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Signatures for magnetospheric substorms in the geomagnetic field of dayside equatorial region: Origin of the ionospheric component

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[1] An event-based study is made of the conditions that lead to the ionospheric current component in the geomagnetic field signature for magnetospheric substorms in the dayside dip equatorial region. The substorm activity studied here is characterized by two onsets separated by ~40 min: The first one occurred during steady southward interplanetary magnetic field (IMF) and steadily increasing cross-polar cap potential and enhanced energy input into the magnetosphere, while the second one occurred in close association with a northward transition of IMF and a rapid reduction of the polar cap potential and energy input into the magnetosphere. Earlier studies using multispacecraft data as well as ground-based optical, radar, and magnetic recordings ascertained the first onset to be associated with a pseudo-breakup and the second onset with a "true" breakup. Magnetometer recordings from a meridional network of stations in the Indian and Pacific sectors revealed the response of daytime equatorial H-field to the pseudo-breakup to be weak and not readily identifiable. In contrast, a distinct negative bay-like disturbance with an unambiguous dip equator enhancement prevailed in the H-field starting with the onset of the expansive phase of the fully developed substorm. This behavior indicative of a significant contribution of ionospheric currents to the negative H-field bay is seen both in the Indian and Pacific sectors covering the 1200–1600 LT region. The present case study thus suggests that a sudden and prominent reduction in the cross-polar cap potential at the substorm expansive phase is responsible for the prevalence of the ionospheric current component in the geomagnetic disturbance in the dayside equatorial region. It is also found for the first time that the amplitude of the negative H-field disturbance in the afternoon sector exhibits a marked hemisphere asymmetry at midlatitudes: It is higher by a factor of about 3 in the summer hemisphere than in the winter hemisphere. The equatorial enhancement of the negative H-component disturbance is interpreted as the signature of the "over-shielding" effect, namely, direct penetration of the perturbation component of the large-scale electric field associated with the rapid reduction in convection atthe onset of the substorm expansion phase. The marked summer-winter asymmetry of the H-field disturbance at midlatitudes is suggested as the outcome of the competing magnetic effects of field-aligned currents and polar origin DP2 currents. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2788 Magnetospheric Physics: Storms and substorms; 2409 Ionosphere: Current systems (2708); 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; *KEYWORDS:* equatorial geomagnetic field, high-latitude-low-latitude coupling, substorm

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1. Introduction

[2] Global-scale perturbations in the ground-level magnetic field during the expansion phase of magnetospheric substorms are commonly understood in terms of the effects of the substorm current wedge (SCW) consisting of the westward electrojet fed by downward field-aligned currents (FACs) on the dawn side and upward FACs on the dusk side with the circuit closure through a part of tail current [e.g., *McPherron*, 1991]. SCW models show that at low latitudes, the H-component variation is a positive bay with a peak in amplitude about the wedge central meridian and it is a negative bay outside the wedge, in agreement with obser-

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vations [*McPherron et al.*, 1973; *Kamide et al.*, 1974; *Clauer and McPherron*, 1974]. The model-based calculations of the relative contributions of the individual segments of the wedge current circuit to the bay characteristics at different latitudes indicate that FACs contribute the most to H-component bay at low latitudes [*Kamide et al.*, 1974; *Crooker and Siscoe*, 1974]. Statistical studies show that the amplitude of the H-component bay in the midnight sector at the substorm maximum epoch increases with increase of latitude, which implies that FACs, in general, determine the strength of the positive bays in the sub-auroral region on the nightside [*Reddy et al.*, 1988; *Kamide*, 1994]. This does not necessarily mean the absence of any electric field disturbance at equatorial latitudes on the night side during substorms. In fact, credible observational evidence exists to show that short-lived zonal electric field disturbances occur quite commonly at low and equatorial latitudes during the nighttime preferentially in association with the decay of auroral electrojet activity and/or asymmetric ring current and intensification of symmetric ring current [e.g., *Fejer*, 1991, and references therein; *Sastri et al.*, 1992, 1997, 2002]. However, whether the auroral electrojet activity in these studies, in fact, corresponded to substorms is not known because of the absence of any rigorous assessment of the substorm expansion phase, and also the fact that they were based mostly on the usage of the auroral electrojet indices (AE/AL) or localized magnetic observations at high latitudes for identifying substorms, with attendant weaknesses. The current understanding is that ionospheric currents are not important in producing positive bays at low latitudes on the nightside during substorm expansion phase, and that large ionospheric electric fields (>5 mV/m) would indeed be required to cause H-component bays of about 20 nT amplitude that are typically observed at low latitudes [*Kamide*, 1994].

[3] The situation regarding the contribution(s) of distant currents and ionospheric currents to ground-level magnetic effects of substorms at equatorial latitudes on the dayside remained unclear due to the absence of systematic studies. This is partly due to the fact that the amplitude of the negative H-bay on the dayside (outside the substorm current wedge) is usually smaller than the positive bay at the same latitude on the nightside (under the substorm current wedge). The dayside negative bay is therefore rather difficult to detect being superposed on the Sq variation which is also a decrease, unlike the positive bay which is relatively easy to recognize because of the steady background field.

[4] Some studies of carefully selected isolated substorm events have been made in recent times, and they consistently demonstrated a significant role of ionospheric currents in substorm effects in the dayside dip equatorial region during the growth phase and/or the expansion phase [*Somayajulu et al.*, 1987; *Kikuchi et al.*, 2000; *Sastri et al.*, 2001]. The ionospheric component manifests as a dip equator enhancement of the H-field disturbance, positive with growth phase and negative with expansion phase. *Kikuchi et al.* [2000] interpreted the latitudinal dependence for the substorm on March 22, 1979 (CDAW-6 event), in terms of the effects of ionospheric currents of polar origin (reduction in region 1 currents and delayed enhancement of region 2 currents). *Sastri et al.* [2001], on the other hand, interpreted the H-component disturbances during the growth and expansion phases as mainly caused by short-lived, directly penetrated electric fields associated with rapid changes in the cross-polar cap potential (region 1 currents) brought about by swift transitions in IMF leading to the substorm growth and expansion phases. No direct evidence for the changes in the cross-polar cap potential is, however, given. It is well known, though, that swift directional changes of IMF result in rapid changes in ionospheric convection over the polar caps and in the cross-polar cap potential [see, e.g., *Ridley et al.*, 1998; *Lu et al.*, 2002, and references therein].

