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Daytime equatorial geomagnetic *H* field response to the growth phase and expansion phase onset of isolated substorms: Case studies and their implications

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Abstract. Observations are presented from the Indian magnetometer network (dipole latitude range 1.2°S to 13.5°N) of short-lived (<1 hr) disturbances in the daytime equatorial geomagnetic *H* field associated with specific phases of isolated substorms. Three well-documented substorms are examined here, of which the expansion onset of each is closely associated with sudden transitions of interplanetary magnetic field (IMF) B_z/B_y after a >40-min interval of southward B_z. A positive baylike perturbation is found to prevail during the substorm growth phase, followed by a negative baylike disturbance starting precisely at the onset of expansion phase activity. The amplitude of the positive as well as negative bay-type disturbance showed a clear-cut enhancement at locations inside the equatorial electrojet belt when compared with stations away from the electrojet influence, indicative of a significant contribution of ionospheric currents to the bays. This pattern of response, which is found in two out of the three events studied, constitutes the first-time evidence for the occurrence of equatorial *H* field perturbations related to the growth phase as well as the expansion phase onset for individual substorms. The *H* field perturbations are suggested to be signatures of prompt penetration by electric fields associated with rapid changes in magnetospheric convection brought about by the swift transitions in the IMF B_z, before shielding by the ring current becomes effective. In the third event, where the growth phase is weak and prolonged, there is no perceptible simultaneous disturbance in the equatorial *H* field, while the expansion phase onset is associated with a positive bay of very small amplitude (≤4 nT).

1. Introduction

The middle- and low-latitude ionosphere is normally shielded from the large-scale convection electric field of the solar wind-magnetosphere dynamo origin by the Alfvén layer at the inner edge of the magnetosphere [*Vasyliunas*, 1972; *Crooker and Siscoe*, 1981]. There is a large body of experimental evidence which shows that the shielding can be weakened or broken at times of rapid changes in magnetospheric convection because of, for example, sharp and prominent transitions in the orientation of the B_z (north-south) component of interplanetary magnetic field (IMF). The signature of the breakdown or inefficient shielding is the coherent appearance of transient (1–2 hours) disturbances in the subauroral ionosphere all the way up to the dip equator [see *Wand and Evans*, 1981; *Blanc*, 1983a; *Mazaudier et al.*, 1984; *Fejer et al.*, 1990a, 1990b; *Kikuchi et al.*, 2000; *Kobea et al.*, 2000; see also *Fejer*, 1986, and references therein]. At dip equatorial latitudes of primary concern here, the typical effect of a northward turning of B_z is a transient reversal of the zonal electric field from the quiet time pattern with maximum amplitude in the midnight-dawn local time sector, occasionally as large as 4 mV/m [e.g., *Reddy and Nishida*, 1992; *Somayajulu et al.*, 1994; *Sastri et al.*, 1992a, 1997; see also *Fejer*, 1986, and references therein]. Sudden and prominent southward turnings of B_z are also observed to lead to electric field disturbances of opposite polarity, i.e., in phase with the quiet time diurnal pattern, but their occurrence is noticed to be not as frequent as with northward wings in B_z [*Fejer*, 1986]. Semianalytical and numerical simulation studies helped to understand the short-lived electric field disturbances at low and equatorial latitudes in terms of the penetration of magnetospheric or high-latitude electric fields due to under-shielding and over-shielding effects [e.g., *Kamide and Matsushita*, 1981; *Blanc*, 1983b; *Spiro et al.*, 1988; *Denisenko and Zamay*, 1992; *Tsunomura*, 1999; *Peymirat et al.*, 2000].

Perturbations in the equatorial ionospheric electric fields and currents during auroral disturbances, though basically understood, still have many aspects that need clarification and consolidation. One of the unclear aspects is the temporal relationship of the observed transient electric fields to the different phases of the substorm. Most of the case studies done so far have not paid due attention to substorm phases, based as they are on the use of auroral electrojet indices (usually hourly values) and high-latitude magnetograms for identification of bays. This weakness reflects to some extent in the varied nature of reports in the literature on the temporal association between the equatorial low-latitude electric field disturbances and phases of substorms or auroral disturbances. For example, the commonly noticed eastward reversal of the zonal electric field in the midnight-dawn sector at low and equatorial latitudes is reported to occur sometimes at the onset of the auroral disturbance, sometimes at the peak of the geomagnetic bay, and very often during its recovery phase triggered by a northward turning of B_z (this is particularly the case for isolated auroral activity), and sometimes it is delayed with reference to the northward B_z transition [see *Fejer*, 1986, and references therein; *Sastri et al.*,

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1992a, 1992b, 1997; *Reddy and Nishida*, 1992; *Fejer et al.*, 1990a, 1990b]. To our knowledge, very few studies [*Somayajulu et al.*, 1987; *Kikuchi et al.*, 2000] specifically dealt with the substorm phase-related perturbations in the equatorial low-latitude electric fields and currents. Careful consideration of substorm phases is important and necessary to improve our understanding of the physical processes operative in different phases of the phenomenon on a global basis [e.g., *Kamide et al.*, 1996]. For example, the auroral electrojet is now generally accepted to consist of two components, the directly driven (DD) component and the unloading (UL) component, and the relative importance of the two components varies significantly depending on the substorm phase and even from one substorm to another [see *Kamide and Kokubun*, 1996, and references therein]. The purpose of this paper is to report the results of a preliminary study of the response of equatorial geomagnetic H component in the daytime sector to three isolated substorms with clear-cut growth phase and expansion phase onsets. *Rostoker* [1983] demonstrated that the expansion onset of all the three substorms is due to external IMF triggering.

2. Substorm Event Selection

Figure 1 shows the temporal profiles of the auroral electrojet (AU/AL) indices for August 19, 1978, February 12, 1978, and January 20, 1978, reproduced from the data by *Kyoto University Faculty of Science* [1981a, 1981b]. The occurrence over the interval 0400–1100 UT of an isolated substorm with a distinct growth phase and a well-defined expansion phase onset (sudden decrease in AL) preceded by quiet conditions for ≥ 3 hours is quite apparent on all the three days shown in Figure 1. To help identification, the start times of the growth phase and the onset of the expansion phase are indicated by dashed vertical lines marked G and E, respectively, on the plots. These substorms were studied in detail by *Rostoker* [1983] using data from the University of Alberta International Magnetospheric Study magnetometer array and supplemented by data of a few selected observatories. The substorm on August 19, 1978, was also analyzed by *Nagai* [1982] with specific reference to magnetic field changes at geosynchronous orbit in addition to those at ground level. We have selected this substorm sample for our preliminary study for several reasons. They are isolated in nature and occurred over the time interval 0400–1100 UT, which corresponds to the period around local noon at Indian longitudes. The high noontime ionospheric conductivity is felt to be conducive to identifying the substorm phase-related effects in the equatorial H component. We are also guided in our substorm event selection by the views that investigation of carefully studied substorms is desirable because of the limitations in the usage in isolation of auroral electrojet indices or high-latitude magnetograms for identifying and distinguishing substorms from other types of geomagnetic disturbances in the auroral region and in timing the substorm phases [e.g., *Lyons*, 1996; *Rostoker*, 1996].

