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Westward ionospheric electric field perturbations on the dayside associated with substorm processes

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[1] A controversy has risen in the direction of ionospheric electric field perturbation on the dayside caused by substorm expansion phase in recent years, i.e., eastward or westward. To exclude the effect of interplanetary magnetic field northward turning, the substorms without interplanetary field (IMF) trigger are required to investigate this issue. Previous works, such as that by Huang et al. (2004), showed that the eastward electric field perturbations caused by substorms can be observed. However, our case suggests that some substorms can produce strong westward electric field perturbations and drive westward equatorial electrojets on the dayside ionosphere. This westward electric field is created by an overshielding-like imbalance state of field-aligned currents (FACs), Region 2 (R2) FAC greater than Region 1 (R1) FAC, which is built up through R2 FAC enhancement rather than R1 FAC reduction due to IMF northward turning. The substorm processes should be responsible for the westward electric field especially through polar cap shrinkage and magnetic field dipolarization.

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1. Introduction

[2] It is well known that ionospheric electric field can respond to solar wind variations during geomagnetic active period [*Nishida et al.*, 1966; *Kelley*, 1989; *Fejer et al.*, 1979; *Gonzales et al.*, 1979; *Kikuchi and Araki*, 1979; *Sastri et al.*, 1997; *Huang et al.*, 2005; *Wei et al.*, 2008a]. Many observations suggest that the interplanetary electric field (IEF) or the magnetospheric electric field can promptly penetrate into the equatorial ionosphere during large storms [e.g., *Abdu et al.*, 2007; *Zhao et al.*, 2008]. The penetration electric field is closely related to the orientation of interplanetary magnetic field (IMF). Taking the situation on the dayside equator for example, southward IMF B_Z frequently results in eastward electric field disturbance (so-called "undershielding") [e.g., *Huang et al.*, 2005], while abrupt northward turning of IMF B_Z after a prolonged southward orientation may produce westward electric field disturbance (so-called "overshielding") [e.g., *Kelley et al.*, 1979].

[3] The undershielding and overshielding can be explained as imbalance between Region 1 (R1) and Region 2 (R2) field-aligned currents (FACs) [*Wolf et al.*, 2007]. A rapid southward turning of IMF B_Z will immediately cause the R1 FAC to increase, but the R2 FAC will take longer time (tens of minutes to several hours) to balance the enhanced R1 FAC, because the R2 FAC depends on charge accumulations on the Alfven layer. Hence the duskward IEF will penetrate into the equator and be eastward on the dayside before the R2 FAC is fully developed. Conversely, an abrupt northward turning of IMF B_Z after a prolonged southward orientation may cause the R2 FAC to be stronger than the R1 FAC for a while, when the dawnward shielding electric field can penetrate into the equator and be westward on the dayside. Please note that the term "northward turning" also includes significant decrease of the magnitude of southward B_Z (still remains southward).

[4] In recent years, a controversy raised in the direction of ionospheric electric field perturbations on the dayside caused by substorms. On one hand, many cases indicate that westward electric field perturbations are observed during substorm expansion phases [e.g., *Kelley et al.*, 1979; *Fejer et al.*, 1979; *Gonzales et al.*, 1979; *Kikuchi et al.*, 2000, 2003; *Sastri et al.*, 2001, 2003]. On the other hand, *Huang et al.* [2004] argued that the substorm-related perturbations of ionospheric electric field over the equator could not be directly identified through those substorms triggered by IMF northward turning, because the IMF northward turning might produce westward overshielding electric field alone. Furthermore, to avoid this kind of logical awkwardness, they chose sawtooth substorms to investigate this issue, because most of cycles of one sawtooth substorm are independent on IMF variations [*Huang et al.*, 2003], thus the substorm-related perturbations of ionospheric electric field can be separated. They found that the substorm-related electric field perturbations

