Penetration electric fields at the nightside dip equator associated with the main impulse of the storm sudden commencement of 8 July 1991

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[1] The geomagnetic storm sudden commencement (ssc) of 8 July 1991 was reported [*Wilson et al.*, 2001] to be characterized by a reduction (enhancement) of *X* component at midlatitudes in the noon (midnight) sector in the 1-hour period after its start at 1636 UT. This distinctive feature is seen even after accounting for the effects of the Chapman-Ferraro current by subtracting the step-like increase of *X*/*H* component at low-latitude stations on the same magnetic meridian from the midlatitude data. We present evidence to show that over the same 1-hour period after the start of the ssc on 8 July 1991 an eastward electric field disturbance (peak value ≈1.2 mV/m) grew up and decayed at the premidnight dip equator. The eastward electric field evidenced at the nightside dip equator is interpreted as the signature of the penetration of the dawn-to-dusk electric field associated with an enhancement of region 1 field-aligned currents (FACs) driven by the solar wind. The negative disturbance in the *H*/*X* component at midlatitudes in the noon sector is explained as the magnetic effect of FACs that carry the large-scale electric fields from the magnetosphere to the polar ionosphere as well as the disturbance of polar origin-type 2 ionospheric currents excited by the large-scale electric field. *INDEX TERMS:* 2411 Ionosphere: Electric fields (2712); 2409 Ionosphere: Current systems (2708); 2415 Ionosphere: Equatorial ionosphere; 2431 Ionosphere: Ionosphere/magnetosphere interactions (2736); *KEYWORDS:* storm sudden commencement (ssc), ssc models, penetration electric fields, field-aligned currents, ionospheric current system, midlatitude and equatorial effects

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1. Introduction

[2] Recently, *Wilson et al.* [2001] presented the salient and important aspects of global electrodynamics during the severe magnetic storm of 8–9 July 1991 and discussed their implications to issues concerning solar wind-magnetosphere-ionosphere coupling. Measurements of energetic particle fluxes, electric fields, and plasma densities with instruments aboard well-positioned satellites in the interplanetary medium, magnetosphere, and the topside ionosphere as well as data of numerous ground-based magnetometers spread around the world were used to characterize the storm time evolution of the global currents and electric fields and their effects on the stability of equatorial *F* region plasma. We will summarize in the following the distinctive features of the geomagnetic storm sudden commencement (ssc), especially the physical situation over the ≈1-hour period thereafter corresponding to the main impulse (mi) of the ssc and the initial phase of the magnetic storm as they are of direct relevance to the present work.

[3] An interplanetary shock impacted the Earth's magnetosphere and led to a storm sudden commencement (ssc) at 1636 UT on 8 July 1991 and the associated compression pushed the magnetopause earthward of the geosynchronous orbit for the next 3 hours. The global pattern of the ground level geomagnetic field variation for an hour from the start of the ssc exhibited interesting features, and this is the focus of the present paper. A sudden magnetospheric compression produces a step-like increase of ground level magnetic field due to the Chapman-Ferraro currents in the magnetopause [*Araki*, 1977, 1994, and references therein]. The ssc of 8 July 1991 is no exception, and it indeed manifested as a sharp positive deflection in *X* component ($X = H \cos D$) at low- and middle-latitude stations all over the globe except at midlatitudes in the forenoon (North American) sector, where it was seen as a conspicuous negative deflection in *X* component. This feature can be seen from Figure 1 which shows the variation of ΔH at a pair of low- and middle-latitude stations in the noon sector (San Juan (SJG) MLAT 29.4°, MLONG 5.2°; Fredricksburg (FRD) MLAT 49.1°, MLONG 352.2°) and midnight sector (Kakioka (KAK) MLAT 26.6°, MLONG 207.8°; Memambetsu (MEM) MLAT 34.6°, MLONG 210.2°), for the interval 1600–1830 UT on 8 July 1991. Note that the ΔH values shown are relative to the value at 1636 UT, the time of ssc. It is quite evident that at Fredricksburg the ssc waveform was a negative deflection in *H* component, while it was a positive