3. Equatorial Observations

We have studied for the three substorm days the data of the Indian magnetometer network stations, Trivandrum (TRD) (geographical latitude 8.5°N, longitude 76.9°E; dipole latitude 1.2°S), Kodaikanal (KOD) (geographical latitude 10.2°N, longitude 77.5°E; dipole latitude 0.6°N), Annamalainagar (ANN) (geographical latitude 11.4°N, longitude 79.7°E; dipole latitude 1.4°N), Alibag (ABG) (geographical latitude 18.6°N, longitude 72.9°E; dipole latitude 9.5°N) and Ujjain (UJJ) (geographical latitude 23.2°N, longitude 75.8°E; dipole latitude 13.5°N) covering the equatorial electrojet region and well beyond. Out of these Trivandrum and Kodaikanal are well within the electrojet belt, and Annamalainagar is on its northern fringe, while Alibag and Ujjain are well away from the influence of the electrojet. In sections 3.1–3.3 we present the equatorial geomagnetic observations with reference to IMF behavior and substorm characteristics by event and discuss and interpret the salient features of the same in section 4.

3.1. Event of August 19, 1978

Magnetometer data of IMP 8 for this day showed IMF B_z to be northward for ~4 hours prior to the sharp southward turning at 0700 UT, which is estimated to have impacted the dayside magnetopause at 0727 UT [*Lyons*, 1995]. IMF remained steadily southward thereafter until 0815 UT with an amplitude of 6–7 nT in the presence of a solar wind flow speed of 450 m s^{-1} [see *Rostoker*, 1983, Figure 10]. This led to enhanced magnetospheric convection and the growth phase of the substorm as may be seen in the behavior of auroral electrojet indices in Figure 1 [see also *Rostoker*, 1983, Figures 9 and 11; *Nagai*, 1982, Figures 2–4]. Magnetic field measurements at geosynchronous orbit on the nightside also showed changes in the northward (H) and radial (V) components characteristic of the growth phase [e.g., *McPherron et al.*, 1973] just after the arrival of southward IMF at 0727 UT [*Nagai*, 1982].

Figure 2 shows the variation of H field at stations in the Indian local noon sector on August 19. The H field variation on the quiet day, August 20 (dashed curve), is superposed to serve as a reference and to help evaluate the substorm-related perturbations. The reference quiet day is chosen following two criteria: (1) It is one of the designated international quiet days of the month, and (2) there is no significant auroral electrojet activity on the day between 0400 and 1100 UT, the time interval of focus here. The quiet-day curve in Figure 2 shows the usual steady decrease of H field in the afternoon due to solar zenith angle-dependent variation of ionospheric conductivity. Note that this feature is more prominent at stations close to the dip equator (TRD, KOD, and ANN) than at stations farther away (ABG and UJJ) because of the well-known contribution of the equatorial electrojet [e.g., *Matsushita*, 1967; *Richmond*, 1973]. In contrast, on August 19 a distinct positive baylike increase of H field (marked by arrows in Figure 2) is seen at all the stations from Trivandrum to Ujjain starting around 0730 UT, i.e., during the initial stage of the substorm growth phase. The bay profile is somewhat distorted later on by the H field decrease due to the ring current buildup (hourly average values of the equatorial Dst index were −9, −13, and −10 nT at 0700, 0800, and 0900 UT, respectively). The time interval over which the H component increase took place before the ring current effect dominated is ~20 min. The noteworthy feature of the H field perturbation (with some fine structure) is the conspicuous dip equator enhancement of its amplitude. When measured from the undisturbed trace to the peak value, the amplitude at Trivandrum, Kodaikanal, Annamalainagar, Alibag, and Ujjain is 13.3, 11.0, 9.8, 1.8, and 1.7 nT, respectively. The ratio of the amplitude at Trivandrum (close to the dip equator) to Alibag (well outside the electrojet region) is 7.3. If the amplitude is reckoned from the line joining the values at 0730 UT and 0800 UT (which are more or less the same, in deviation to the quiet-day decrease over the same interval of 8.3–10 nT at the electrojet stations), then this ratio works out as 4.0. As argued by *Reddy et al.* [1988], in the Indian sector the amplitude of a bay disturbance (duration of <1 hour) in H field due to a zonal ionospheric electric field disturbance is to be higher by a factor of at least 2.0 at Trivandrum compared with its value at Alibag. The strong latitude dependence of the positive bay amplitude evidenced here therefore demonstrates the occurrence of a short-lived enhancement of the daytime eastward electric field starting with the growth phase of the substorm. *Somayajulu et al.* [1987] reported earlier a similar positive baylike disturbance in the H component and in the mean Doppler frequency of