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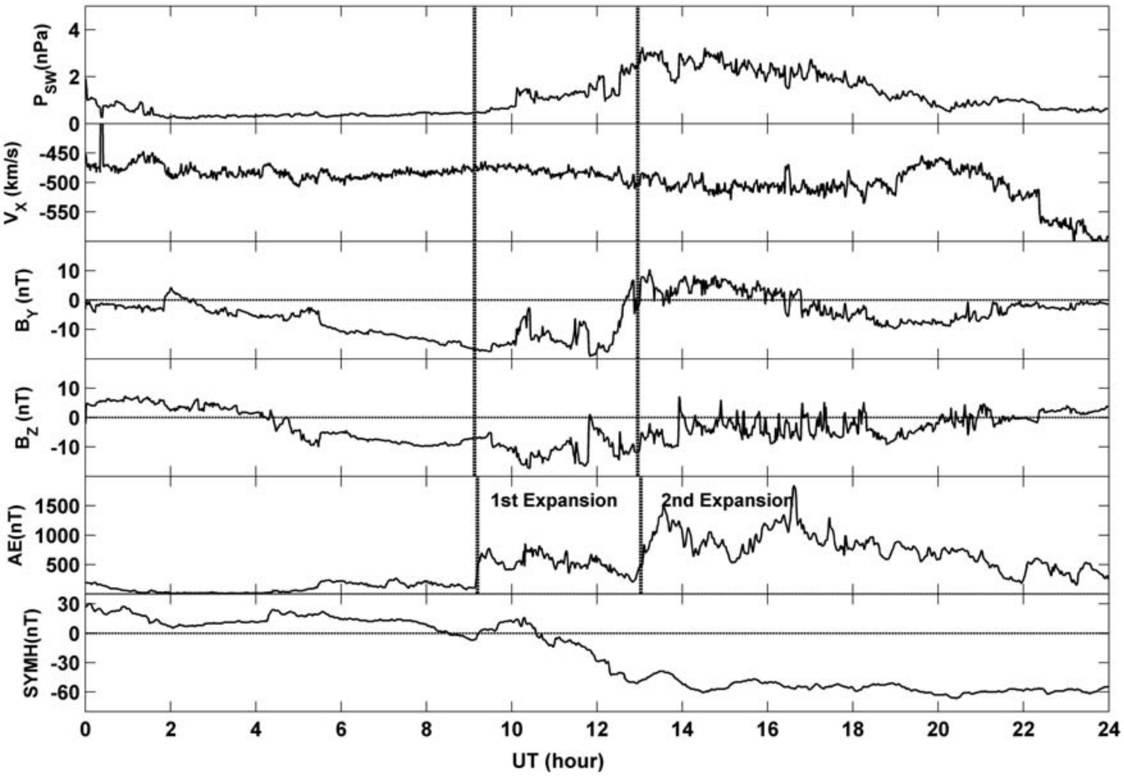

Figure 1. Geotail observations (in GSM) and geomagnetic indices on 20 November 2007. The first through fourth panels are solar wind dynamic pressure P_{SW}, solar wind velocity V_X, IMF B_Y, and IMF B_Z. The fifth and sixth panels are AE and symmetric ring current index SYMH. The two vertical lines marked on the AE are onsets of substorm expansion phases identified from AE and synchronous orbit observation presented in Figure 2. The two vertical lines marked on the Geotail data plots correspond to the two substorm onsets but apply the time shift 4.4 min (see the text).

are eastward, which is contrary to previous conclusions. However, it is still not clear what mechanism should be responsible for the eastward electric field, and *Huang et al.* [2004] did not discuss it further. *Miyashita et al.* [2008] presented the response of large-scale ionospheric convection to substorm expansion onsets on the basis of two weak substorms of 1 May 2001, and suggested that the ionospheric convection was enhanced during expansion phases. These observations are consistent with the conclusions of *Huang et al.* [2004].

[5] Some newly published observations made this controversy more complicated. *Wei et al.* [2008b] proposed that except for IMF northward turning, sharp decrease of the solar wind dynamic pressure also plays an import role in the formation of some overshielding events through the magnetospheric reconfiguration or the Alfven layer motion. More interestingly, *Ebihara et al.* [2008] found that the antisunward plasma flow in the subauroral region appeared without IMF B_Z northward turning. They speculated that it was attributed to a sudden contraction of the polar cap associated with the substorm or to a sudden strengthening of the inertial current converted from the abrupt injection of magnetospheric ions. The studies of *Ebihara et al.* [2008] implied that the substorms probably produce a westward electric field on the dayside ionosphere through enhancing the partial ring current which is closed by the R2 FAC. If the enhanced R2 FAC is greater than the R1 FAC, as mentioned above, the westward overshielding electric field perturbations on the dayside are expected to occur.

[6] The motivation of this paper is to observationally verify the westward ionospheric electric field perturbations over the dayside equator caused by substorms. We show the westward ionospheric electric field perturbations occurred under the southward IMF B_Z during an intense substorm (AE < 1800 nT) but a medium storm (Dst > -71nT). The westward electric field was identified through the strong equatorial counter electrojet (CEJ) inferred from geomagnetic measurements in Peru sector. Furthermore, the CEJ variations during substorm expansion phases and intensification were closely related to the partial ring current and R2 FAC variations.