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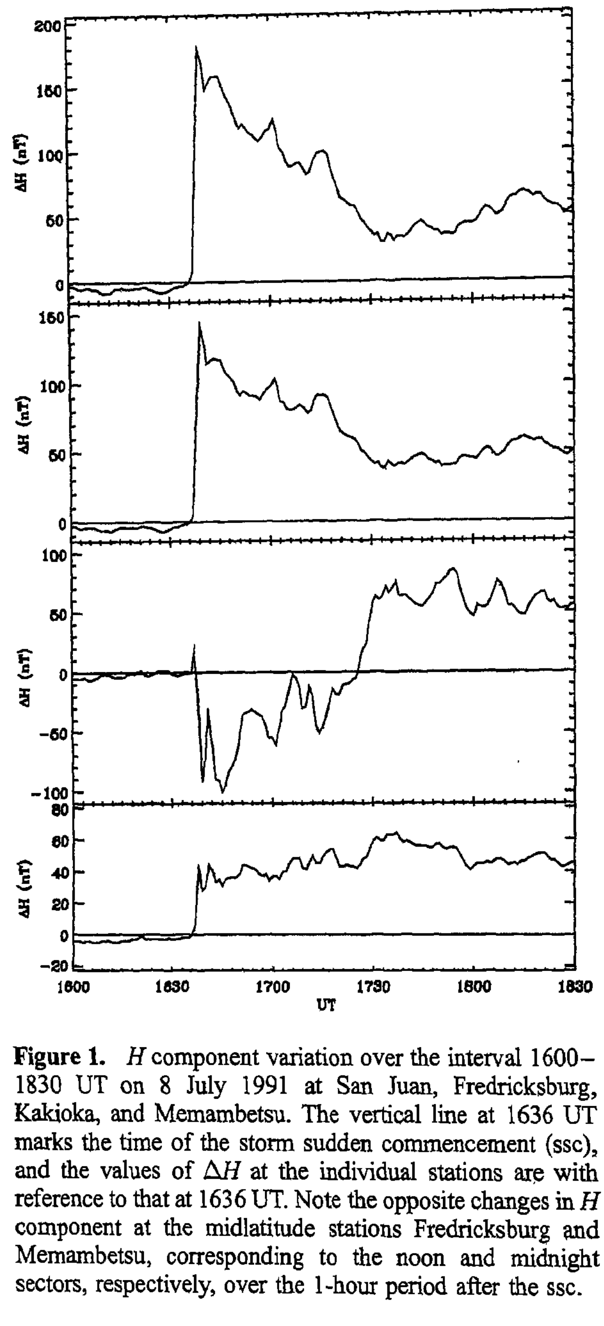


Figure 1. H component variation over the interval 1600–1830 UT on 8 July 1991 at San Juan, Fredricksburg, Kakioka, and Memambetsu. The vertical line at 1636 UT marks the time of the storm sudden commencement (ssc), and the values of ΔH at the individual stations are with reference to that at 1636 UT. Note the opposite changes in H component at the midlatitude stations Fredricksburg and Memambetsu, corresponding to the noon and midnight sectors, respectively, over the 1-hour period after the ssc.

deflection at Memambetsu in the midnight sector. The ssc was a conventional step-like positive change in H component at the lower-latitude stations San Juan and Kakioka in the noon and midnight sectors, respectively. The amplitude of ssc is, however, higher at Kakioka compared to San Juan and we shall return to this observation latter in the paper.

[4] The other noteworthy aspect of the ssc is the similarity, in the first hour after the ssc, of ground level magnetic variations at stations on the nightside (covering the MLAT range 4.6°–61.6°) with the AE index and the in-phase variations in AL and AU indices themselves such that they are mirror images of one another [see *Wilson et al.*, 2001, Figures 1 and 5]. *Wilson et al.* [2001] presented evidence to show that these variations in AU and AL correspond to the excitation of a disturbance of polar origin-type 2 (DP-2) rather than a disturbance of polar origin-type 1 current system and the magnetic field changes at high latitude stations on the nightside like Tixie Bay (MLAT 61.6°) are due to rapid increase in ionospheric conductivity brought about by enhanced rate of energetic electron production. These and other observations in the ≈1-hour period after the ssc were interpreted by *Wilson et al.* [2001] as the effects of an enhancement of the large-scale region 1 current system driven by the solar wind (before region 2 shielding currents developed), with an additional contribution from some DP-2 currents. They have relied on the simulation results of *Nopper and Carovillano* [1978] in support of the interpretation. These show that during periods of ineffective shielding (no region 2 currents), the global convection associated with region 1 currents would extend to the equator with stronger electric fields on the nightside than on the dayside, and with an eastward electric field in the premidnight (1800–2400 LT) hours [see *Nopper and Carovillano*, 1978, Figure 1].

[5] We have studied earlier the response of the nightside equatorial zonal electric field to the preliminary impulse (pi) of sscs including the one on 8 July 1991 using F region vertical plasma drift at the dip equatorial station Kodaikanal [*Sastri et al.*, 1993]. The results substantiated the view that the polar electric field responsible for the preliminary impulse of the ssc is transmitted instantaneously to the dip equator on the nightside as on the dayside. The aim of this report is to present the results of a further study of the ssc of 8 July 1991 focusing on the behavior of the equatorial zonal electric field in the ≈1-hour period after the ssc, which has a direct bearing on the work of *Wilson et al.* [2001] mentioned above. We present evidence to show that an eastward electric field disturbance also prevailed at the nightside dip equator over the ≈1-hour period after the ssc and that it grew up and decayed in step with the H component variations of opposite polarity at midlatitudes near the noon and midnight meridians discussed above (Figure 1). This observation confirms the inference of *Wilson et al.* [2001] that penetration electric fields of eastward polarity might have been present at the duskside magnetic equator and contributed to the growth rate of equatorial plasma bubbles (EPB) detected by DMSP 10 satellite in the evening MLT sector after the ssc (at 1754 UT, 30°E). We shall also discuss the geomagnetic and ionospheric electric field observations in the 1-hour period after the ssc within the framework of the physical model of ssc due to *Araki* [1977, 1994] and the recent theoretical results of the low- and middle-latitude geomagnetic effects of field-aligned currents (FACs) that couple the magnetospheric electric fields to the polar regions [*Tsunomura*, 1998, 1999; *Kikuchi et al.*, 2001; *Sastri et al.*, 2001].