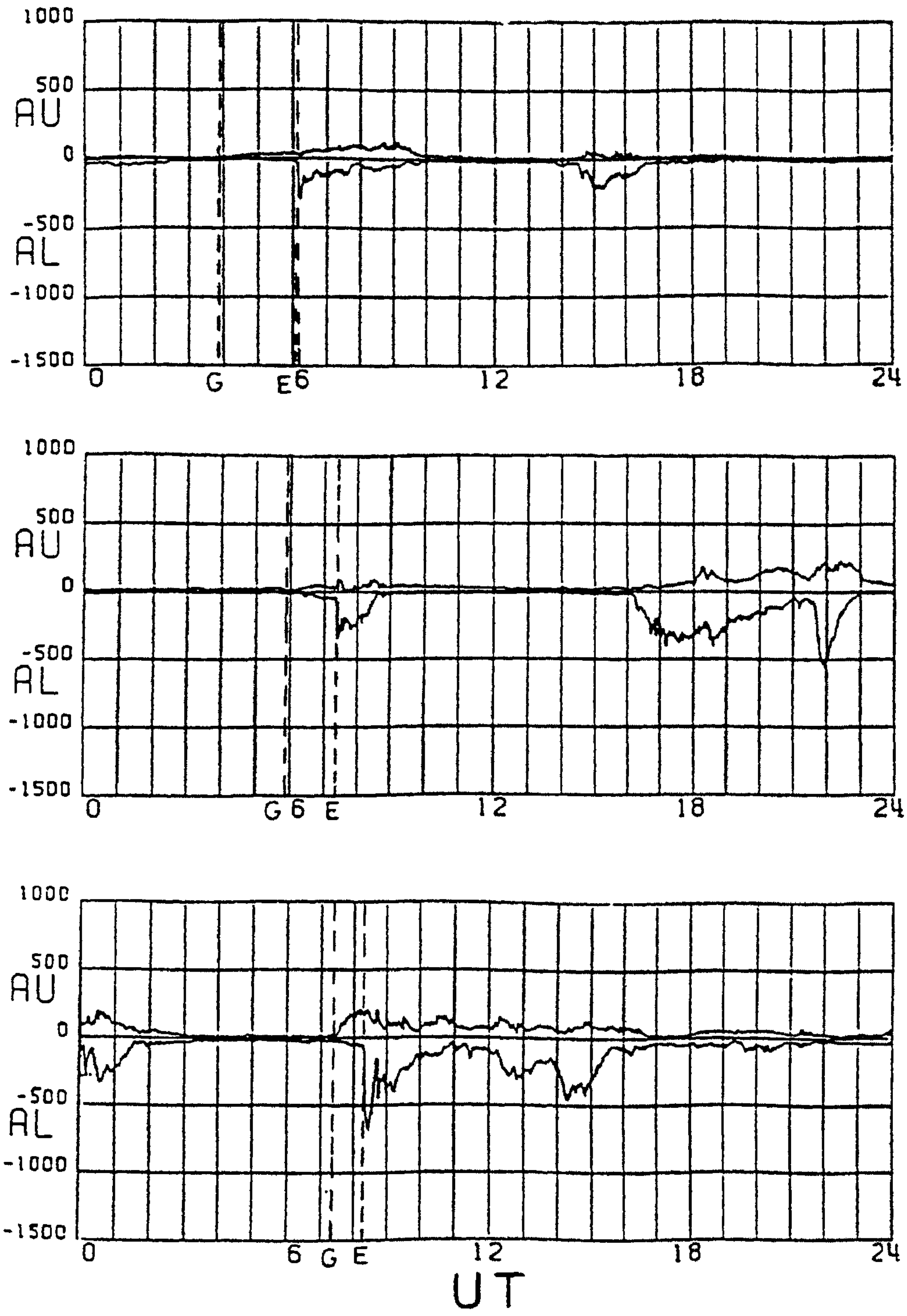

Figure 1. Time variation of the auroral electrojet indices (*AU/AL*) on August 19, 1978, February 12, 1978, and January 20, 1978 (*AE* of 12). The occurrence of an isolated substorm between 0400 and 1100 UT on all the 3 days may be noted. The dashed vertical lines marked G and E indicate the start time of the growth phase and the onset of expansion phase, respectively, of the substorms.

coherent backscatter from equatorial electrojet irregularities at Trivandrum (both indicative of an increase in the eastward electric field) during the growth phase (1020–1054 UT) of the substorm on March 22, 1979. However, in their event the positive bay in *H* field was not seen away from the dip equator (at Alibag) unlike in the event dealt with here. The shielding time (20 min) of the substorm growth phase-related response noticed here is, however, quite consistent with their observations.

The sharp northward turning of B_z (and the simultaneous large positive change in B_y) starting sometime between 0815 and 0820 UT is associated with the expansion phase onset, which is precisely determined to be at 0816 UT [*Rostoker*, 1983]. The expansion phase-related dipolarization of the magnetic field at the