[5] The ionospheric component in the dayside magnetic effects of substorms at low latitudes does not obviously prevail in all substorms. This feature is seen even in the very limited cases of well-identified substorms of the IMF-triggered variety studied by *Sastri et al.* [2001]. The unmistakable ionospheric component is seen in two out of the three events analyzed by them. There are in fact substorms of various types: substorms without any identifiable external trigger, the so-called spontaneous substorms [*Henderson et al.*, 1996], substorms triggered exclusively by changes in IMF By [*Troshichev et al.*, 1986], substorms that follow interplanetary shocks depending on IMF Bz conditions [e.g., *Kokubun et al.*, 1977; *Zhou and Tsurutani*, 2001], and, above all, storm-time and non-storm time substorms [e.g., *Baumjohann et al.*, 1996; *McPherron and Hsu*, 2002, and references therein]. Moreover, it is being increasingly realized now that not all auroral and magnetic field intensifications are substorm onsets and there are substorm-like disturbances (in terms of auroral luminosity and strength of magnetic perturbations) termed pseudo-breakups and poleward boundary intensifications (PBI), and these have to be properly evaluated with adequate observational coverage of auroral latitudes, especially during the storm main phase and understood within the framework of solar wind-magnetosphere-high latitude ionosphere interactions [see, e.g., *Rostoker*, 1998; *Lyons*, 2000; *Kamide*, 2001; *Rostoker*, 2002; and references therein].

[6] The question therefore arises as to with what type of substorms or substorm-like auroral disturbances and under what conditions the ionospheric component manifests in their corresponding magnetic effects at equatorial latitudes on the dayside. In this paper we address this question through a case study. We show that a sudden and substantial reduction in cross-polar cap potential has to take place at the onset of the substorm expansion phase for a negative bay-like disturbance in H-component to occur in the sub-auroral region of the afternoon sector with a marked dip equator enhancement. The present study also brings to light the fact that at midlatitudes the expansion phase-related H-field disturbance manifests in the afternoon sector with a significantly larger amplitude in the summer hemisphere compared to the winter hemisphere. We shall present these and other results discussing current understanding of magnetosphere-ionosphere coupling processes.

2. Overview of High-Latitude Disturbances on May 15, 1996

[7] The substorm event in focus here occurred on May 15, 1996 (A_p = 8; ΣK_p = 15), and is of isolated type. Studying

simple-looking isolated substorms such as this, free from other disturbances, it is expected to identify basic processes that are crucial for triggering the substorm expansion phase. This event was studied in considerable detail by *Pulkkinen et al.* [1997, 1998] using an extensive set of satellite measurements of solar wind, magnetospheric particles and fields, and global auroral images, and ground-based instrumentation consisting of networks of magnetometers and SuperDARN radars. In the following, we will summarize the salient characteristics of the auroral event and their implications that are relevant to the present study. The interested reader is referred to *Pulkkinen et al.* [1997, 1998] for further details.

[8] Observations of the upstream solar wind by the WIND, IMP8, and Interball satellites showed a sharp southward turning of IMF around 0535 UT, and this orientation was maintained by IMF for more than an hour when a northward transition took place [see *Pulkkinen et al.*, 1998, Figure 2a]. Using the solar wind speed measurements from the three spacecraft, the IMF front was estimated to have arrived at the magnetopause between 0548 and 0550 UT and at the subsolar magnetopause between 0551 and 0553 UT. No sharp and large variations were seen in the solar wind speed and density. Calculations using the "epsilon" parameter of *Perreault and Akasofu* [1978] showed that the energy input into the magnetosphere increased and remained above 2×10^{11} W (i.e., above the substorm threshold of 10^{11} W [*Akasofu*, 1981]) throughout the interval of southward IMF [see *Pulkkinen et al.*, 1998, Figure 2b] and decreased rather sharply later, associated with the northward transition of IMF which was estimated to have impacted the magnetopause between 0705 and 0707 UT [*Pulkkinen et al.*, 1997].

[9] Individual stations of the Canadian Auroral Network for the Open Program Unified Study (CANOPUS) magnetometer array (in the evening and midnight sector at the time of the substorm event) and the Greenland magnetometer network (in the morning sector) showed the successive onset of two magnetic disturbances at 0623 UT and 0706 UT [see *Pulkkinen et al.*, 1998, Figures 4a and 4b]. The two disturbances were, however, distinctly different in their spatial manifestation across the networks mentioned as also in the global conditions under which they occurred. The first negative excursion in the X-component was seen at the near-midnight stations of the CANOPUS array but was limited in latitudinal extension. Moreover, it was not apparent in the Greenland network stations, which recorded mainly the enhancement of the westward electrojet driven by the southward IMF conditions. On the other hand, the second negative excursion onset at 0706 UT was seen throughout the CANOPUS chain and also quite clearly at some stations (FHB, SKT, STF spanning the CGMLat. range 68 to 73.2°) of the Greenland network.

[10] The VIS imager aboard the POLAR spacecraft provided complimentary and confirmatory information on the strikingly different nature of the global auroral evolution between the two onsets. The auroral expansion with the first onset was brief and did not lead to any major changes in the auroral oval, while the second onset led to major expansion of the auroral bulge well into the highest latitudes. On the basis of these and other observations, *Pulkkinen et al.* [1997, 1998] interpreted the first onset at 0623 UT to be a pseudo-breakup and the second one at 0706 UT to be a global-scale substorm expansion.