2. Observations

[6] We have studied the continuous measurements of the Doppler velocity, V_d (time rate of change of phase path) of ionospheric reflections at normal incidence with the HF phase path sounder at Kodaikanal ~10.2°N; 77.5°E; dip 3°N). The details of the experimental set up were published elsewhere [*Sastri et al.*, 1985]. The Doppler velocity measurements that were made on a probing frequency of 4 MHz correspond to the bottomside F region during nighttime

conditions and represent the F region vertical plasma motion due to $\mathbf{E} \times \mathbf{B}$ drift, with a minor contribution from chemical loss when the reflection height is <300 km. Ionograms from a co-located ionosonde at Kodaikanal showed that on 8 July 1991, the altitude of bottomside F region ($h'F$) remained above 350 km before and well after the ssc at 1636 UT [see *Sastri et al.*, 1993, Figure 3]. The same F region height condition was evidenced on 6 July 1991, the nearest of the ten international quiet days of the month with $A_p = 8$ and $\Sigma K_p = 15^+$ that is taken as the reference quiet day. Doppler velocity (V_d) measurements on these two nights therefore represent essentially the F region vertical plasma drift V_z ($V_d/2$) due to the zonal electric field.

[7] Figure 2 (top panel) shows the time variation at 1-min resolution of F region V_z over Kodaikanal for the interval 1600–1830 UT on 8 July 1991 and on 6 July 1991 (reference quiet day). Also shown at the same time resolution are the variations of the H component at the middle latitude stations Fredricksburg (FRD) and Memambetsu (MEM), which were in the noon and midnight sectors, respectively, over the time interval mentioned. The ssc waveform at ground level is known to represent the combined effects of the current systems of the magnetosphere-ionosphere circuit, namely, the Chapman-Ferraro (C-F) currents, field-aligned currents (FACs), and ionospheric currents as well as currents induced in the Earth [*Araki*, 1977, 1994]. The effect of Chapman-Ferraro currents alone is best seen at low latitudes for which reason the low-latitude geomagnetic data are used to establish the quantitative relationship between the change in upstream solar wind dynamic pressure and the ground level H component response [*Russell et al.*, 1992, 1994; *Araki et al.*, 1993]. We have therefore taken the ssc waveform at the low-latitude station San Juan as representing entirely the C-F current and subtracted it from that at Fredricksburg and Memambetsu to ascertain the contribution of other current sources. The residual H component variations at Fredricksburg and Memambetsu (MEM1) are the ones presented in Figure 2 (middle panel). This procedure was also adopted by *Wilson et al.* [2001] for the ssc event under discussion here (see Figure 10 of their paper) and also by *Kikuchi et al.* [2001] in their study of the origin of the preliminary positive impulse (ppi) of ssc at midlatitudes. MEM2 in Figure 2 represents the residual H component variation at Memambetsu when the ssc waveform at the low-latitude station Kakioka on the same magnetic meridian as Memambetsu is subtracted. This is felt to give a better picture of the nightside physical situation. Normally, the effect of Chapman-Ferraro current will be larger on the dayside than on the nightside a few minutes after the compressional MHD waves propagated through the magnetosphere. However, in the ssc event of 8 July 1991, the amplitude of the step-like increase in H component is larger at Kakioka than at San Juan by a factor of $\approx$3.3 (Figure 1) implying that the H component not only at Fredricksburg but also at San Juan is affected by current sources besides the Chapman-Ferraro currents.

[8] Prior to the ssc on 8 July 1991, the F region vertical plasma drift V_z over Kodaikanal was downward with a magnitude around 21 m/s, and this is consistent with the established nighttime pattern of F region vertical drift at and close to the dip equator [see *Fejer*, 1991, and references therein]. The onset of the ssc at 1636 UT (2206 IST) is just preceded by an abrupt cessation of the ambient downward drift and immediately followed by enhanced downward drift for 2–3 min as may be seen from Figure 2 (top panel). We have already studied in detail the transient response of equatorial F region vertical plasma drift V_z to this ssc event