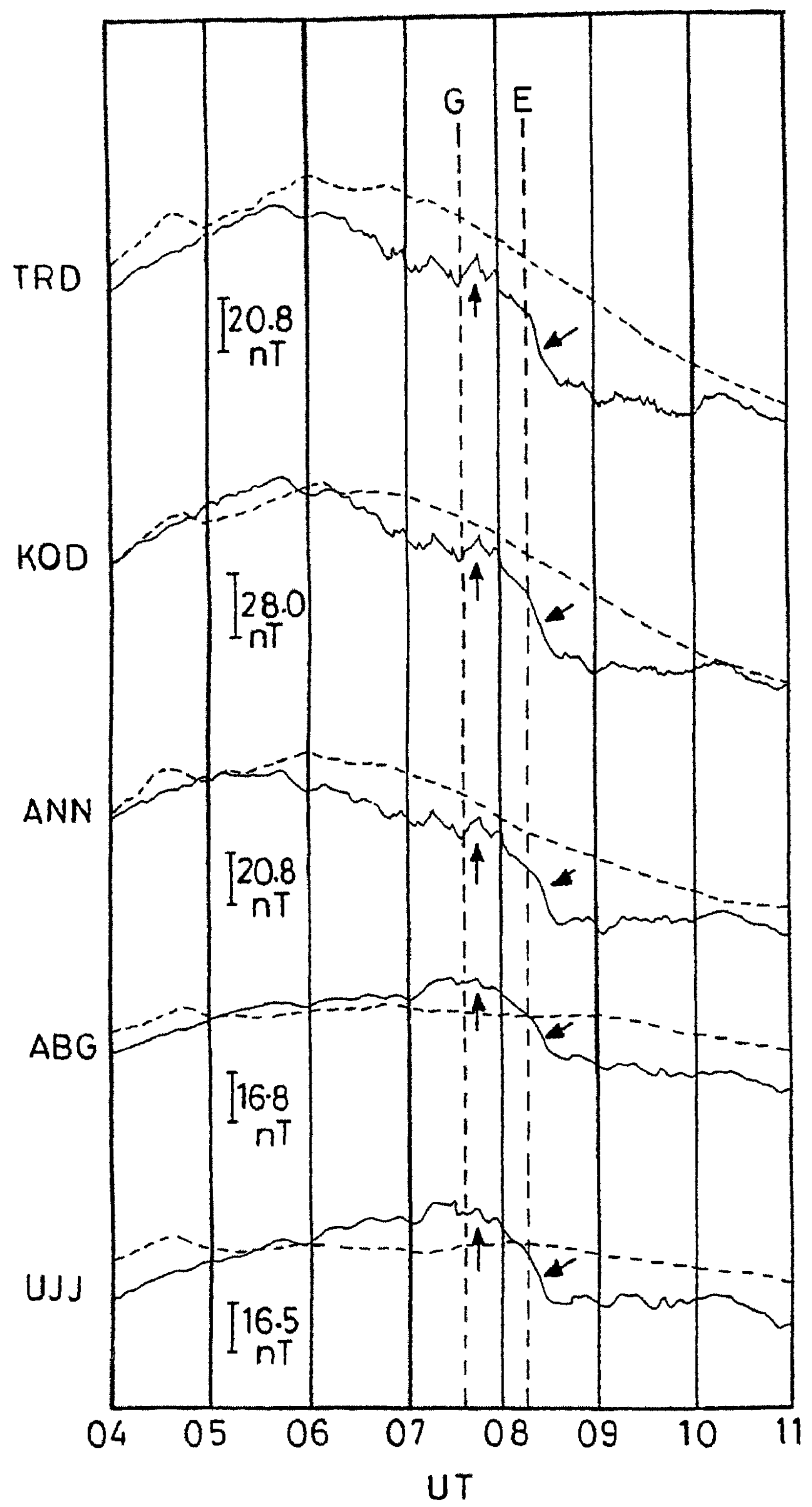

Figure 2. Geomagnetic *H* field variation at equatorial stations in the Indian sector on August 19, 1978 (solid curve). The start times of the substorm growth phase and expansion phase onset are indicated by dashed vertical lines marked G and E, respectively. The arrows indicate the substorm phase-related perturbations in the *H* field with a marked dip equator enhancement. The *H* field variation on August 20, 1978 (dashed curve), an international quiet day, is also shown for reference; see text for details. Station abbreviations are as follows: TRD, Trivandrum; KOD, Kodaikanal; ANN, Annamalainagar; ABG, Alibag; and UJJ, Ujjain.

geosynchronous orbit was also seen [*Nagai*, 1982]. The equatorial H component in the local afternoon sector responded quite sensitively to the onset of expansion phase as a bay-type decrease (marked by arrows in Figure 2) starting at 0820 UT at all the stations from Trivandrum to Ujjain. The amplitude as well as the sharpness of the H field reduction is remarkably enhanced close to the dip equator when compared with stations farther away. The amplitude of the H field decrease from 0820–0840 UT is 30.0, 24.3, 19.7, 14.2, and 15.7 nT at Trivandrum, Kodaikanal, Annamalainagar, Alibag, and Ujjain, respectively, giving a value of 2.1 for the ratio of amplitude between Trivandrum and Alibag. The disturbance amplitude is also estimated for individual stations by subtracting the quiet day change in H field over the same time interval from the data of August 19, yielding the net change in H field attributable to the substorm expansion phase. This procedure, which assumes that there is no change in the other current system(s) during the expansion phase, gives an amplitude ratio of 1.7 between Trivandrum and Alibag. It is to be noted in this context that not only the diurnal range but also the daytime variation of H field in the dip equatorial region exhibits considerable day-to-day variability even on quiet days, and, occasionally, the temporal pattern may be dissimilar at locations inside and outside the electrojet [see *Kane*, 1976, and references therein]. In fact, on August 19 (Ap = 11, $\sum Kp$ = 18), H field decreased at TRD, KOD, and ANN, while it increased conspicuously at UJJ from 0600 to 0700 UT, i.e., prior to the growth phase. Variability in the position of Sq focus due to, for example, the IMF B_y effect [*Matsushita*, 1975] could account for some but not all aspects of such behavior [see *Kane*, 1976, and references therein]. The enhanced amplitude of the H field perturbation at Trivandrum relative to Alibag is a clear pointer to the role of ionospheric currents in the equatorial negative bay effect of the substorm expansion phase. The duration over which the H field decrease took place, which is indicative of the shielding time by ring current, is again ~20 min. This observation is consistent with and confirms the very recent finding of *Kikuchi et al.* [2000] of a negative bay effect in H-field in the afternoon sector with a dip equatorial enhancement during the expansion phase of the substorm on April 20, 1993. *Kikuchi et al.* [2000] could not, however, ascertain the equatorial H field response to the substorm growth phase as it was superposed by a DP 2 fluctuation event.

3.2. Event of February 12, 1978

The changes in IMF that led to this substorm, the characteristics of the substorm, and the equatorial geomagnetic response are more or less identical to those evidenced in the event on August 19, 1978. A prominent southward turning of IMF occurred at 0548 UT, preceded by a 23-min interval of northward orientation [see *Rostoker*, 1983, Figure 4]. IMF remained remarkably southward from 0550 UT to 0718 UT leading to intensification of symmetric ring current and a slow build up of the driven system of auroral electrojets from just after 0600 UT (see Figure 1). We believe that the temporal pattern of noontime equatorial H field in the Indian sector during the interval 0604–0718 UT shown in Figure 3 reflects the effects associated with both the enhanced convection-driven auroral electrojets and the ring current. Note that there is a sharp reduction in H field at all the stations beginning at ~0545 UT (just prior to the marked southward turning of B_z at 0548 UT and slow buildup of growth phase) with an amplitude in the range 13.1–21.8 nT. The H field decrease is also seen prominently at low-latitude stations, San Juan (at the time of southward turning of B_z) and Guam (just prior to B_z transition). *Rostoker* [1983] opined that the sharp negative H field deflection at San Jaun and Guam was indicative of ring current intensification starting at ~0550 UT. The origin or physical significance of this feature is unclear to us. We hold the view that is unlikely to be related to the growth phase processes because of the uncertainties in timing the onset of growth