[11] The time evolution of the cross-polar cap potential difference deduced from measurements with the SuperDARN radar network and the polar cap size calculated from the auroral images acquired by the POLAR spacecraft during the auroral event were in accordance with the current understanding of pseudo-breakups and substorms [e.g., *Rostoker*, 1998] and substantiate the identification made by *Pulkkinen et al.* [1998]. During the growth phase and right through the first onset the polar cap potential steadily increased from a low value of less than 50 kV, reaching 91 kV at 0645 UT. There was a minor and short-lived reduction of the potential after 0645 UT, but a swift and prominent decrease of the polar cap potential took place only with the second onset at 0706 UT and the potential reached the pre-event level of less than 50 kV by about 0720 UT [see *Pulkkinen et al.*, 1998, Figure 2b]. It is to be noted, however, that the small changes in the cross-polar cap potential associated with the pseudo-breakup would not be expected to be discernible in the SuperDARN data due to the absence of complete local time coverage of the polar cap by radar echoes [see *Pulkkinen et al.*, 1998, Figure 5]. The temporal changes in the polar cap area followed closely those of the cross-polar cap potential mentioned above. The energy input to the magnetosphere ("epsilon" parameter) suddenly reduced to close to pre-event levels around 0702 UT closely associated with the sudden northward turning of IMF. It is worth noting in this context that the estimated time of impact of northward IMF at the magnetopause between 0705 and 0707 UT was based only on WIND satellite data and is prone to uncertainties. We shall touch on this point later in the paper.

[12] The temporal sequence of the events described above thus provided a unique opportunity to study and contrast the responses of the dayside equatorial geomagnetic field to the two auroral disturbances and seek an answer to the question as to the conditions under which the ionospheric component prevails. In particular, it is well suited to assess the role of sharp and prominent changes in cross-polar cap potential in the manifestation of the negative H-component bay in the afternoon sector in association with the expansion phase onset of IMF-triggered global substorms, emphasized in the recent studies of *Kikuchi et al.* [2001] and *Sastri et al.* [2002]. We have used data of the Pacific sector stations of the Circum-pan Pacific Magnetometer Network, CPMN [*Yumoto et al.*, 1996], the meridional network of equatorial stations in the Indian sector, and a few other low-latitude stations around the globe for the study. Detailed information on the stations is given in Table 1.

3. Observations

3.1. Auroral Electrojet in Evening Sector

[13] From the time evolution of the quasi-AL index constructed from the data of CANOPUS and Greenland magnetometer arrays and the approximate MLT of the stations contributing to the index, *Pulkkinen et al.* [1998] demonstrated that directly driven westward electrojet in the morning sector contributed most to the index throughout the growth phase, while the substorm current wedge (SCW) in the midnight sector dominated the westward electrojet

Table 1. Magnetometer Stations Whose Data are Used in the Study

Station Name	Geographic Latitude, °	Coordinates Longitude, °	Geomagnetic Latitude, °	Coordinates Longitude, °
		Pacific Sector (210 MM)		
Kotel'nyy (KTN)	75.94	137.71	69.94	201.02
Tixie (TIX)	71.59	128.58	65.67	196.88
Zyryanka (ZYK)	65.75	150.78	59.62	216.72
Magadan (MGD)	59.97	150.86	53.56	218.66
Moshiri (MSR)	44.37	142.27	37.61	213.23
Chichijima (CBI)	27.15	142.30	20.59	213.00
Guam (GUA)	13.58	144.87	4.57	214.76
Yap (YAP)	9.30	138.50	−0.30	209.00
Biak (BIK)	−1.08	136.05	−12.18	207.30
Weipa (WEP)	−12.68	141.88	−21.93	214.44
Birdsville (BSV)	−25.54	139.21	−36.58	212.96
Adelaide (ADL)	−34.67	138.65	−46.46	213.66
		Indian Sector		
Gulmarg (GUL)	34.10	74.60	25.24	149.36
Ujjain (UJJ)	23.20	75.80	14.29	149.24
Alibag (ALB)	18.60	72.90	10.00	146.00
Pondicherry (PON)	11.40	79.70	2.20	151.87
Trivandrum (TRD)	8.50	76.90	−0.44	148.86
		Other Stations		
Fort Churchill (FCC)	58.80	265.90	69.40	330.80
Lunping (LNP)	25.00	121.20	13.80	189.50
Tucson (TUC)	32.20	249.30	40.10	315.80
Tamaransset (TAM)	22.80	5.50	24.70	81.60

activity during the first expansion onset. The situation during the second onset was different when most of the changes in the quasi-AL index were determined by the morning sector stations rather than the SCW. We shall return to this point later in the paper with reference to the low-latitude signatures of the two onsets on the night side.

[14] We have examined the behavior of the eastward auroral electrojet in the afternoon sector since this is relevant to our study and was not studied earlier by *Pulkkinen et al.* [1998]. Figure 1 shows the auroral region magnetograms of CPMN stations, KTN, TIK, and ZYK (see Table 1 for the coordinates) for the period 0500–1000 UT on May 15, 1996. The magnetogram of the CANOPUS station, FCC of the midnight sector, is also shown in the top panel to serve as a reference because it recorded the negative H excursions for both the pseudo-breakup and the subsequent global expansion phase onset. It is quite evident from Figure 1 that during the growth phase, the eastward electrojet in the afternoon sector underwent a continuous enhancement in consonance with that of the westward electrojet in the morning hours at the Greenland chain of stations. The onset of the pseudo-breakup at 0623 UT is accompanied by only a short-lived and minor reduction of the driven electrojet activity in the evening sector and a momentary cessation of the growth of the westward electrojet in the morning sector [see *Pulkkinen et al.*, 1998, Figure 4b]. In contrast, the onset of the fully developed expansion phase at 0706 UT is associated with a rapid and prominent reduction of the eastward electrojet. This, when coupled with the behavior of the westward electrojet in the morning sector mentioned earlier, clearly shows that the expansion phase onset is associated with a substantial reduction of the large-scale directly driven auroral electrojet activity, presumably because of the northward transition of IMF. It is worth noting here that the sharp decline of the eastward electrojet particularly at TIK and ZYK started at 0700 UT. It thus shows better temporal correlation with the rapid drop in the energy input into the magnetosphere that started at 0702 UT, as mentioned earlier, than with the onset of the expansion phase on the nightside which is identified to be at 0706 UT. This finding is consistent with and complements the very recent results of *Lyons et al.* [2003] which show that the reduction in the strength of the large-scale convection of the dayside ionosphere occurs a few minutes before the substorm onset on the nightside. In order to retain the contextual reference to substorm expansion phase onset, however, we have evaluated the subauroral H-field disturbances on the dayside with respect to the substorm onset time (0706 UT) identified earlier, as described in the next section.