2. Observations

2.1. Solar Wind Condition and Substorm Features

[7] Figure 1 shows an overview of Geotail ((29, 3, -8) R_E) observations and geomagnetic indices on 20 November 2007. The first through fourth panels plot solar wind dynamic pressure (P_{SW}), solar wind velocity X component (V_X), IMF B_Y and B_Z. Please note that the GSM coordinate system is applied for space-based measurements throughout this paper. Assuming the dayside magnetopause at X = 10 R_E, if only consider propagation along *x* axis and take V_X = -460 km/s, the propagating time

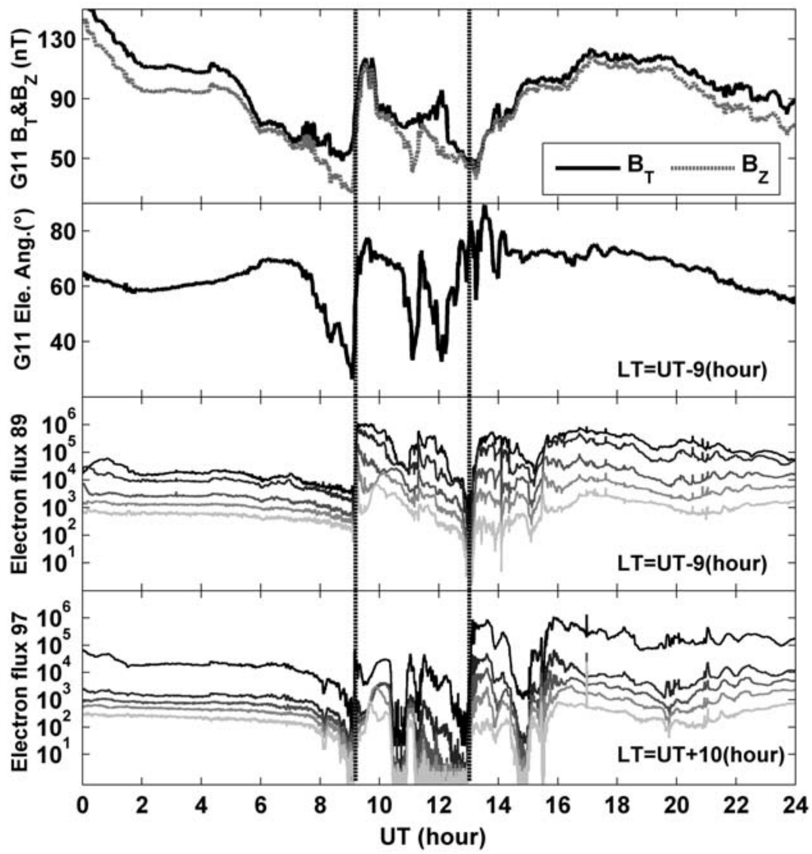

Figure 2. The first panel shows total magnetic field (B_T) and its Z component (B_Z) observed by GOES 11, which was located at midnight at 0900 UT (LT = UT − 9 h). The second panel plots the corresponding elevation angle. The third and fourth panels show energetic electron fluxes in #/cm^2/s/sr/keV observed by LANL 1989-046 and 97A, respectively. The energetic electron energy channels (first panel) are 50–75, 75–105, 105–150, 150–225, and 225–315 keV. The two vertical lines show two onsets of substorm expansion phases.

between Geotail and the magnetopause can be estimated at 4.4 min.

[8] The fifth and sixth panels of Figure 1 show the AE index and the symmetric ring current index (SYMH). The AE index abruptly increased from 121 to 703 nT at 0912 UT (first vertical dashed line), and from 237 to 1485 nT around 1302 UT (second vertical line), indicating two onsets of substorm expansion phase. The SYMH had been positive since 1812 UT on 19 November till 0832 UT on 20 November (not all shown), which was caused by continuous high solar wind dynamic pressure (2–6 nPa). This medium magnetic storm did not exhibit storm sudden commencement (ssc) but featured very prolonged recovery phase. However, it is clear that the symmetric ring current grew from 1020 UT to 1430 UT, and then it remained for tens of hours without obvious decay.