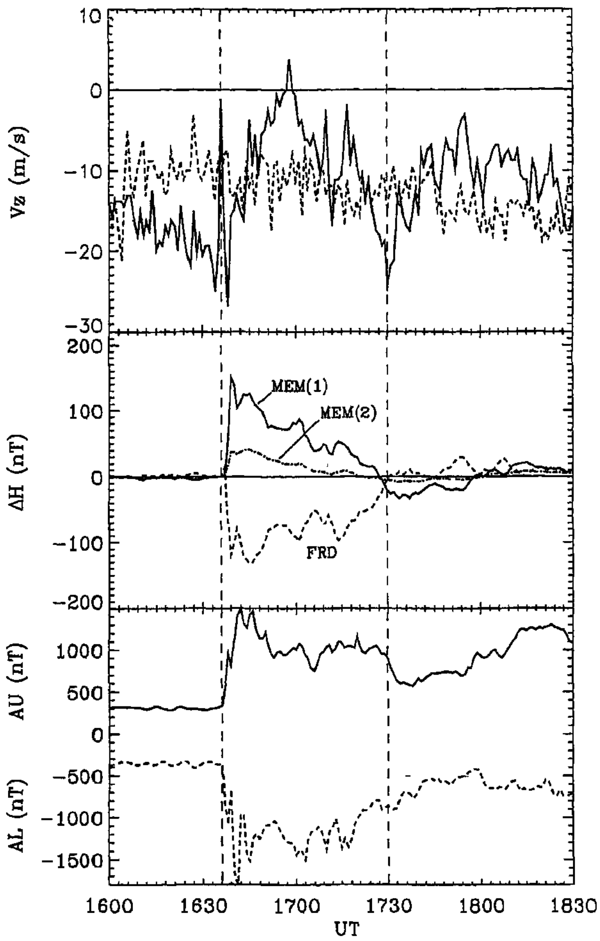


Figure 2. Temporal profile for the period 1600–1830 UT on 8 July 1991 of (top) F region vertical plasma drift, V_z over Kodaikanal (dip 3°N); (middle) ΔH at Fredricksburg and Memambetsu; and (bottom) AU and AL indices. ΔH values at Fredricksburg (FRD) and Memambetsu (MEM1) were obtained by subtracting the corresponding values at the dayside low-latitude station San Juan that are taken to represent entirely the effects of Chapman-Ferraro current (D_L field). MEM2 represents the ΔH profile at Memambetsu when the data of the low-latitude station Kakioka on the same magnetic meridian as Memambetsu were subtracted. Note the reduction and subsequent recovery of the downward plasma drift over the $\approx$1-hour period 1639–1730 UT on 8 July 1991 (when oppositely directed ΔH variations are seen at Fredricksburg and Memambetsu as well as in AU and AL indices) and the absence of a such a long-period (1-hour) disturbance in Vz on 6 July 1991 (dashed curve), the reference quiet day ($A_p = 8$ and $\Sigma K_p = 15^+$). The sharp and short-lived (1-min) cessation of downward plasma drift around 1634 UT is associated with the preliminary impulse (pi) of the ssc (see *Sastri et al.* [1993] for details).

at high time resolution and discussed its implications to the physics of sscs [*Sastri et al.*, 1993]. The focus here is on the slower changes in F region V_z spanning the ≈1-hour interval after the start of the ssc. It is quite evident from Figure 2 that starting from 1638 UT, the downward plasma drift slowly decayed to become weakly upward around 1657 UT and then recovered back to being strongly downward by ≈1730 UT. This F region vertical drift disturbance (peak amplitude ≈31 m/s), which lasted for about 1-hour signifies the growth and decay of an eastward electric field disturbance after the ssc with a peak amplitude of ≈1.2 mV/m. That the F region vertical drift at dip equatorial locations like Kodaikanal undergoes quasiperiodic fluctuations over a wide range of timescales from a few minutes to a few hours is well known [e.g., *Earle and Kelley*, 1987; *Nair et al.*, 1992; *Sastri*, 1995]. Magnetospheric electric fields and atmospheric waves are identified as the most likely sources of the longer-period (1–10 hour) segment of the V_z fluctuations, and the commonly occurring medium-scale gravity waves are generally considered as responsible for the shorter-period (<1 hour) variations. Our recent statistical study of the characteristics of short-period (5–33 min) variations in V_z at Kodaikanal for the period sunset-midnight supported the prevailing understanding in terms of medium-scale gravity waves [*Sastri*, 1995]. We have carefully examined the V_z database available for the quiet days of the month to assess whether the vertical drift disturbance on 8 July 1991 can be distinguished form the commonly present fluctuations. We have not found any clear cut waxing and waning of V_z over a 1-hour period in the interval 1600–1830 UT on the quiet days, although shorter periods (<30 min) are present on all the days as is usually the case. This behavior can clearly be seen form the time variation of V_z at Kodaikanal on 6 July 1991 (the reference quiet day) presented as a dashed curve in the top panel of Figure 2. The differences in temporal variability of V_z on 8 July and 6 July 1991 testifies to the inference that the 1-hour long disturbance in V_z beginning with the ssc at 1636 UT on 8 July 1991 is unique to that day and is thus related to the ssc.