3.2. Dayside Subauroral Observations

3.2.1. Equatorial Region

[15] Recordings of the subauroral stations of the CPMN chain showed the absence of any discernible response of the equatorial H-field to the pseudo-breakup at 0623 UT. The expansion phase onset of the global substorm at 0706 UT, on the other hand, is accompanied by a distinct negative H-component disturbance from subauroral latitudes down to the magnetic equator with a unique latitudinal profile. This can be seen in Figure 2 where the H-component variations at the stations MGD, GUA, YAP, BIK, and ADL of the CPMN chain are shown for the interval 0400–1000 UT. Out of these stations, YAP, is closest to the dip equator and under the influence of the equatorial electrojet (EEJ), while GUA and BIK are outside the EEJ influence. Note that the data of other stations of the CPMN chain are not shown so as not to clutter the figure; the interested reader is referred to the stack plot of the data of all the stations at http://stdb2.stelab.nagoya-u.ac.jp/mm210/. Also shown in Figure 2 is the H-component variation (dashed curves) at the equatorial stations, GUA, YAP, and BIK on the quiet

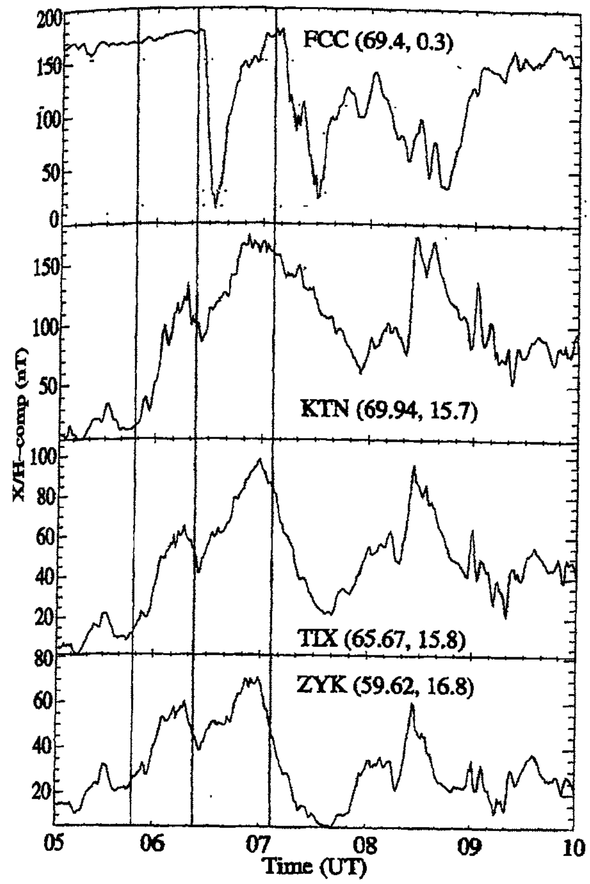


Figure 1. Magnetic X/H-component variation at the high-latitude stations in the midnight sector (Fort Churchill, FCC) and in the evening sector (Kotel'nyy, KTN; Tixie, TIK; and Zyryanka, ZYK) for the period 0500–1000 UT on May 15, 1996. The solid vertical lines from left to right mark the times of start of the growth phase (0548 UT), pseudo-breakup (0623 UT), and the expansion phase (0706 UT), respectively, of the substorm as ascertained by *Pulkkinen et al.* [1998]. The two numbers (within brackets) by the side of the station code are the geomagnetic latitude and magnetic local time at 0700 UT, respectively, of the station. Note the increase of the eastward auroral electrojet in the evening sector during the growth phase and its conspicuous decrease with the onset of the expansion phase. The latter is indicative of an abrupt reduction of the convection electric field at the substorm expansion phase: see text for further details.

day, May 23, 1996 (A_p = 4; ΣK_p = 9), to serve as a reference and help evaluate the substorm expansion phase-related perturbations in the equatorial H-field.

[16] The quiet day H-field variation in Figure 2 exhibits the normal pattern of a steady decrease during the afternoon hours due to the solar zenith angle-dependent variation of ionospheric E-region conductivity, and this characteristic behavior is more prominent at YAP compared to GUA and BIK because of the well-known contribution of the equatorial electrojet [*Matsushita*, 1967]. As can be seen from Figure 2, the onset of the pseudo-breakup at 0623 UT is accompanied by a negative H-component bay only at the high-latitude station, MGD, in the Northern Hemisphere and at the midlatitude station, ADL, in the Southern Hemisphere. There is no perceptible bay-like disturbance in the H-field at any of the equatorial stations, suggesting a rapid latitudinal attenuation of the negative bay in the afternoon sector associated with the pseudo-breakup. The equatorial H-component, in fact, continued to decrease steadily at GUA, YAP, and BIK, though at a rate that was slightly higher than that on the reference quiet day.

[17] The onset of the expansion phase of the global substorm at 0706 UT, however, led to a coherent negative