[9] Figure 2 reveals more details of the substorm signatures on the synchronous orbit. The first panel shows total magnetic field (B_T) and its Z component (B_Z) observed by GOES 11, which located midnight at 0900 UT (LT = UT − 9 h). The second panel plots the corresponding elevation angle defined as $\tan^{-1}(B_Z/(B_X^2 + B_Y^2)^{1/2})$. The third and fourth panels show energetic electron fluxes measured by LANL 1989-046 (LT = UT − 9 h) and 97A (LT = UT + 10 h). For the first onset, GOES 11 and LANL 1989-046 at midnight recorded typical substorm characteristics, i.e., strong magnetic filed dipolarization and energetic electron injection. At 1101 UT, there was an intensification identified from GOES 11 and LANL 1989-046 observations. For the second onset, LANL 97A on 2300 LT showed significant energetic electron injection. GOES 11 did not capture distinct dipolarization because it was located on 0400 LT and far from midnight.

[10] To determine the triggers of the two substorm expansion phase onsets, now we turn to Figure 1. The two vertical dashed lines on Geotail plot correspond to substorm onsets considering the time shift 4.4 min. It is known that the time delay between magnetopause contact of an IMF trigger and substorm onset is several minutes, e.g., ~9 min [*Lyons et al.*, 1997]. However, there were no obvious IMF and solar wind dynamic pressure changes responsible for the first onset and the followed intensification, even though considering the trigger time delay. Thus the substorm expansion phase onset at 0912 UT was not induced by IMF northward turning. The second onset might be or might be not triggered by the changes in both of B_Y and B_Z prior to the onset time. However, the IMF B_Z only show slight northward turning (a bit of decrease in southward component) around the onset.

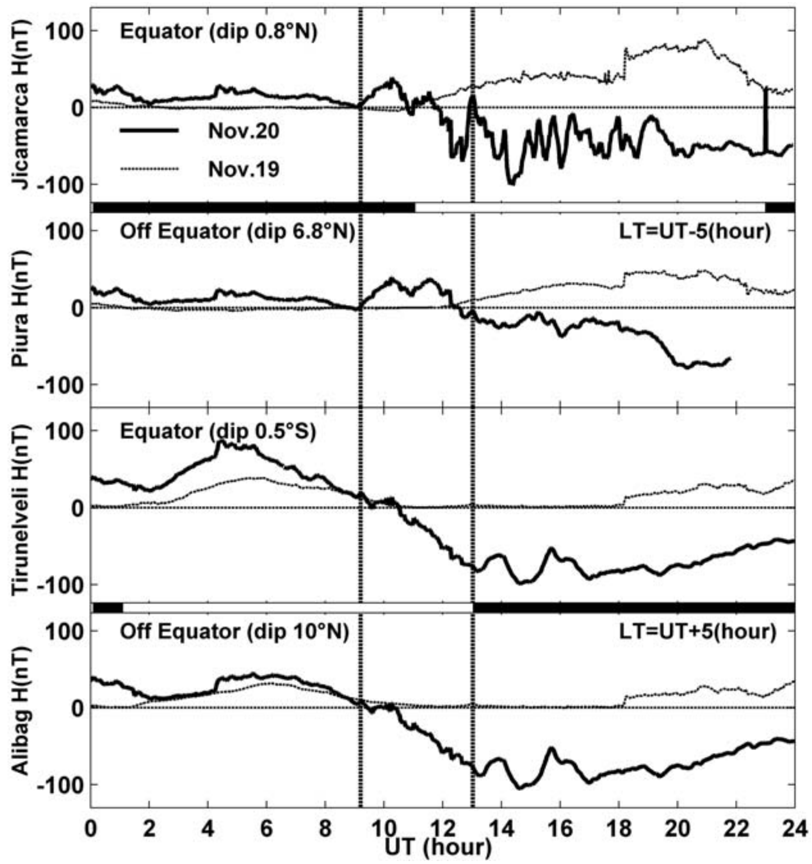

Figure 3. Geomagnetic H measurements at two pairs of stations located in Peru and India, respectively. Peru: Jicamarca (dip equator) and Piura (off equator). India: Tirunelveli (dip equator) and Alibag (off equator). The bold lines are H components observed on 20 November, while the dashed lines are those on 19 November, for reference. The two vertical lines are the same as in Figure 2.

2.2. Equatorial Geomagnetic Observations

[11] It is known that the equatorial ionospheric electric field can be inferred from geomagnetic H components of a pair of stations, of which one is located at geomagnetic equator and the other one is located off equator [*Anderson et al.*, 2002]. We have examined two pairs of such stations in Peru and India, respectively. The two geomagnetic stations in Peru (LT = UT − 5 h) are Jicamarca (JIC, 11.9°S, 283.1°E, dip 0.8°N) and Piura (PIU, 5.2°S, 279.4°E, dip 6.8°N), and the other two geomagnetic stations in India (LT = UT + 5 h) are Tirunelveli (TIR, 8.7°N, 76.9°E, dip 0.5°S) and Alibag (ABG, 18.6°N, 72.9°E, dip 10°S). Figure 3 shows H components of these stations on 20 November (bold solid lines), and those on 19 November (thin dashed lines) for reference. We should point out that the sharp increase at 1812 UT on 19 November for all stations was cause by solar wind dynamic pressure enhancement as mentioned above for SYMH. The white/black bars illustrate local day (white) and night (black).