[9] It is quite interesting that the electric field disturbance at Kodaikanal manifested more or less over the same interval (marked by the two dashed vertical lines in Figure 2) of the magnetic disturbances (after subtracting the contribution of Chapman-Ferraro currents) of opposite polarity at Fredricksburg (FRD) and Memambetsu (MEM1/MEM2). Note that, however, the temporal relationship between F region V_z over Kodaikanal and ΔH at Fredricksburg and Memambetsu is not perfect on finer timescales. This could partly be due to the fact that unlike ΔH, the temporal profile of V_z also reflects the contribution of the westward electric field (downward drift) associated with the Chapman-Ferraro current at least initially.

[10] A noteworthy aspect of the ΔH pattern at Memambetsu in Figure 2 is the reduced amplitude of the magnetic disturbance (MEM2) when the effect of Chapman-Ferraro current is taken to be represented by the ssc waveform at the nightside low-latitude station Kakioka instead of the dayside station San Juan. This indicates that the magnetic disturbance at midlatitude in the noon sector (at Fredricksburg) is not only negative but also of larger amplitude compared to the positive perturbation in the midnight sector (at Memambetsu), when referenced to the ssc waveform at a low-latitude station on the respective meridians. The near equal magnitude (≈140 nT) of the magnetic disturbances at midlatitudes near noon (Fredricksburg) and midnight (Memambetsu) emphasized by *Wilson et al.* [2001] is because of the fact that San Juan, unlike Kakioka, was affected not only by Chapman-Ferraro currents but also by other currents as mentioned earlier (see Figure 1).

3. Discussion and Conclusions

[11] The ground level ssc waveform shows a complex dependence on latitude and local time reflecting the effects of multiple current systems that develop in the magnetosphere-ionosphere system as a result of sudden magnetospheric compression. According to the model of *Araki* [1977, 1994], the ssc typically consists of two successive pulses of opposite polarity, namely, the preliminary impulse (pi) and the main impulse (mi) that arise because of different physical processes and their effects. The fundamental effect of magnetospheric compression is an enhancement of Chapman-Ferraro current on the magnetopause resulting in a step-like increase of northward H component that predominates at low latitudes, that is refereed to as the DL (L stands for low latitudes) component of ssc. Chronologically, the first effect seen in the ssc waveform is the preliminary impulse (pi), which is due to the imposition of a dusk-to-dawn electric field on the polar ionosphere by field-aligned currents (FACs) that are inward on the duskside and outward on the dawnside [*Slinker et al.*, 1999; *Moretto et al.*, 2000]. The FACs are driven into the high-latitude ionosphere by shear Alfven waves generated due to magnetospheric inhomogeneities. The large-scale electric field propagates to the dip equator as an electromagnetic wave in the Earth-ionosphere waveguide and excites a twin-vortex DP-2 type ionospheric current system consisting of Hall and Pedersen currents [*Kikuchi et al.*, 1978; *Kikuchi and Araki*, 1979]. This component of ssc is termed as DP_{pi} and is considered responsible for the preliminary impulse of ssc*, i.e., ssc with a preliminary reverse impulse (pri) at high latitudes on the afternoon side and at the dayside dip equator. The preliminary impulse of ssc is thus exclusively due to electric fields and currents of polar origin. The DL field mentioned above is the second effect in the time domain as it manifests at low latitudes with a delay of about a minute with reference to the preliminary impulse at high latitudes which, as already mentioned, is due to the dusk-to-dawn electric field imposed on the polar ionosphere [*Kikuchi*, 1986].

[12] The third effect comes into play a few minutes after the compression is completed by the interplanetary shock and in the form of enhanced magnetospheric convection if the ram pressure is kept high behind the interplanetary shock [*Araki*, 1977, 1994]. The FACs associated with this process carry a dawn-to-dusk electric field to the polar ionosphere [*Slinker et al.*, 1999], and the outcome is the same as for the preliminary impulse but of opposite polarity. This component of ssc disturbance field termed DP_{mi} contributes to the large amplitude of the main impulse (mi) at auroral latitudes and at the dayside magnetic equator. The main impulse therefore receives contributions from both DL and DP fields, with the former generally playing a dominant role in the initial part of the main impulse. The generation in quick succession of transient current systems in the magneto-

sphere-ionosphere domains and their characteristics (strength and spatial distribution) thus determine the global pattern of the ground level ssc waveform in any given event.