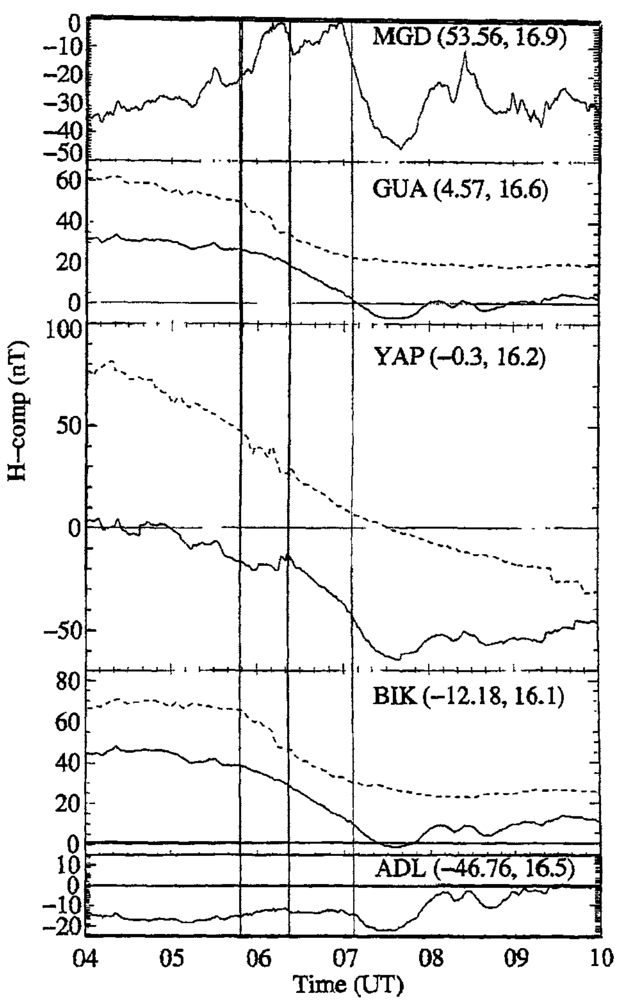


Figure 2. Geomagnetic H-field variation at sub-auroral and equatorial stations of the 210 MM network in the Pacific sector on May 15, 1996 (solid curves); see text for station coordinates. The variation at the equatorial stations, GUA, YAP, and BIK on the quiet day, May 23, 1996 (dashed curves), is also shown for reference. The two numbers (within brackets) by the side of the station code are the geomagnetic latitude and magnetic local time at 0700 UT, respectively, of the station. The vertical lines at 0548 UT, 0623 UT, and 0706 UT indicate the start of substorm growth phase, pseudo-breakup, and the substorm expansion phase, respectively. Note the conspicuously enhanced negative bay close to the magnetic equator at YAP that started with the onset of the substorm expansion phase.

bay-like decrease in the H-component throughout the subauroral region in the afternoon sector. The rapidity and magnitude of the H-field reduction is remarkably enhanced close to the magnetic equator at YAP, when compared to GUA and BIK farther away. The amplitude of the H-component decrease from 0706 UT to the peak negative value is higher at YAP by a factor of 2.38 (2.0) when compared to GUA (BIK). Note that the peak negative value of H-field occurred in the interval 0736–0738 UT at the three equatorial stations. Estimates of the amplitude of the bay-like disturbance in H-field at the equatorial stations are also made by subtracting the quiet day change in the H-field over the same time interval from the data of May 15, yielding the net change attributable to the substorm expansion phase. This procedure [e.g., *Horning et al.*, 1974] which assumes that the current systems on May 15 are essentially the same as on the reference quiet day but for the substorm expansion phase gives an amplitude ratio of 1.8 (1.9) between YAP and GUA (BIK). It is to be kept in mind that this assumption may or may not be valid in view of the well-known day-to-day variability, even during quiet days, of the strength and pattern of diurnal variation of H-field in the dip equatorial region [see, e.g., *Kane*, 1976, and references therein].

[18] The nature of H-field response at low and equatorial stations in the Indian noon sector to the two disturbances at high latitudes is identical to that evidenced in the Pacific afternoon sector, namely, a distinct negative bay-type perturbation with an unambiguous dip equator enhancement, but only with the onset of the expansion phase of the global substorm and not that of the pseudo-breakup. This may clearly be seen from Figure 3 wherein the H-component variations at the meridional network of Indian stations are presented for the interval 0400–1000 UT on May 15, 1996, and the reference quiet day. Out of these stations, TRD is closest to the magnetic equator and PON is farther but within the equatorial electrojet belt, while the rest of the stations (ABG, UJJ, and GUL) are well outside the influence of the electrojet: see Table 1 for details of the station coordinates. The amplitude of the H-field decrease as reckoned for the value at 0706 UT to the peak negative value is higher at TRD by a factor of 2.5 when compared to ABG. The ratio of the H-field reduction at TRD to ABG is 2.0 when the quiet-day variation is taken into account, as detailed earlier. Taken together, the Pacific and Indian sector observations amply demonstrate that a temporally coherent and identical response of the equatorial H-field occurred over the entire 1200–1600 LT region, but only to the substorm expansion onset and not to the pseudo-breakup that preceded it on May 15, 1996.

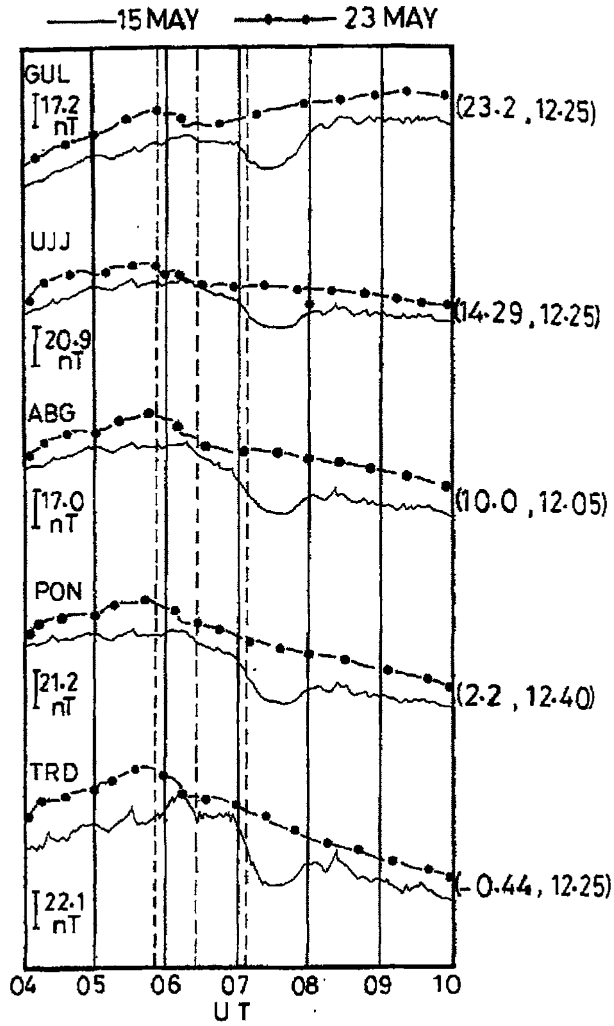
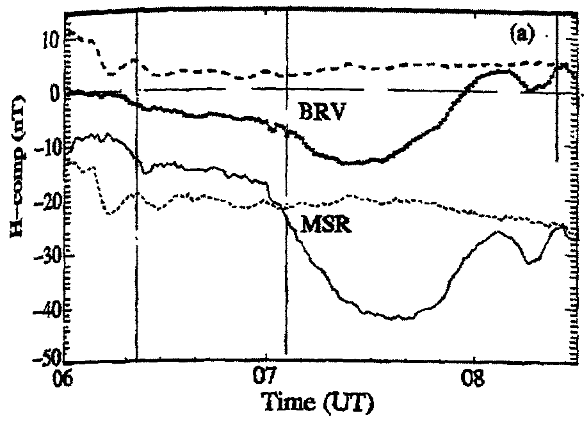