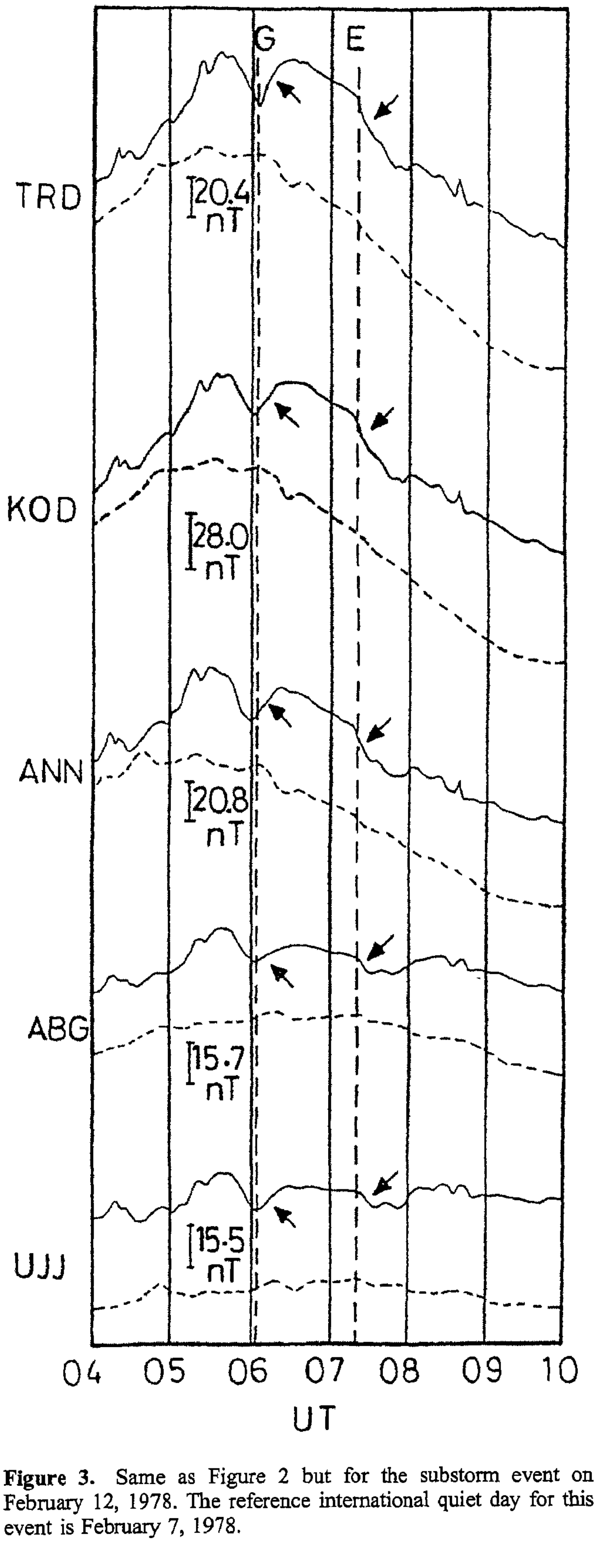

Figure 3. Same as Figure 2 but for the substorm event on February 12, 1978. The reference international quiet day for this event is February 7, 1978.

phase in this event (as compared with the event of August, 19; see Figure 1).

We consider, on the other hand, the H field increase for 21 min from 0603 to 0624 UT as the unmistakable signature of the disturbance related to enhanced magnetospheric convection for the reason that its amplitude is markedly enhanced at locations in the electrojet region when compared with locations outside it, in contrast to what is expected of the distant ring current. The magnitude of the H field increase over the said interval at Trivandrum, Kodaikanal, Annamalainagar, Alibag, and Ujjain is 22.6, 18.8, 16.4, 6.6, and 8.9 nT, respectively. The ratio of the amplitude between Trivandrum and Alibag is 3.4, a clear pointer to a short-lived increase of the eastward electric field that drives the daytime equatorial electrojet. It is pertinent to add here that weak expansive phase-type magnetic perturbations were noticed in the Alberta magnetometer array data from 0630 UT until the major expansion phase onset at 0718 UT [*Rostoker*, 1983]. This weak expansive phase activity could have contributed to the larger and sharper decrease of H field at the equatorial electrojet stations (TRD, KOD, and ANN) compared with the low-latitude stations (ABG and UJJ) over the said interval besides the ring current (see Figure 3).

The explosive onset of the substorm expansion phase as evidenced in the Alberta array is closely associated with the sudden northward swing of B_z at 0718 UT and a simultaneous large positive change in B_y. B_z remained stable in the northward orientation until 0750 UT, when the gap occurred in IMF data [see *Rostoker*, 1983, Figure 4]. As an immediate response to the onset of expansion phase, the equatorial H field underwent a prominent decrease in two stages with the first major decrease from 0718 to 0736 UT and the second minor one from 0742 to 0751 UT. The fine structure of the H field disturbance is conspicuously seen at the stations close to dip equator than at locations farther away. The total amplitude of the H field decrease at Trivandrum, Kodaikanal, Annamalainagar, Alibag, and Ujjain is 35.5, 33.1, 27.0, 8.6, and 7.0 nT, respectively, with a high value of 4.1 once again for the ratio of amplitude between Trivandrum and Alibag. The amplitude ratio becomes 2.7 when the amplitudes at these stations are evaluated with reference to the quiet-day pattern following the procedure described earlier. These observations are strongly suggestive of a significant reduction in the noontime equatorial electrojet current in association with the substorm expansion phase. The quarter-hourly ionosonde data of Kodaikanal for the day (ionosonde data are not available for August 19, 1978) corroborate the inference as they showed a sudden disappearance of equatorial sporadic (E_{sq}) on bottomside ionograms (partial counter-electrojet condition because the H field level is well above the mean midnight value even after the substorm effect) at 0745 UT (1245 LT (LT equals UT plus 5.0 hours)) and E_{sq} did not reappear during the day. It is to be recalled in this context that the occurrence of E_{sq} is a regular feature during daytime at and close to the dip equator, and its morning onset and evening disappearance are closely related to the strength of the equatorial electrojet [see *Kane*, 1976, and references therein].

3.3. Event of January 20, 1978

The IMF conditions that caused this substorm and the characteristics of the substorm are quite different in detail from the two events described in sections 3.1 and 3.2. A slow and steady southward turning of IMF B_z occurred on this day around 0340 UT, reaching a magnitude of about −4 nT at ~0500 UT, and that level of strength was maintained until 0600 UT [see *Rostoker*, 1983, Figure 7]. The slowly varying southward IMF of moderate strength led to a weak and long drawn-out growth phase as may be seen from the temporal pattern of *AU*/*AL* indices in Figure 1. Signatures of the development of the ring current were seen at low-latitude stations in the midnight and afternoon sectors with a simultaneous intensification of the auroral electrojet in the evening sector [see *Rostoker*, 1983, Figures 6 and 8]. This behavior of IMF and the associated substorm growth phase differ from those on August 19 and February 12, wherein the southward transition of B_z is swift and prominent, and the duration of southward B_z leading to a stronger growth phase was relatively shorter (48–88 min).

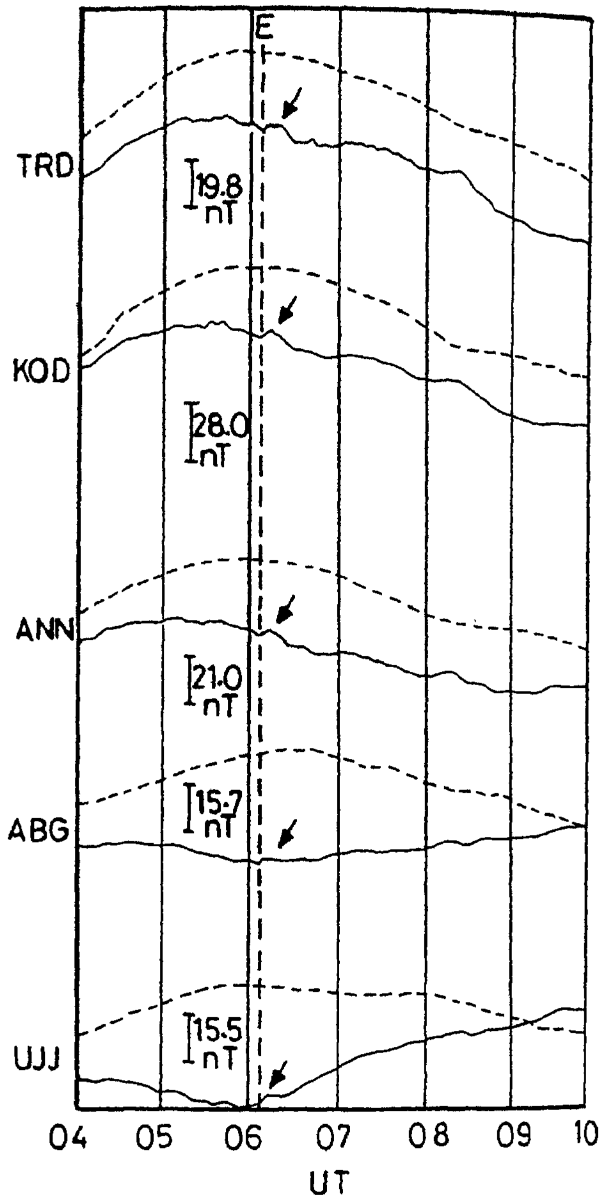

Figure 4. Same as Figure 2 but for the substorm event on January 20, 1978. The reference international quiet day for this event is January 21, 1978.