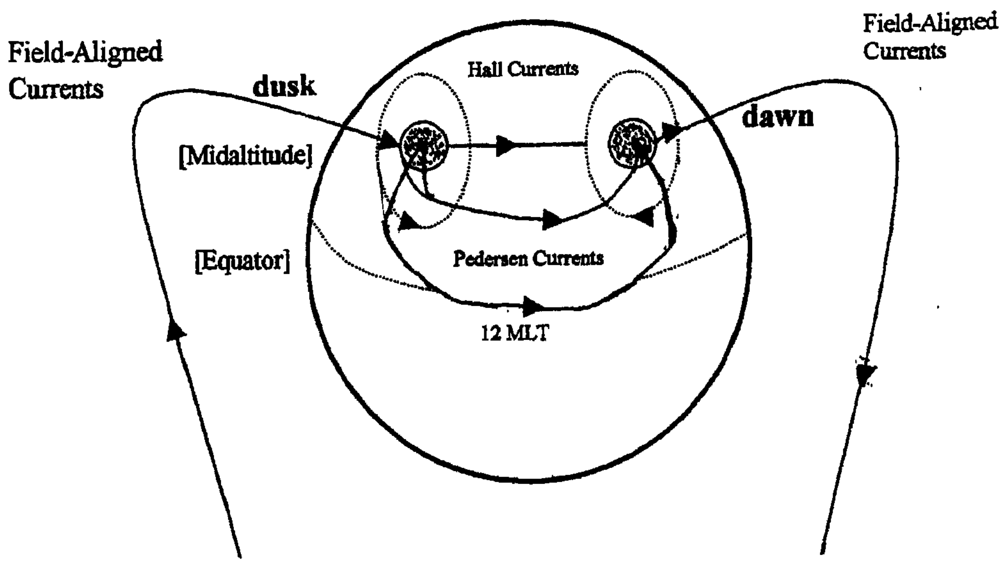
[13] Let us consider now the ionospheric and geomagnetic observations of the ssc of 8 July 1991 presented in the previous section. As we discussed earlier [*Sastri et al.*, 1993], the sudden decrease of the ambient downward drift for about a minute (indicative of a transient eastward electric field) at Kodaikanal just prior to the ssc finds an interpretation in terms of the low-latitude penetration of the dusk-to-dawn electric field responsible for the preliminary impulse of the ssc. This ssc was indeed found to possess a preliminary impulse and hence was labeled ssc* by 16 out of the 27 geomagnetic observatories that reported the event (Solar-Geophysical Data, vol. 571, part I, p. 148, 1992). The downward plasma drift (westward electric field) that immediately followed for 2–3 min is to due to DL field as it occurred in close association with the step-like increase of H field (main impulse (mi)) at low-latitude stations (see Figures 1 and 2) and with a polarity that is consistent with what is expected.

[14] The behavior in the ≈1-hour period after the ssc of F region vertical plasma drift V_z at Kodaikanal and the near-simultaneous magnetic disturbance at middle- and low-latitude stations in the noon and midnight sectors can be understood in terms of the current systems in the magnetosphere-ionosphere during the main impulse of the ssc. Figure 3a shows a schematic of the current systems adapted from that the one presented by *Kikuchi et al.* [2001] for the preliminary positive impulse (ppi)/preliminary reverse impulse (pri) of ssc by reversing the directions of FACs and the associated ionospheric currents. According to the ssc model of *Araki* [1977, 1994], the current circuit in the magnetosphere-ionosphere during the main impulse is supplied by a source current in the intensified magnetospheric convection due to elevated ram pressure behind the interplanetary shock. We could not verify the high ram pressure conditions behind the shock because of the unfortunate gap in the solar wind plasma (velocity and number density) measurements by IMP 8 satellite from 1530 UT onward on 8 July 1991. The ground level magnetic fields at the dayside midlatitude in the Northern (summer) Hemisphere and at the dip equator due to FACs and ionospheric currents are sketched in Figure 3b based on the model calculations of *Kikuchi et al.* [2001]. It is to be recalled here that the main impulse depends on the contributions of FACs and ionospheric (Hall and Pedersen) currents in addition to the DL field. While the contribution of FACs depends on latitude and local time, that of ionospheric currents depends on latitude, local time, and season.

[15] Ionospheric Hall currents practically determine the magnetic field changes at high latitudes, while Pedersen currents do the same at the dayside magnetic equator. The latter feature is because of the amplification of Pedersen current by the Cowling effect, and it accounts for the well-known dip equator enhancement of the main impulse. At midlatitudes, on the other hand, all the current systems contribute to the ground level magnetic field and depending on their relative contributions produce characteristic local time dependence of the amplitude and polarity of the main impulse in individual events. The main impulse could even be a negative change in H/X component if the net magnetic effect of FACs and ionospheric currents is negative and is able to swamp the positive change due to the DL field. The statistical and case studies of *Tsunomura* [1995, 1999] show the prevalence in reality of such a physical situation in the forenoon hours at midlatitudes. From simultaneous data of Fredricksburg and Memambetsu for a number of ssc events, *Tsunomura* [1999] demonstrated that whenever either of the two stations is in the forenoon (0600–1200 LT) sector, the main impulse was smaller in amplitude compared to the other station in the evening to midnight LT sector. Moreover, in some ssc events the main impulse was a negative (positive) impulse in the morning (night) sector with a large event-to-event variability in amplitude and duration of the negative impulse. These results establish the global nature of the unique forenoon behavior of main impulse at midlatitudes.

