the latter represents the combined effects of DP_{pi} and DL fields in the initial phase of the event. The simulated amplitude of H field perturbation at the magnetic equator at 0900, 1300, and 1730 LT is -27, -6 and 4 nT, respectively (see Figure 9). Since it is not possible to estimate the DL field owing to lack of data of the interplanetary shock, we follow a simple but logical procedure to infer the same and attempt the comparison. As may be seen from Figure 6 at Mokolo in the afternoon sector (1300 LT), the preliminary reverse impulse is not seen, but the H field increased by 6 nT during the interval of the preliminary reverse impulse at Alcantara. This implies that the DL field is 12 nT so as to overcome the preliminary reverse impulse and still result in the observed increase of 6 nT. If we assume the DL field

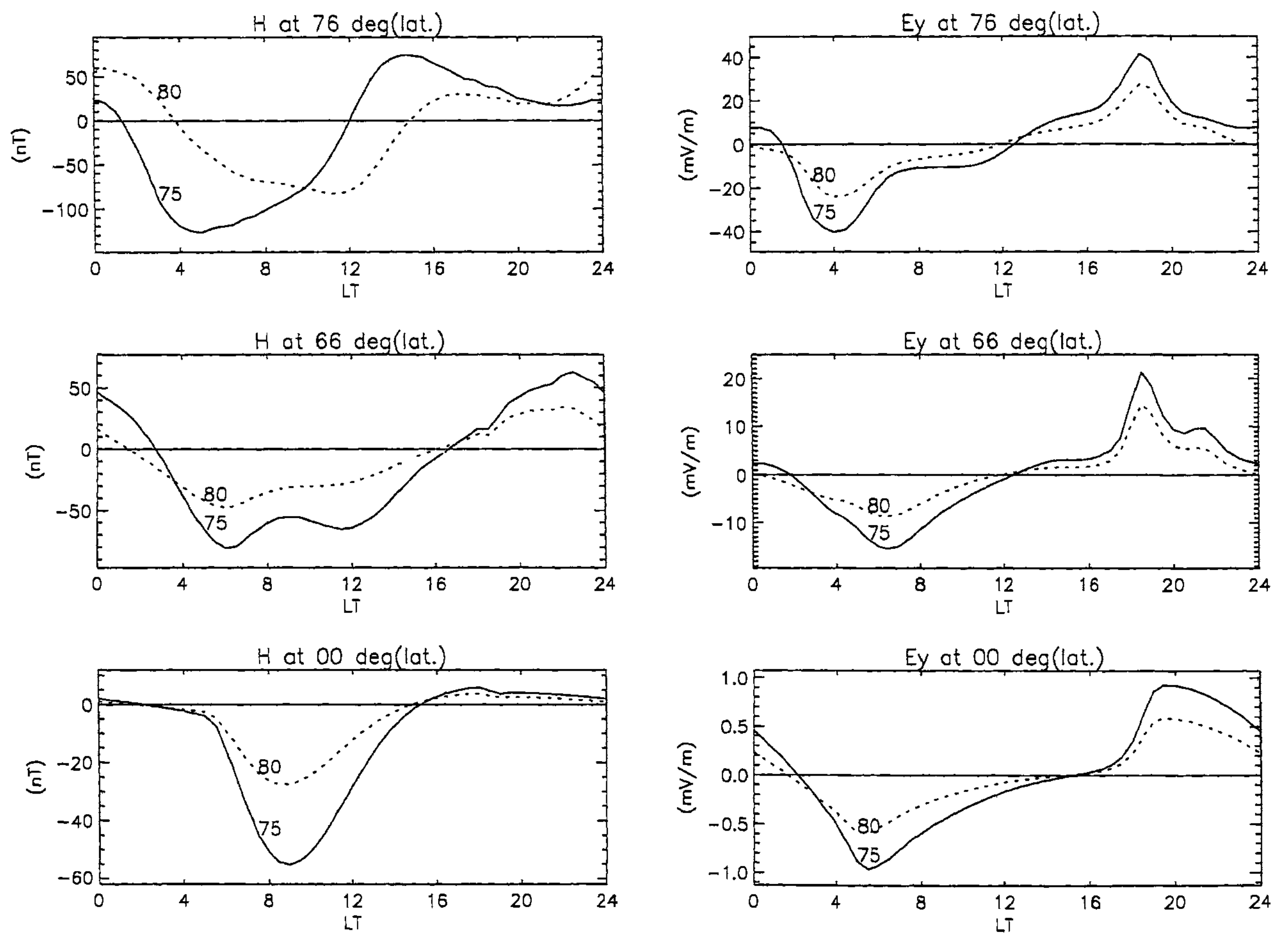

Figure 9. Local time variation of the H component of geomagnetic field and the eastward component E_y of ionospheric electric field at 76° and 66° and the magnetic equator for source currents at 75° and 80° and shifted to the morningside (centers at 1300 and 0300 LT).

to be local time invariant, then the amplitude expected at 0900 LT of the preliminary reverse impulse is 15 nT. This is higher than the value of 9 nT observed at Alcantara (0900 LT), but the agreement improves if we consider the fact that Alcantara is not on the magnetic equator but just away from it. Extension of the logic to the near-dusk sector, however, leads to a major discrepancy between theory and observations. As may be seen from Figure 9, the simulated H field perturbation at the near-dusk (1730 LT) dip equator is 4 nT, and that in E_y is 0.4 mV/m. The initial change in the H field there is therefore to be an increase of 16 nT due to the additive effects of the DL and DP_{pi} fields, while the observations at Peradenia show an increase of only 6 nT. The disagreement persists even if allowance is made for the off-equator location of Peradenia (dip -2.7°). The HF Doppler radar observations at Kodaikanal substantiate this discrepancy because they show the polarity of the SC-related electric field disturbance to be essentially westward. To state more explicitly, there is no evidence at Kodaikanal for the short-lived (about 1 min duration) eastward electric field (0.4 mV/m) of the preliminary impulse predicted by the simulation (see Figures 7 and 9). As already mentioned, the negative DP_{pi} field could also be present near the duskside equator with an amplitude at least the same as at Mokolo (see Figure 6).