Figure 3. Same as in Figure 2 but for the Indian sector; see text for details of station coordinates. The dashed vertical lines at 0548 UT, 0623 UT, and 0706 UT indicate the start of substorm growth phase, pseudo-breakup, and the substorm expansion phase, respectively. The two numbers (within brackets) on the right-hand side of the magnetogram trace are the geomagnetic latitude and magnetic local time at 0700 UT, respectively, of the relevant station. Note the unambiguous enhancement of the negative bay in H-component at stations within the equatorial electrojet belt (TRD, PON) when compared to stations well outside its influence (ABG, UJJ, and GUL), in association with the substorm expansion phase.

3.2.2. Midlatitude Signatures: North-South Asymmetry

[19] In addition to the conspicuous dip equator enhancement described above, the expansion phase-related negative H-component disturbance exhibited another important spatial characteristic. It is a significant north-south asymmetry of its amplitude at midlatitudes. The temporal pattern of H-field at the magnetic conjugate stations, MSR (summer hemisphere) and BSV (winter hemisphere), shown in the top panel of Figure 4 exemplifies this behavior. It is quite evident that the magnitude of the H-field reduction reckoned from the expansion phase onset value at 0706 UT is higher by a factor of 3.8 at MSR compared to that at BSV. The amplitude ratio between MSR and BRV turns out as 2.9 when the quiet day (Sq) variation is taken into consideration as detailed earlier. The latitudinal profile of the amplitude of the negative bay-like disturbance (after correcting for Sq effects) presented in the bottom panel of Figure 4 indicates that the north-south asymmetry prevails over the GML range 30° to 50°. To the best of our knowledge, this is the first time such a hemisphere asymmetry of the substorm expansion phase-related magnetic disturbance is found at the dayside midlatitudes. This feature is a clear pointer to a



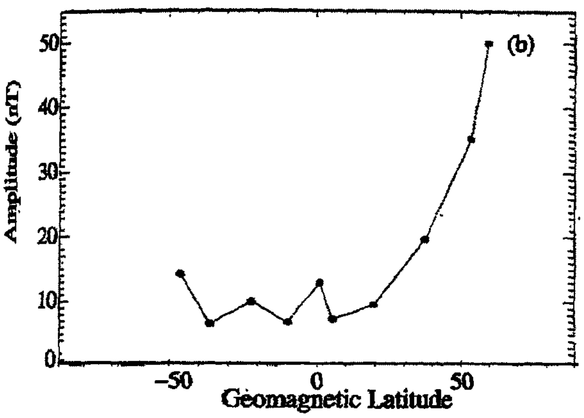


Figure 4. (a) H-component variation at the midlatitude magnetic conjugate stations, MSR (summer hemisphere) and BRV (winter hemisphere), over the period 0600–0830 UT on May 15, 1996, and (b) latitudinal profile of the amplitude of the negative H-component disturbance reckoned form 0706 UT to its peak value, associated with the expansion phase onset of the substorm. The dashed curves in the top panel represent the quiet day (May 23) variations at MSR and BRV. Note the significant dip equator enhancement of the H-field disturbance and its north-south symmetry with higher amplitudes in summer hemisphere compared to winter hemisphere. The amplitude at the individual stations is corrected for quiet day (Sq) effects.

significant role of ionospheric conductivity in the manifestation of the expansion phase effects at midlatitudes, and is consistent with what is implied by the observations in the equatorial region presented in the previous section.

3.2.3. Low-Latitude Effects on the Nightside and Relationship to Ring Current Indices

[20] As mentioned in section 1, the substorm current wedge is well known to produce positive H-component bays at low-/midlatitudes in the midnight sector, i.e., under the wedge and positive bays outside it. Since the current wedge is a time-dependent and dynamical system with sizable longitudinal expansion from the time of its formation near local midnight, the local time or longitudinal extent of the wedge effect changes during the course of an individual substorm and even from one substorm to another [e.g., *Kamide et al.*, 1974; *Belehaki et al.*, 1998], thereby contributing to the asymmetric ring current indices, ASY (H/D). The low-/midlatitude H component data are traditionally used to construct the Dst index (or its improved version, the SYM-H index) by averaging the H-component deviations at a few widely distributed stations, and these indices are quite commonly taken as quantitative measures of the strength of the symmetric component of the ring current. It is now well recognized, however, that current systems other than the symmetric ring current which include field- aligned currents, magnetotail current, partial ring current, magnetopause current, and even ionospheric current, could contribute to changes in SYM-H/Dst indices at times of magnetic storms and substorms [see, e.g., *Campbell*, 1996; *Kamide et al.*, 1998; *Ohtani et al.*, 2001, and references therein]. We have, therefore, considered it appropriate and instructive to examine the low-latitude signatures in different longitude sectors of the two magnetic disturbances on May 15 and their specific relationship to the symmetric and asymmetric ring current indices, SYM-H and ASY (H/D), respectively.