[16] The recent theoretical calculations of *Kikuchi et al.* [2001] also indicate the possible forenoon occurrence of a negative main pulse at midlatitudes of the summer hemisphere and provide an insight as to its origin. These authors used the model of *Tsunomura* [1999] that enables evaluation of the ground magnetic effects of stationary FACs and ionospheric currents of polar origin for a given set of latitude and local time distributions of FACs. The model incorporates realistic representations of ionospheric conductivity in the equatorial region and its seasonal (north-south) asymmetry. The effects of Chapman-Ferraro currents (DL field) were neglected. It is to be noted that the model calculations presented by *Kikuchi et al.* [2001] refer to the preliminary impulse and the polarities of the local time distribution of the magnetic field changes (Figure 6 of their paper) due to FACs and ionospheric currents are to be reversed to visualize the situation for the main impulse under discussion here. Their results, which correspond to FACs with maximum amplitude at 75° GML and local time maximum (minimum) at 0700 MLT (1700 MLT), clearly show that at midlatitudes (35°) the net effect of FACs and ionospheric currents in ground H component is negative during most of the daytime in the winter hemisphere due to the dominance of the contribution of FACs over that of ionospheric currents. In contrast, in the summer hemisphere such a negative H component effect develops only in the forenoon period due to the combined contributions of FACs and ionospheric currents of the same polarity [see *Kikuchi et al.*, 2001, Figure 6b]. At other times of the day, the net effect in the ground H component will be positive because of the dominance of the positive changes due to ionospheric currents over the negative changes due to FACs. The characteristics (amplitude and polarity) of the main impulse of the ssc at midlatitudes in summer thus depend on the interplay between the DL field and the net effect of FACs and ionospheric currents. The main impulse can be a negative disturbance in H field in the forenoon hours if the net magnetic effect of FACs and ionospheric currents swamps the positive effect due to DL. This will not happen at other times of the day because then DL field adds on to the net positive effect of FACs and ionospheric currents. Similarly, the main impulse in ground H component will be positive throughout the nighttime period irrespective of the season because of the in-phase contribution of FACs and DL field, and its amplitude increases with increase of latitude. The negative disturbance in H field at midlatitudes in the forenoon hours of summer decreases

a) Current Circuit of main impulse (mi) in the Magnetosphere & Ionosphere



b) Ground Magnetic Fields

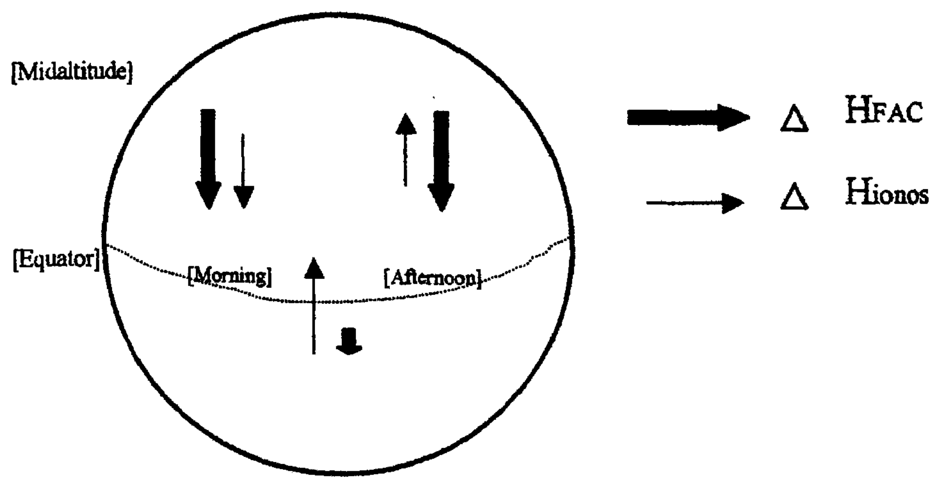


Figure 3. (a) Schematic of the current systems in the magnetosphere-ionosphere during the main impulse (mi) of the storm sudden commencement (ssc) consisting of field-aligned currents (FACs) and ionospheric currents caused by the dawn-to- dusk electric fields carried by the FACs. (b) North-south magnetic fields (ΔH) due to FACs and ionospheric currents at midlatitudes of the Northern (summer) Hemisphere and at the dip equator (adapted from *Kikuchi et al.* [2001]).

toward the equator because of the reduced effect of FACs, while the DL field gains prominence. As a result, the main impulse at low latitudes will be the conventional step-like increase of H field, but its amplitude can be smaller in the forenoon than around midnight because in the former time sector (unlike in the latter) the DL field is opposed by the net negative magnetic effect of FACs and ionospheric currents.