[12] During 0900–1100 UT, JIC and PIU on the dawn sector (0400–0600 LT) exhibited similar increased H components. This feature can be attributed to substorm current wedge created by cross-tail current disruption, which produces positive H perturbations on the nightside [*Clauer and McPherron*, 1974]. During 1100–2300 UT, JIC and PIU was on the daytime. In contrast to positive solar quiet (Sq) type, JIC (equator) measured highly fluctuated and strongly negative H. Meanwhile, PIU (off equator) also observed negative H with smaller magnitude and more smooth shape. These observations imply that a westward electric field was overlapped on the equatorial ionosphere and drive the CEJ through Cowling effect. On the other hand, during the first expansion phase, TIR and ABG also observed negative deviations from Sq pattern on the dayside, but their H components looked almost the same, thus may be mainly contributed by the magnetic storm ring current. The electric field disturbances at India discerned by calculated ΔH will be shown in Figure 4.

2.3. Relationship Between the CEJ and the Substorms

[13] We further derive ΔH as a proxy of equator electric field followed the method suggested by *Anderson et al.* [2002]. Figure 4 (sixth and seventh panels) shows ΔH on 20 November (bold lines), and ΔH on 19 November (thin lines) for a reference, here positive (negative) corresponds to eastward (westward) electric field. The most striking feature is the negative ΔH in Peru maintained for almost whole daytime. During the first expansion onset, Peru was located on the nightside, but TIR-ABG ΔH in the afternoon exhibited immediate decrease, which implied a westward electric field disturbance. The negative JIC-PIU ΔH started at 1022 UT indicated that JIC had moved into CEJ region and that a westward electric field was imposed on the