The equatorial H field data presented in Figure 4 reveal the absence of any perturbation during the 2-hour-long substorm growth phase, unlike in the two events detailed in sections 3.1 and 3.2. At stations close to the magnetic equator (Trivandrum, Kodaikanal, and Annamalainagar), the H field showed the regular solar zenith angle-dependent variation of the equatorial electrojet current, namely, intensification in the forenoon hours and weakening in the afternoon period. In contrast, the H field at Alibag and Ujjain underwent a slow and steady decrease in the forenoon hours and an increase in the afternoon. The strikingly opposite temporal variation of H field between the stations close to the dip equator and those farther away could be partly due to a change in the position of the Sq focus (note the absence of this behavior on January 21, the reference quiet day). An equatorward shift of Sq focus may result in the H field assuming lower values around local noon compared with other times at stations outside the electrojet region as observed. This seems possible because IMF B_y was negative (toward sector) for most of the day, and *Matsushita* [1975] showed earlier that the Sq focus moves equatorward on days with toward polarity (B_y negative) compared with days with away polarity (B_y positive).

The expansion phase onset of the substorm occurred at 0607 UT just after the northward turning of B_z (and a simultaneous large negative swing in B_y) at 0605 UT. *Rostoker* [1983] opined that substorm onset in this case could also have been triggered by the change in B_y, and this opinion was endorsed by *Lyons* [1995]. Data of Alberta array and other auroral zone stations showed the expansion phase activity to be extended in longitude, while at low latitudes it is seen as a positive bay in the midnight sector (San Juan) and as a negative bay in the afternoon sector (Guam) [see *Rostoker*, 1983, Figures 6 and 8]. It is indeed interesting that there is no negative baylike disturbance in the equatorial H component at any of the stations in the Indian forenoon sector with the onset of expansion phase as may be seen from Figure 4. What is seen instead is the presence of a small-amplitude positive bay over the period 0608–0630 UT. It is to be noted that the small amplitude (1.6–4.0 nT at the various stations) and the presence of pulsations (see Figure 4) rendered the amplitude estimate rather difficult, so much so that all that can safely be inferred is that there is no obvious dip equator enhancement of the positive bay.

We note in passing that auroral electrojet activity persisted after the substorm onset until at least 0915 UT (see Figure 1). During this period, B_z experienced another northward transition between 0815 and 0820 UT (albeit rather slower compared with the one at 0605 UT) with a simultaneous strengthening of westward electrojet at the auroral zone stations up to ~0900 UT [see *Rostoker*, 1983, Figures 6 and 7]. This seems to be accompanied by a reduction in H field starting from ~0822 UT at the Indian equatorial stations, which moved into the afternoon sector by that time. As may be seen in Figure 4, the H field decrease is sharper, larger, and continued until 0915 UT at Trivandrum, Kodaikanal, and Annamalinagar, while at Alibag and Ujjain the reduction is apparent only for a short period (0822–0830 UT), and thereafter the H-field slowly and steadily increased until 0915 UT.

4. Discussion and Conclusions

We have investigated the response of the daytime equatorial geomagnetic H field to three isolated substorms, paying particular attention to substorm phases and the changes in IMF B_z/B_y responsible for them. We found a repeatable pattern of perturbations in the H field in two of the events wherein the onset of expansion phase is unambiguously associated with a northward turning of IMF, after an interval (>40 min) of southward IMF. The response pattern is characterized by an increase of H field at all the equatorial stations spanning the dipole latitude range 1.2°S to 13.5°N for ~20 min starting with the substorm growth phase and followed by a sharper decrease for 20–36 min beginning precisely at the onset of the expansion phase. The amplitude of both H field perturbations exhibits a significant enhancement inside the equatorial electrojet region, when compared with stations well away from the influence of the electrojet. The findings not only confirmed the earlier reports of a positive bay effect (negative bay effect with a marked dip equator enhancement) in the equatorial H field of the afternoon sector during the substorm growth phase (expansion phase activity) [*Somayajulu et al.*, 1987; *Kikuchi et al.*, 2000] but also brought to light the fact that both the positive and negative bays do occur in that order in individual isolated substorms. Our results are therefore an important addition to the observational knowledge of the response of equatorial geomagnetic H field on the dayside to substorm phases. It is pertinent to mention that in this context such disturbances of composite polarity in the nighttime equatorial F region height (hence in the zonal electric field) have also been identified earlier during isolated auroral substorms [*Sastri et al.*, 1992a, 1992b], but the substorms in these studies were ascertained solely from the hourly AE index and high-latitude magnetograms with attendant weaknesses mentioned earlier.

It is generally accepted that the sequence of processes leading to a substorm starts with the arrival and persistence (≥30 min) of southward IMF at the dayside magnetopause resulting in enhanced solar wind-magnetosphere coupling and hence enhanced plasma convection in the outer magnetosphere. The large-scale convection electric field maps on to the polar caps and drives the two-cell type ionospheric current system. These and other changes in the magnetosphere and high-latitude ionosphere domains identify the substorm growth phase wherein the directly driven component is usually dominant. There could be a simultaneous accumulation of magnetic energy (loading), but its role is secondary compared with the driven process of auroral electrojet intensification. If the IMF direction-related change in the convection electric field is sudden and prominent, then the convection electric field can penetrate all the way to the dip equator through the polar ionosphere and manifest until such a time when the ring current shielding reasserts itself. Theoretical and numerical simulations studies consistently show that a sudden (idealized) increase of magnetospheric convection (represented by the polar cap potential drop and region 1 field-aligned currents (FACs)) leads to a short-lived disturbance in the equatorial zonal electric field with a polarity in phase with the quiet time pattern, namely, eastward on the dayside and westward on the nightside [e.g., *Blanc*, 1983b; *Spiro et al.*, 1988; *Denisenko and Zamay*, 1992; *Tsunomura*, 1999]. *Kikuchi et al.* [1978] and *Kikuchi and Araki* [1979] also showed that the polar electric field can penetrate instantaneously to the dip equator as a zero-order transverse magnetic mode in the Earth-ionosphere waveguide with no cutoff frequency. The increase of H field with a dip equatorial enhancement starting with the growth phase of the substorms on August 19 and February 12 thus finds an explanation in terms of prompt penetration electric fields. The shielding time of 20 min noticed in these events for the growth phase-related H field perturbation is also in agreement with theoretical estimates [*Senior and Blanc*, 1984; *Spiro et al.*, 1988] as well as earlier observations [*Somayajulu et al.*, 1987; *Kikuchi et al.*, 2000]. The absence of such a growth phase-related H field increase in the substorm event of January 20, 1978, could be due to the relatively slower and weaker enhancement of magnetospheric convection to be effectively shielded by region 2 field-aligned currents associated with the magnetospheric ring current.