[21] Figure 5 shows the time variation of the H-field at TUC (midnight sector), TAM (morning sector), and LNP (afternoon sector) and the SYM-H and ASY-(H/D) indices over the interval 0400–1000 UT (see Table 1 for station coordinates). It is quite evident from Figure 5 that the onset of the pseudo-breakup at 0623 UT is associated with a well-defined positive bay only in the midnight sector at TUC and there is no readily identifiable H-field perturbation at TAM and LNP. As can be expected, this longitudinal dependence of the current wedge effect reflects in the simultaneous growth of the asymmetric ring current indices, ASY-H/D, and a decrease of the SYM-H index at least initially due to the overriding contribution of the positive bay in the midnight sector (TUC). On the other hand, the onset of the global expansion phase at 0706 UT led to a H-field reduction at all the three stations, at least to start with, as may be seen from Figure 5. While this effect persisted and manifested most prominently at LNP and to a lesser extent at TAM, at TUC the H-field decrease is soon overtaken (from 0712 UT) by the positive effect of the substorm current wedge. As a result, the minimum in the H-component is reached first at TUC and at increasingly later times at TAM and LNP, i.e., from midnight to afternoon through morning. This wide spread nature of the H-field decrease is the primary cause of the rapid decay of ASY indices in the interval 0706–0718 UT, i.e., in the early stage of the expansion phase. The simultaneous intensification of the symmetric ring current index, SYM, could be due to the combined effects of the expansion phase-related plasma injection and the large longitudinal (local time) extent of the negative H-component bay at dayside low latitudes. In other words, the substorm expansion-phase related low-latitude H-field disturbances on the dayside played a role in transforming temporarily the existing asymmetric magnetic disturbance to a more symmetric one.

4. Discussion and Conclusions

[22] Evaluation of the characteristics of pseudo-breakups and understanding of their relationship to the substorm process is a topic of much current interest. It is known that pseudo-breakups constitute short-lived, localized substorm-like disturbances that typically precede the expansion phase

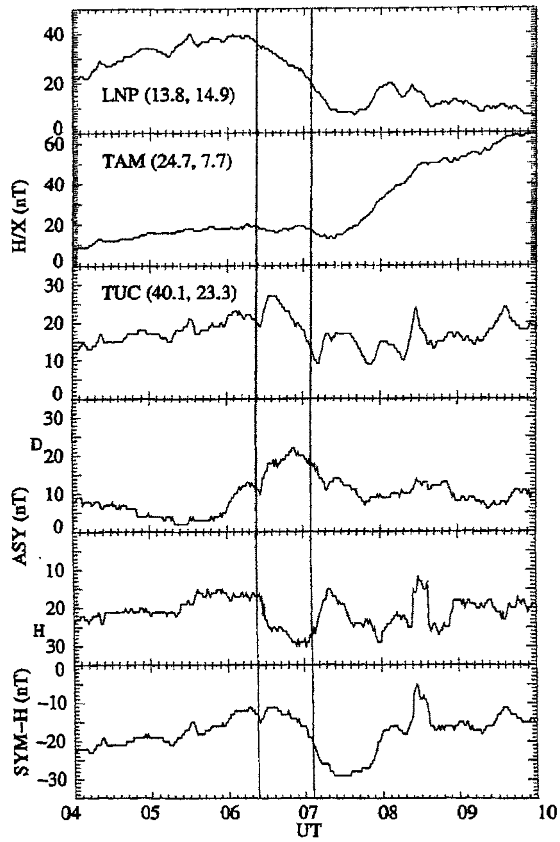


Figure 5. Time variation of the symmetric ring current index (SYM-H) and asymmetric ring current indices (ASY-H/D) and H/X-component at low-latitude stations in the midnight sector (TUC), morning sector (TAM), and afternoon sector (LNP) at the time of the two auroral disturbances at 0623 UT and 0706 UT on May 15, 1996. The two numbers (within brackets) by the side of the station code are the geomagnetic latitude and magnetic local time at 0700 UT, respectively, of the station.

of fully developed substorms. Recent studies show that the manifestations of pseudo-breakup disturbances in the magnetosphere and ionosphere domains do not differ very much from those of substorms [see, e.g., *Pulkkinen et al.*, 1998; *Rostoker*, 1998; *Partamies et al.*, 2003]. This leads to the interesting but unsettled question as to the nature of the "choking" mechanisms that suppress the seemingly similar conditions from developing at times into a full-scale substorm expansion, although several ideas are currently being discussed in the literature [see *Partamies et al.*, 2003, and references therein]. The only distinguishing feature as demonstrated by *Pulkkinen et al.* [1998] for the auroral event on May 15, 1996, examined here and also by others, is that a pseudo-breakup typically occurs during the period of continuing energy input into the magnetosphere, i.e., the growth phase. The logical inference, as also argued by *Rostoker* [1998], is that one can expect a "true" or global-scale expansion onset only when the energy input to the magnetosphere begins to decline due to northward turning of IMF, with attendant reductions in global parameters that represent solar wind-magnetosphere-polar ionosphere interactions such as the size of polar cap and the cross-polar cap potential. The status of the rate of energy transfer from the solar wind into the magnetosphere which seems to be the differentiating factor between pseudo-breakups and global substorms constitutes a useful and reliable means of identifying the deterministic conditions under which the ionospheric component prevails in the substorm expansion phase effects at the dayside low latitudes. The present event-based study testifies to the merit of this approach as it demonstrates that the pseudo-breakup and the "true" substorm break-up differ not only in their expansion characteristics in the nightside auroral latitudes but also in their global effects in the dayside subauroral region.

[23] We found that the pseudo-breakup on May 15, 1996, which occurred under conditions of a steady southward IMF and steadily increasing energy input to the magnetosphere, is accompanied by a negative bay-like disturbance in H-field in the afternoon sector but restricted to high latitudes (GML > 40°) and by a well-defined positive bay at low latitudes in the midnight sector. The H-field at lower latitudes including the dip equatorial region of the noon sector remained practically unaffected. In sharp contrast to this, the onset within 40 min of a global-scale expansion phase resulted in a negative bay-like disturbance in H-field throughout the subauroral region in the afternoon sector and at low and equatorial latitudes in the noon sector. The latitudinal profile of the H-field disturbance exhibited two distinctive characteristics: an unambiguous dip equator enhancement along two meridians spanning the 1200-1630 LT region and a marked hemisphere asymmetry at midlatitudes in the afternoon sector. This unique latitudinal pattern strongly suggests an important role of ionospheric currents in the manifestation of the substorm expansion-related effects in the dayside subauroral region, besides the three-dimensional current system of the substorm current wedge.