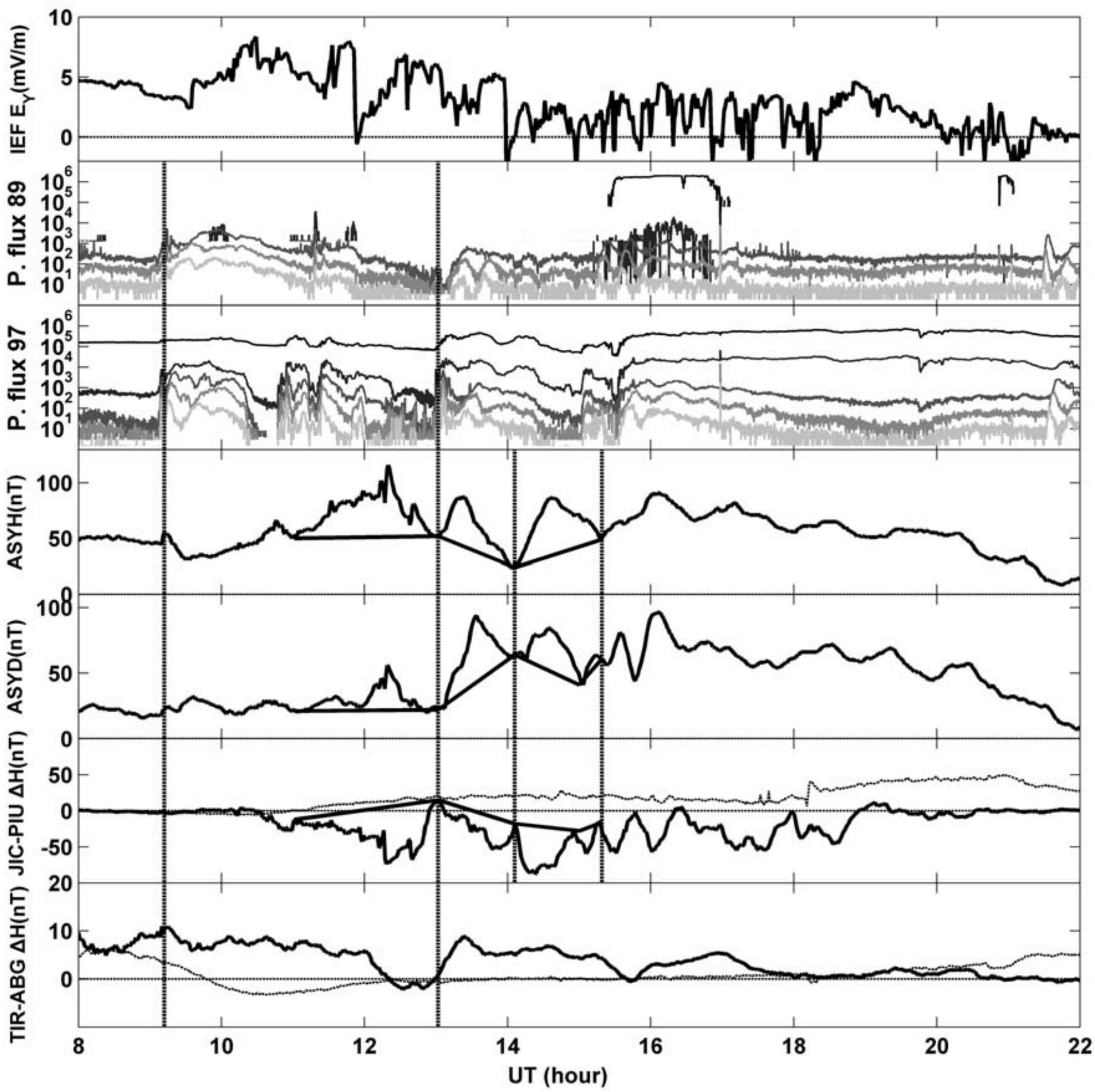

Figure 4. The first panel shows time-shifted IEF E_Y (duskward is positive). The second and third panels show energetic proton fluxes in #/cm^2/s/sr/keV observed by LANL 1989-046 and 97A, respectively. The energetic proton energy channels are 50–75, 75–113, 113–170, 170–250, and 250–400 keV. The fourth and fifth panels show the asymmetric ring current indices, ASYH and ASYD, to illustrate the variations of partial ring current and FACs. The sixth and seventh panels show the ΔH calculated from H observations presented in Figure 3 for the Peru and India sectors, respectively. The solid and dashed lines correspond to 19 and 20 November, respectively. This negative ΔH in the Peru sector implies a westward electric field and a westward electrojet. The two vertical lines on the left (onset time) are the same as in Figure 2.

equatorial ionosphere. One may note that the westward electric field over India was too weak to cause CEJ before 1200 UT. It can be explained as local time dependence of penetration electric field [e.g., *Nopper and Carovillano*, 1978], and *Fejer et al.* [2007] further suggested that the penetration electric field is highly variable, and has the largest values near dawn. There was only slightly negative value in TIR-ABG ΔH during 1200–1300 UT. However, the TIR-ABG ΔH did not show similar tendency as those in JIC-PIU ΔH around second onset. It is known that the electrodynamic processes are more complicated near dusk terminator than dawn terminator, and the so-called prereversal enhancement can produce a strong eastward electric field [e.g., *Fejer and Scherliess*, 1997]. Moreover, India almost entered the night at the second onset, thus the TIR-ABG ΔH might not correctly estimate the real equatorial electric field. Therefore, we will not discuss the TIR-ABG ΔH for the second expansion phase.

[14] Figure 4 also plots asymmetric ring current indices, ASYH (H component) and ASYD (D component). These two indices and SYMH are derived from observations primarily from six midlatitude stations, which are randomly selected from a station group consisting of 10 low- and middle-latitude stations in which only two are from low latitudes. Thus, they generally represent the symmetric or asymmetric variation of H and D component at middle

latitudes [*Iyemori and Rao*, 1996]. The ASYH is interpreted as an indicator of asymmetric (partial) ring current, and the ASYD can be used as a good indicator of the strength of the FACs, because the ring current and the Chapman-Ferraro current do not contribute significantly to the D perturbation, only FACs do [*Shi et al.*, 2005]. The striking feature is the one-to-one correspondence between the JIC-PIU ΔH and the ASYH and ASYD indices. As marked by the vertical dashed lines and bold line segments, when the ASYH and the ASYD showed pulse-like enhancements, the JIC-PIU ΔH responded as pulse-like decreases which implied westward electric field perturbations. This suggested that the westward electric field perturbations were closely related to the partial ring current and the FACs.