The origin of the explosive onset of expansion phase, which is what distinguishes substorms from other types of auroral disturbances, is an unsettled problem in spite of the extensive and intensive research done so far. Since the substorms whose equatorial geomagnetic response is evaluated here belong the category of IMF B_z/B_y-triggered substorms, we consider the model of *Lyons* [1995] to be the relevant one for the discussion of our results. According to this model the expansion phase onset is due to a sudden reduction in the large-scale electric field imparted to the magnetosphere from the solar wind that is enhanced during the preceding growth phase by the southward IMF. The electric field reduction which can be caused by directional changes in B_z as well as B_y leads to the formation of the substorm current wedge consisting of reduced cross-tail current, field-aligned currents and the auroral elctrojet. It follows conceptually that a sudden reduction in a large-scale electric field will be accompanied by a similar reduction in the polar cap potential drop and region 1 FAC and a westward ionospheric electric field disturbance (decrease in the dayside equatorial electrojet current) close to the dip equator, before shielding by ring current gains control. This over-shielding effect is just the opposite of what happens with a sudden increase of the polar cap potential drop and has been extensively studied [e.g., *Blanc*, 1983b; *Spiro et al.*, 1988; *Denisenko and Zamay*, 1992; *Tsunomura*, 1999; *Peymirat et al.*, 2000]. We therefore interpret the negative baylike perturbation in H field with marked dip equator enhancement noticed precisely with the onset of expansion phase of the substorms on August 19 and February 12 as the signatures of penetration electric fields associated with the expansion phase reduction in convection electric field. Our observations, in fact, lend indirect support (though limited to just two events) to the theory of *Lyons* [1995], the key element of which is the sudden reduction of convection electric field due to directional changes in IMF.

The geomagnetic negative (positive) bay at middle and low latitudes in the afternoon (midnight and morning sectors) with a monotonic decrease of amplitude from midlatitudes to the equator is generally understood in terms of the three-dimensional current system of the substorm current wedge [e.g., *Kamide and Fukushima*, 1972; *Reddy et al.*, 1987]. The bay is thus perceived as being primarily due to distant currents, namely, the cross-tail current, the partial ring current, and FACs. The occurrence of a positive bay in close association with the expansion phase onset of the substorm on January 20 is therefore rather puzzling. Moreover, since the expansion phase in this event seems to be associated with a large negative change in B_y itself, it is unclear as to why the B_y-induced reduction in convection electric field is not accompanied by penetration electric fields at the dayside dip equator as in the other two events.

In conclusion, the present case studies showed that a short-lived (<1 hour) increase and a subsequent decrease in the equatorial ionospheric eastward electric field occurs with the growth phase and expansion phase onset, respectively, of some isolated IMF-triggered substorms. Therefore there seems to be an ionospheric current component in the dayside equatorial magnetic perturbations associated both with the growth phase and expansion phase of some substorms, contrary to prevailing perceptions. In general, the validity of the results of our case studies needs to be ascertained and established through analysis of a large number of carefully identified IMF-triggered substorms. Further work is also required to characterize the effects on the dayside equatorial magnetic field of substorms without any identifiable external IMF trigger [*Henderson et al.*, 1996], substorms triggered exclusively by changes in IMF B_y [*Troshichev et al.*, 1986], and substorms induced by enhancements in solar wind dynamic pressure [e.g., *Kokubun et al.*, 1977].

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References

Blanc, M., Magnetospheric convection effect at midlatitudes, 1, Saint-Santin observations, *J. Geophys. Res*, *88*, 211–223, 1983a.

Blanc, M., Magnetospheric convection effects at midlatitudes, 3, Theoretical derivation of the disturbance convection pattern in the plasmasphere, *J. Geophys. Res.*, *88*, 235–251, 1983b.

Crooker, N. U., and G. L. Siscoe, Birkeland currents as the cause of the low-latitude asymmetric disturbance field, *J. Geophys. Res.*, *86*, 11,201–11,210, 1981.

Denisenko, V. V., and S. S. Zamay, Electric field in the equatorial ionosphere, *Planet. Space Sci.*, *40*, 941–952, 1992.

Fejer, B. G., Equatorial ionospheric electric fields associated with magnetopsheric disturbances, in *Proceedings of Chapman Conference on Solar Wind-Magnetosphere Coupling*, edited by Y. Kamide and J. A. Slavin, D. Reidel, Norwell, Mass., 1986.

Fejer, B. G., R. W. Spiro, R. A. Wolf, and J. C. Foster, Latitudinal variation of penetration electric fields during magnetically disturbed periods: 1986 SUNDIAL observations and model results, *Ann. Geophys.*, *8*, 441–454, 1990a.

Fejer, B. G., et al., Low and mid-latitude ionospheric electric fields during the January 1984 GISMOS campaign, *J. Geophys. Res.*, *95*, 2367–2377, 1990b.

Henderson, M. G., G. D. Reeves, R. D. Belian, and J. S. Murphree, Observations of magetospheric substorms occurring with no apparent solar wind/IMF trigger, *J. Geophys. Res.*, *101*, 10,773–10,791, 1996.

Kamide, Y., and N. Fukushima, Positive geomagnetic bays in evening high latitudes and their possible connection with partial ring current, *Rep. Ionos. Space Res. Jpn.*, *26*, 79–101, 1972.

Kamide, Y., and S. Kokubun, Two-component auroral electrojet: Importance for substorm studies, *J. Geophys. Res.*, *101*, 13,027–13,046, 1996.

Kamide, Y., and S. Matsushita, Penetration of high latitude electric fields into low latitudes, *J. Atmos. Terr. Phys.*, *43*, 411–425, 1981.