[24] The origin of the expansion onset of global substorms continues to be a topic of controversy, debate and active research [see, e.g., *Baker et al.*, 1999; *Lui*, 2001; *Kamide*, 2001, and references therein]. Keeping in view the main objective of the present study, we discuss its findings in the context of the evidenced behavior of the global parameters that represent solar wind-magnetosphere-high latitude ionosphere interactions, at the time of the substorm expansion phase onset. Issues as to why such behavior is seen and what its implications are to the various substorm models is beyond the scope of this paper. As detailed in section 2, the expansion phase onset at 0706 UT on May 15, 1996, is marked by a rapid reduction in the energy input to the magnetosphere with corresponding decreases in the polar cap size and cross-polar cap potential. These parameters underwent a steady enhancement during the preceding growth phase. The abrupt reduction of the rate of energy input to the magnetosphere presumably by the northward turning of IMF imposes a dusk-to-dawn large-scale electric field on the polar cap ionosphere through FACs that are inward on the dusk side and outward on the dawn side. The large-scale convection electric field drives a twin-vortex DP2 current system with Hall and Pedersen currents, and the polar cap electric potential distribution is characterized

by a positive cell on the dusk side and a negative cell on the dawn side. The residual polar cap potential patterns derived by *Ridley et al.* [1998] using the AMIE technique for convection decreases triggered by northward turnings of IMF testify to this physical situation.

[25] Theoretical and numerical simulation studies consistently show that a sudden decrease in the cross-polar cap potential leads to short-lived electric field perturbations in the subauroral region with the zonal electric field having a westward component at low latitudes on the dayside [see *Spiro et al.*, 1988; *Tsunomura*, 1999; *Peymirat et al.*, 2000, and references therein]. The ionospheric current driven by this prompt penetration electric field gets amplified in the equatorial electrojet region because of the Cowling effect. The negative H-field disturbance in the afternoon sector (1200–1600 LT) that is noticed to develop concurrent with the onset of the substorm expansion phase and with a marked dip equator enhancement thus finds a logical interpretation in terms of prompt penetration electric fields associated with expansion phase-related reduction in the cross-polar cap potential that, in fact, is observed, as detailed in section 2. In other words, Pedersen currents associated with the global DP2 current system influence the ground-level magnetic field changes at the dayside magnetic equator.

[26] A different situation, however, obtains at midlatitudes where all the current systems, namely, the FACs that couple the large-scale convection electric field to the polar ionosphere, the Hall and Pedersen ionospheric currents of polar origin (DP2), contribute to the ground-level magnetic field changes. The effect of FACs on the ground-level magnetic field depends on latitude and local time while that of ionospheric currents depends on local time, latitude, and, more importantly, on season. Thus the ground-level magnetic field may exhibit characteristic local time and seasonal dependencies, caused by the relative magnitudes of the contributions of the various current systems. The recent theoretical calculations of *Kikuchi et al.* [2001] help visualize the origin of the north-south asymmetry of the expansion phase-related H-component disturbance at midlatitudes found for the first time in the present study. These researchers computed the ground magnetic effects of stationary FACs and ionospheric currents of polar origin for a given set of spatial and local time distributions of FACs, as obtained during the preliminary reverse impulse (pri) of storm sudden commencements (and also during rapid decreases in polar cap potential of relevance here), using the model of *Tsunomura* [1999]. The model incorporates a realistic representation of ionospheric conductivity including its seasonal (north-south) asymmetry though climatological in nature.

[27] The results show that the net effect of FACs and ionospheric currents in the H-component is negative throughout the afternoon sector (1200–1800 LT) in the summer hemisphere, while it is positive in the winter hemisphere in the same local time period. This seasonal dependence stems from the fact that the negative contribution of ionospheric currents dominates over the positive effect of FACs in the summer hemisphere, while the opposite situation prevails in the winter hemisphere due to reduced ionospheric conductivity [see *Kikuchi et al.*, 2001, Figure 6b]. Since the relative contributions of FACs and ionospheric currents may change from one event to another depending on the spatial distribution and strength of the FACs, it is quite plausible that the FAC effects could at times only oppose the effects of ionospheric currents to the extent of significantly reducing the amplitude but not reversing the polarity of the H-field disturbance in the winter hemisphere. This can lead to a significant seasonal asymmetry of the H-field perturbation as observed with the substorm event studied here. It should be emphasized that the model calculations described above only help to gain insight as to the origin of the seasonal asymmetry. Comparison of the model results with the present observations on quantitative terms needs event-specific calculations with databased information on the global ionospheric conductivity for the specific day among other things, and this we intend to attempt in future.

[28] It is to be borne in mind that the physical situation qualitatively sketched above corresponds to the one obtained starting with the rapid reduction in the polar cap potential and just before the formation of the substorm current wedge. The effects of the current wedge, namely, the low-latitude positive bay and development of asymmetric ring current are seen a little later (see Figure 5) by which time the negative H-field disturbance on the dayside reached its peak amplitude. The current wedge effects are thus perceived not to have played a significant role in the dayside disturbances evidenced in the substorm event analyzed here.

[29] To conclude, the present study reaffirms the view that ionospheric currents of polar origin play a significant role in the manifestation of substorm expansion phase effects in the dayside subauroral region. This is in addition to the three-dimensional magnetospheric current system that is well known to produce positive H-component bay effects at low latitudes on the nightside. A rapid and precipitous reduction in the cross-polar cap potential (magnetospheric convection) in close association with a northward transition of IMF at the expansion phase onset of global-scale substorm is found to be responsible for the ionospheric component in the event studied. Whether the global (interplanetary, magnetospheric, and polar ionospheric) conditions identified here constitute the necessary and sufficient (or necessary but not sufficient) conditions for the ionospheric component to prevail remains to be assessed through further studies of carefully identified externally triggered substorms.

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