[17] In the light of the above considerations, we interpret the negative disturbance in ΔH at Fredricksburg and the

reduced amplitude of positive disturbance in ΔH at San Juan (compared to Kakioka) in the forenoon sector as the outcome of the effects of both the region 1 FACs and the ionospheric currents of polar origin. The significant difference in the magnitude of the main impulse between San Juan and Kakioka (Figure 1) could partly be due to the southward orientation of IMF B_z at the time of the ssc on 8 July 1991. *Russell et al.* [1994] found that under southward IMF conditions, the steady state response (i.e., 10 min after the step-like increase when the transients decayed) of the low-latitude H field on the nightside (dayside) to sudden changes in solar wind dynamic pressure is at times much greater (smaller) than that expected from a simple model involving only magnetopause currents and the currents induced in the interior of the Earth. The nonavailability of solar wind plasma data for the ssc event on 8 July 1991 precluded attempting estimates of this contribution. The positive disturbances in ΔH at Memambetsu and Kakioka on the nightside are due entirely to FACs, and the slightly larger amplitude of the ΔH at Memambetsu compared to Kakioka (MEM2 in the middle panel of Figure 2) is consistent with the interpretation.

[18] The conspicuous upward drift disturbance in F region vertical drift (eastward electric field) at Kodaikanal that is seen nearly simultaneously with the midlatitude magnetic disturbances finds a logical explanation in terms of the penetration of the dawn-to-dusk electric field carried by the FACs. The eastward polarity of the electric field disturbance is consistent with model predictions (time-dependent and independent) of penetration electric fields at the premidnight dip equator for a sudden increase in cross polar cap potential or region 1 FACs that couple a dawn-to-dusk electric field to the polar ionosphere [e.g., *Nopper and Carovillano*, 1978; *Kamide and Matsushita*, 1981; *Senior and Blanc*, 1984; *Spiro et al.*, 1988; *Tsunomura*, 1999]. To the best of our knowledge, this is the first time evidence for eastward electric fields at the nightside magnetic equator simultaneous with the negative (positive) main impulse of the ssc at midlatitudes in the noon (midnight) sector attributable to the effects of both region 1 FACs and ionospheric currents of polar origin (DP). The HF Doppler observations of *Kikuchi et al.* [1985] did show the presence of eastward electric fields (negative Doppler frequency deviations) at low latitudes on the nightside in association with the main impulse of ssc. However, these are transient effects lasting only a few minutes unlike the slower variations studied here; moreover, the low-latitude ionospheric Doppler observations were studied in isolation without specific reference to the ssc waveform at midlatitudes on the dayside as is done here. The present study confirms the inference of *Wilson et al.* [2001] that eastward penetration electric fields might have prevailed at the duskside magnetic equator to aid the growth rate of equatorial plasma bubbles (EPB) detected by DMSP 10 satellite in the evening MLT sector after the ssc (at 1754 UT, 30°E).

[19] Before concluding the discussion, it is necessary to point out the apparent disagreement between theory and observations as regards the polarity of the penetration electric fields at Kodaikanal associated with the preliminary impulse (pi) of the ssc of 8 July 1991. As we emphasized earlier [*Sastri et al.*, 1993], for the preliminary impulse of this ssc which occurred at 2206 IST (1636 UT), the two-dimensional model calculations of *Tsunomura and Araki* [1984] predict a weak westward electric field at the magnetic equator, whereas the Doppler velocity measurements at Kodaikanal show the transient electric field to be eastward and strong (≈0.95 mV/m). With the result the penetration electric fields at Kodaikanal associated with the preliminary and main impulses of the ssc are of the same polarity (eastward), instead of being of opposite polarity as expected from the model of *Araki* [1977, 1994] detailed earlier. The results of the recent theoretical studies, however, help reconcile these discrepancies at least in conceptual and qualitative terms. The numerical MHD simulations of *Slinker et al.* [1999] indicate that during the magnetospheric compression, the foot points of FACs move toward the dusk and dawn terminators and the FACs that carry the dawn-to-dusk electric field responsible for DP_{mi} are located at lower latitudes and are more intense than the ones associated with the DP_{pi}. The calculations of *Sastri et al.* [2001] using the model of *Tsunomura* [1999] show that the global electric fields set up by a pair of region 1 FACs at 80° latitude and shifted to the morningside (centers at 1300 and 0300 LT) could indeed have a strong (0.5–0.9 mV/m) eastward component at the magnetic equator in the dusk-midnight sector (see Figure 9 of their paper), as actually observed at Kodaikanal with the preliminary impulse of the ssc of 8 July 1991. It follows from these theoretical and experimental findings that the amplitude and polarity of the penetration electric fields associated with the preliminary impulse of sscs depend sensitively on the characteristics (latitude and local time distributions) of the causative FACs. Further studies are therefore required to enhance our comprehension of the variability of FACs generated in magnetospheric compressions to better understand the global characteristics of the ground level ssc and the associated ionospheric electric fields.

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