[15] Though the ASYD represents the sum effects of R1 and R2 FACs, it is still obvious that the R2 FAC was significant. For the second expansion phase, the ASYH and the ASYD exhibited synchronously pulse-like increases, and their magnitudes were comparable, which indicated that the partial ring current and associated R2 FAC were main contributors to these two indices. If the R1 FAC is overwhelming, i.e., undershielding, the ASYD should have similar variations as the IEF and the JIC-PIU ΔH should increase when the magnetospheric electric field associated with R1 FAC penetrated into equatorial ionosphere. This is not consistent with the observations, thus the ASYD was mainly caused by R2 FAC. For the first expansion phase, the ASYD was relatively lower, and it was even in the same level as the prestorm (20–30 nT). We attribute this to two reasons: (1) the R2 FAC takes longer times to develop through charge accumulations at the Alfven layer; (2) the southward IMF drives R1 FAC to increase and then partially cancel the contributions of the R2 FAC to the ASYD.

[16] Comparing the JIC-PIU ΔH with the Y component of IEF, E_Y, which is calculated from $E_Y = V_X B_Z$ (first panel), it is seemingly that the ΔH occasionally related to the duskward IEF E_Y (for example, around 1300 UT). Please note the IEF had been shifted by 4.4 min (see section 2.1). However, the direct penetration electric field caused by duskward IEF was eastward on the dayside, thus the IEF E_Y might partially cancel the westward electric field, but the westward electric field must be caused by other mechanisms. There were several "northward turnings" corresponding to IEF decreases, e.g., around 1148 UT, but JIC-PIU ΔH did not significantly decrease as a response as predicated by the overshielding theory. Moreover, the ASYH and ASYD suggested that there was no strong R2 FAC prior to the first expansion phase, thus it was less possible to create overshielding imbalance of FACs only through IMF northward turning. Though the overshielding electric field caused by IMF northward turning could not be completely excluded, the JIC-PIU CEJ features must be mainly caused by other mechanisms inside the magnetosphere-ionosphere system.

[17] The TIR-ABG ΔH showed immediate decrease after the first expansion onset, and the JIC-PIU ΔH also showed similar variations after the second expansion onset. During later time of the first expansion and the following intensification, JIC-PIU ΔH was almost monotonously decreasing, implying that the westward electric field continued to develop. For the second expansion, JIC-PIU ΔH showed more complicated characteristics as multiple pulses. We suggest that the substorm should be responsible for these observations. It is likely that the overshielding imbalance state of FACs, R2 FAC greater than R1 FAC, was built up through R2 FAC enhancement due to substorm processes rather than R1 FAC reduction due to IMF northward turning. However, in Figure 4 the energetic particle injections only related to equatorial westward electric field at the onsets. The substorm involves other global-scale electric and dynamic processes which can impact on shielding electric field, and we will discuss later.

3. Discussion and Conclusions

[18] The CEJ is often observed at the dayside equator, but it rarely persists for whole daytime at Peru sector. Though the substorm effect is very clear, for completeness, we should comment the other two mechanisms possibly existing in our case. First, the so-called "disturbance dynamo" can also cause CEJ on the dayside ionosphere. During storm period, Joule heating in the polar ionosphere can drive eastward hall current in dayside midlatitude ionosphere, which closes through equatorial westward electrojet [*Blanc and Richmond*, 1980]. However, it takes several hours for the disturbance dynamo to become effective and the dynamo continues to work for a longer time (up to tens of hours) [*Fejer and Scherliess*, 1997]. In this case (medium magnetic storm) the disturbance dynamo may be effective to suppress the positive Sq electric field, but the global-scale wind dynamo cannot produce those rapid variations (e.g., brief pulses or sharp jumps) of equatorial electric field. Second, the CEJ can also appear during quiet days due to atmospheric tide dynamo [e.g., *Rastogi*, 1974]. The nearest quiet day CEJ was observed at JIC and PIU during 1600–2200 UT on 24 November (Dst > −30). Furthermore, if consider the well known day-to-day variability [*Kane*, 1976], this kind of CEJ also cannot be precluded in our case. However, it still cannot account for the rapid variations of JIC-PIU ΔH seemingly related to partial ring current and IEF.

[19] The overshielding signature (westward electric field perturbation) on the dayside ionosphere does not obviously prevail in all substorms [*Sastri et al.*, 2001]. In our case, there was no CEJ but slightly decrease of ΔH over India in the afternoon when JIC observed strong CEJ in the morning. Previous multilongitude observations for either undershielding or overshielding suggested that the penetration electric field is in global scale [e.g., *Sastri et al.*, 2003; *Kelley et al.*, 2007], but with local time dependence as mentioned above. Therefore, the observers in predawn and morning sector are more possible to capture the electric field disturbances.