Kamide, Y., W. Sun, and S.-I Akasofu, The average ionospheric electrodynamics for the different substorm phases, *J. Geophys. Res.*, *101*, 99–109, 1996.

Kane, R. P., Geomagnetic field variations, *Space Sci. Rev.*, *18*, 413–540, 1976.

Kikuchi, T., and T. Araki, Horizontal transmission of the polar electric field to the equator, *J. Atmos. Terr. Phys.*, *41*, 927–936, 1979.

Kikuchi, T., T. Araki, H. Maeda, and K. Maekawa, Transmission of polar electric fields to the equator, *Nature*, *273*, 650–651, 1978.

Kikuchi, T., H. Luhr, K. Schlegel, H. Tachihara, M. Shinohara, and T.-I. Kitamura, Penetration of auroral electric fields to the equator during a substorm, *J. Geophys. Res.*, *105*, 23,251–23,261, 2000.

Kobea, A. T., A. D. Richmond, B. A. Emery, C. Peymirat, H. Luhr, T. Moretto, M. Hariston, and C. Amory-Mazaudier, Electrodynamic coupling of high and low latitudes: Observations on May 27, 1993, *J. Geophys. Res.*, *105*, 22,979–22,989, 2000.

Kokubun, S., R. L. McPherron, and C. T. Russell, Triggering of substorms by solar wind discontinuities, *J. Geophys. Res.*, *82*, 74, 1977.

Kyoto University Faculty of Science, Auroral electrojet indices (*AE*) for January–June 1978, http://swdcdb.kugi.kyoto-u.ac.jp/, World Data Cent. C2 for Geomagn., Kyoto, Japan, 1981a.

Kyoto University Faculty of Science, Auroral electrojet indices (*AE*) for July–December 1978, http://swdcdb.kugi.kyoto-u.ac.jp/, World Data Cent. C2 for Geomagn., Kyoto, Japan, 1981b.

Lyons, L. R., A new theory for magnetospheric substorms, *J. Geophys. Res.*, *100*, 19,069–19,081, 1995.

Lyons, L. R., Substorms: Fundamental observational features, distinction from other disturbances, and external triggering, *J. Geophys. Res.*, *101*, 13,011–13,025, 1996.

Matsushita, S., Solar quiet and lunar daily variation fields, in *Physics of Geomagnetic Phenomena*, vol. 1, pp. 301–324, Academic, San Diego, Calif., 1967.

Matsushita, S., IMF polarity effects on the *Sq* current focus location, *J. Geophys. Res.*, *80*, 4751–4754, 1975.

Mazaudier, C., M. Blanc, E. Nielsen, and M.-Y. Zi, Latitudinal profile of the magnetospheric convection electric field at ionospheric latitudes from a chain of magnetic and radar data, *J. Geophys. Res.*, *89*, 375–381, 1984.

McPherron, R. L., M. P. Aubry, C. T. Russell, and P. J. Coleman Jr., Satellite studies of magnetospheric substorms on August 15, 1968, 4, OGO5 magnetic field observations, *J. Geophys. Res.*, *78*, 3068–3078, 1973.

Nagai, T., Observed magnetic substorm signatures at synchronous altitude, *J. Geophys. Res.*, *87*, 4405–4417, 1982.

Peymirat, C., A. D. Richmond, and A. T. Kobea, Electrodynamic coupling of high and low latitudes: Simulation of undershielding/overshielding effects, *J. Geophys. Res.*, *105*, 22,991–23,003, 2000.

Reddy, C. A., and A. Nishida, Magnetospheric substorm and nighttime height changes of the F2 region at middle and low latitudes, *J. Geophys. Res.*, *97*, 3039–3061, 1992.

Reddy, C. A., S. Ajith Kumar, and V. V. Somayajulu, An observational test for the ionospheric or magnetospheric origin of night-time geomagnetic positive bays at low and middle latitudes, *Planet. Space Sci.*, *36*, 1149–1156, 1988.

Richmond, A. D., Equatorial electrojet, II, Use of the model to study the equatorial ionosphere, *J. Atmos. Terr. Phys.*, *35*, 1105–1118, 1973.

Rostoker, G., Triggering of expansive phase intensifications of magnetospheric substorms by northward turnings of the interplanetary magnetic field, *J Geophys. Res.*, *88*, 6981–6993, 1983.

Rostoker, G., Phenomenology and physics of magnetospheric substorms, *J. Geophys. Res.*, *101*, 12,955–12,973, 1996.

Sastri, J. H., H. N. R. Rao, and K. B. Ramesh, Transient composite electric field disturbances near the dip equator associated with auroral substorms, *Geophys. Res. Lett.*, *19*, 1451–1454, 1992a.

Sastri, J. H., K. B. Ramesh, and D. Karunakaran, On the nature of substorm-related transient electric field disturbances in the equatorial ionosphere, *Planet. Space Sci.*, *40*, 95–103, 1992b.

Sastri, J. H., M. A. Abdu, and J. H. A. Sobral, Response of equatorial

ionosphere to episodes of asymmetric ring current activity, *Ann. Geophys.*, *15*, 1316–1323, 1997.
Senior, C., and M. Blanc, On the control of magnetospheric convection by spatial gradients of ionospheric conductivities, *J. Geophys. Res.*, *89*, 261–284, 1984.
Somayajulu, V. V., C. A. Reddy, and K. S. Viswanathan, Penetration of magnetospheric convection electric field to the equatorial ionosphere during the substorm of March 22, 1979, *Geophys. Res. Lett.*, *14*, 876–879, 1987.
Somayajulu, V. V., B. V. Krishnamurthy, and K. S. V. Subbarao, Response of nighttime equatorial F region to magnetic disturbances, *J. Atmos. Terr. Phys.*, *53*, 956, 1994.
Spiro, R. W., R. A. Wolf, and B. G. Fejer, Penetration of high latitude electric field effects to low latitudes during SUNDIAL 1984, *Ann. Geophys.*, *6*, 39–50, 1988.
Troshichev, O. A., A. L. Kotikov, B. D. Bolotinskaya, and V. G. Andrezen, Influence of the IMF azimuthal component on magnetospheric substorm dynamics, *J. Geomagn. Geoelectr.*, *38*, 1075–1088, 1986.
Tsunomura, S., Numerical analysis of global ionospheric current system including the effect of equatorial enhancement, *Ann. Geophys.*, *17*, 692–706, 1999.
Vasyliunas, V. M., The interrelationship of magnetospheric processes, in *Earth's Magnetospheric Processes*, edited by B. M. McCormac, pp. 29–38, D. Reidel, Norwell, Mass., 1972.
Wand, R. H., and J. V. Evans, The penetration of convection electric fields to the latitude of Millstone Hill ($\lambda = 56°$), *J. Geophys. Res.*, *86*, 5809–5814, 1981.

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