The characteristics of the preliminary reverse impulse at high latitudes on the afternoonside predicted by the simulation are consistent in general with the observations at the IMAGE network stations, including the increase of amplitude from auroral to polar regions. The simulated amplitudes of the preliminary reverse impulse at 1300 LT at 56°, 66°, and 76° are 7, 21, and 59 nT, respectively. These agree reasonably well with the corresponding observed values of 3, 21, and 68 nT. Conceptually, the increase of the amplitude of the preliminary reverse impulse from auroral to polar latitudes reflects the decreasing influence of the DL field in opposing the reverse impulse with increase of latitude. Since the theoretical simulation attempted here concerns the steady state (time-independent) current system, we could not probe the origin of the other important aspect of the preliminary reverse impulse (PRI) observed at high latitudes, namely, the systematic delay in appearance of its nominal peak from auroral to polar latitudes on the afternoonside (Figure 4).

To sum up, we find that the stationary ionospheric current system driven by a pair of field-aligned currents (FACs) at 80° with a morningside rotation (current centers at 1300 and 0300 LT) is able to explain broadly the characteristics of the preliminary impulse of the SC on November 18, 1993, observed near the dayside magnetic equator and postnoon subauroral-polar regions. A major and enigmatic discrepancy between theory and observations nevertheless remains concerning the polarity of the preliminary impulse near the dusk magnetic equator. The more basic question as to the cause of the morningside rotation of the field-aligned currents could not be addressed owing to lack of data of the interplanetary shock responsible for the SC. The impact of the interplanetary shock from the morningside may produce such an azimuthal shift of the current system, and recent studies provide evidence that such shock impacts away from the noon-midnight line could indeed occur [*Blake et al.*, 1992; *Takeuchi et al.*, 2000]. Further work is required to learn more of this physical situation and its effects as regards the response of magnetic field within the magnetospheric cavity, including that at the Earth's surface studied here.

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