[20] Contrary to most cases reported before [e.g., *Huang et al.*, 2005], Figure 4 has shown that the overshielding took place during storm main phase under southward IMF B_Z. The observations further indicate that the overshielding imbalance state of FACs, R2 FAC greater than R1 FAC, is built up through R2 FAC enhancement rather than R1 FAC reduction due to IMF northward turning. The substorm processes should be responsible for the R2 FAC enhancements that lead to the overshielding. As introduced above, the antisunward plasma flow in the subauroral region without IMF northward turning presented by *Ebihara et al.* [2008] was essentially consistent with our observations,

but there was 12 min time delay between expansion onset and emergence of antisunward flow. Accordingly, they proposed that the shrinkage of the polar cap, i.e., decrease of open flux due to magnetic reconnection in the lobe region, is one possibility. Assuming the magnitudes of R1 and R2 FACs are constant before and after substorm expansion onset, the location of R1 FAC shifts to higher latitude when the polar cap shrinks, thus the middle- and low-latitude electric field associated with R1 FAC will decrease because of the geometrical attenuation of penetrated electric field [*Kikuchi and Araki*, 1979]. Under this condition, the shielding electric field associated with R2 FAC may overcome the decreased electric field with R1 FAC in the middle- and low-latitude region, and then cause overshielding effect, e. g., antisunward plasma flow in the subauroral region or CEJ. This mechanism can be equivalently regarded as R1 FAC reduction when the location of R1 and R2 FACs are constant, similar to the effect of IMF northward turning. The continuously enhancing westward electric field during first expansion and the following intensification was consistent with the time-dependent polar cap shrinkage process. However, this mechanism cannot account for the enhanced CEJ closely related to the increased R2 FAC. There should be some other processes that can enhance shielding electric field in the inner magnetosphere and associated R2 FAC. Now we discuss the second possibility: dipolarization effect.

[21] Magnetic reconfiguration has an important effect to the shielding electric field (see the review by *Wolf et al.* [2007]). It was first proposed by *Fejer et al.* [1990], and recently verified by computer simulations [e.g., *Maruyama et al.*, 2007] and in situ observations [*Goldstein et al.*, 2002; *Wei et al.*, 2008b]. When the cross-tail current disrupts after expansion onset, the magnetic tail becomes less taillike, more dipolar. In this dipolarization process a magnetic field line from given ionospheric location will have its equatorial mapping point move earthward. The motion can be regarded as an E × B drift in the duskward electric field induced by the change of magnetospheric configuration. Thus a dawnward potential electric field must exist near the inner edge of the plasma sheet, just to cancel the inductive electric field and then keep the same distance from the Earth. The dawnward potential electric field maps into ionosphere but the duskward inductive electric field does not. In fact, the dawnward potential electric field is due to the charge accumulations in the Alfven layer, which can also cause partial ring current and R2 FAC to increase. Therefore, the substorm dipolarization prefers to create overshielding.

[22] The directions of ionospheric electric field perturbations on the dayside caused by substorms, say, westward or eastward, are seemingly not conflict. We have discussed that both of the polar cap shrinkage and magnetic field dipolarization incline to produce westward electric field perturbations. Moreover, *Ebihara et al.* [2008] also suggested that the antisunward plasma flow in the subauroral region might appear without IMF B_Z northward turning, though the corresponding physical mechanism has not been confirmed. On the other hand, though *Huang et al.* [2004] did not discuss the physical mechanisms behind eastward electric field disturbances in details, it is obviously the enhanced ionospheric convection [*Miyashita et al.*, 2008] and increased polar cap electric field can penetrate into the equator and drive eastward electric field during their substorms. It is likely that two kinds of substorm-related processes, enhancing convection and shielding electric field, respectively, are coexisting in one substorm. There is no surprise whether one kind of effect is dominated or the two kinds of effects are comparable. This indetermination can be another reason for “the overshielding signature on the dayside ionosphere does not obviously prevail in all substorms” [*Sastri et al.*, 2001]. However, it is still not clear what the key factors are to determine the final direction of ionospheric electric field perturbations on the dayside caused by substorms.

[23] In conclusion, this paper addresses that substorms can produce westward electric field perturbations in the equatorial ionosphere on the dayside through analysis of the relationship between the equatorial counter electrojet and the substorm signatures. The westward electric fields were caused by the overshielding-like imbalance state of FACs, R2 FAC greater than R1 FAC, which is built up through R2 FAC enhancement rather than R1 FAC reduction. The substorm processes should be responsible for the westward electric field especially through polar cap shrinkage and magnetic field dipolarization. However, further works based on more cases are still required to answer what the key factors are to determine the direction of ionospheric electric field perturbations on the dayside caused by substorms.

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