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Key Points:
- Unusually large storm time plasma drifts are observed by JULIA despite small IEFy magnitudes
- Substorms at times can contribute significantly to the disturbed time electric field in equatorial ionosphere
- Substorms induce both eastward and westward electric fields over equatorial latitudes

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Contribution of storm time substorms to the prompt electric field disturbances in the equatorial ionosphere

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Abstract This study tries to bring out the fact that storm time substorms can compete and at times significantly contribute to the geomagnetically disturbed time prompt penetration electric field effects on low and equatorial latitudes. Observations of unusual equatorial plasma drift data from Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere during two space weather events show that substorms can induce both eastward and westward penetration electric fields under steady southward interplanetary magnetic field (IMF B_z) conditions. During the first event on 2 January 2005, the enhancement of the daytime eastward electric field over Jicamarca due to substorm is found to be comparable with the *Sq* and interplanetary electric field (IEFy) generated electric fields combined. During the second event on 19 August 2006, the substorm is seen to weaken the daytime eastward field thereby inducing a westward field in spite of the absence of northward turning of IMF B_z (overshielding). The westward electric field perturbation in the absence of any overshielding events is observationally sparse and contrary to the earlier results. Further, the substorm-induced field is found to be strong enough to compete or almost nullify the effects of storm time IEFy fields. This study also shows quantitatively that at times substorm contribution to the disturbed time prompt electric fields can be significant and thus should be taken into consideration in evaluating penetration events over low latitudes.

1. Introduction

The solar wind or interplanetary electric field (IEFy) enters the Earth's ionosphere through open field lines in the high latitudes during disturbed times, and it penetrates up to the equatorial ionosphere. This penetration of IEFy to equatorial latitudes from high latitudes is almost instantaneous and is referred as prompt penetration electric field. Such a penetrating field can alter the dynamo electric fields over low and equatorial latitudes and as a result changes the electrodynamics of equatorial ionosphere. During geomagnetically disturbed times, the prompt penetration electric field is found to enhance the upward plasma drifts on the dayside up to 2200 LT hours, whereas on the nightside it adds to the downward drifts [*Fejer et al.*, 2008]. The disturbed time winds generate a disturbance dynamo (DD) after a few hours of storm commencement, which opposes the quiet-time drifts polarity [*Scherliess and Fejer*, 1997; *Fejer et al.*, 2008].

Substorms on the other hand are nightside, longitudinally confined events which also affect low-latitude ionosphere through high latitudes. Because of reconnection at magnetotail and dipolarization, the magnetospheric convection changes which in turn causes changes in ionospheric convection on a global scale. Various studies have reported contradicting observations on high-latitude convection changes and polarities of enhanced fields over middle and low latitudes during such times. Substorms have been reported to both enhance [e.g., *Huang et al.*, 2004] and reduce [e.g., *Kikuchi et al.*, 2003; *Sastri et al.*, 2003] the eastward electric field on the dayside [see *Huang*, 2009, and references therein]. In recent times, *Huang* [2012], using magnetometer and Jicamarca radar data during sawtooth type substorm events, claimed that substorms induce only eastward electric fields over low latitudes and suggested that westward drifts due to substorm can be because of the possible overshielding field, which requires northward turning of *Z* component of interplanetary magnetic field (IMF B_z) after being steadily southward and not because of the substorm itself. But it is not clear how physically eastward zonal electric field gets enhanced because of substorms. In contrast, *Kikuchi et al.* [2003] proposed a mechanism of how the current system developed during substorm periods enhances the Region 2 currents and can result in counter electrojet (CEJ) or a westward zonal electric field. *Ebihara et al.* [2014] reproduced substorm-driven CEJ using global MHD simulations supporting the overshielding condition proposed. So the physical mechanism of how substorm changes the convection from high to low latitudes, the resultant polarity of induced electric fields and the penetration efficiency at low latitudes remain unresolved.

Storm time substorms are expected to affect the electric fields over low and equatorial latitudes, but the chroma of impact depends on the substorm intensity and the ionospheric conductivity. For storm time substorms, when IMF B_z is southward, a strong polar-to-equator electrodynamic coupling is established and delineating the contributions from each source is difficult [e.g., *Chakrabarty et al*., 2008]. In this study, in order to find out possible substorm contributions, two unusual vertical plasma drift events as observed by JULIA (Jicamarca Unattended Long-term Investigations of the Ionosphere and Atmosphere) radar are chosen wherein the observed drifts are not consistent with the magnitudes of dawn-dusk IEFy even if one considers highest reported penetration efficiency. Further, these unusual changes in JULIA drifts occurred when substorms were observed under steady IMF B_z conditions. Based on these observations, the polarity of substorm-induced electric fields at low latitudes and quantitative estimates of substorm contribution vis-a-vis tidal and IEFy-induced electric fields are made. During both the cases, IMF B_z is steadily southward and thus overshielding fields do not play any role. This helps us to separate the effects of substorm signatures on equatorial ionosphere. In this work, while deriving the minimum substorm contribution, the effect of disturbance dynamo is also considered, wherever applicable. The results are also compared with linear transfer function models described in the works of *Kelley et al.* [2003], *Huang et al.* [2007], and *Nicolls et al.* [2007].

2. Data

As already stated in the previous section, two cases of unusual vertical plasma drifts measured by JULIA during geomagnetically disturbed times are reported in this study. These $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts are proxy for zonal electric fields. To understand the role of substorms during these two events, different solar and geophysical indicators are used. This study uses solar wind parameters (magnetic fields, velocity, pressure, and interplanetary electric field) from NASA GSFC CDAweb (available at http://cdaweb.gsfc.nasa.gov/), *SYM-H* (symmetric ring current) and *AL* (westward auroral electrojet) data from WDC-C2 (available at http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html), and plasma drift data from JULIA radar at Jicamarca (11.9°S, 76.8°W, magnetic dip 1°N), Peru. All data have a time resolution of 1 min except JULIA plasma drift data which have a time resolution of 5 min. JULIA plasma drift data have uncertainty of <2 m/s. More detailed descriptions about JULIA drifts and its measurements can be found in *Fejer* [2011] and *Chau and Woodman* [2004]. All the solar wind parameters are time shifted to the nose of the terrestrial bow shock.

Jicamarca Radio Observatory is best suited to study the penetration effects of magnetospheric fields for two basic reasons: first, the JULIA radar, operated at Jicamarca, has very narrow spectra because of the special geometry of the magnetic field lines over Jicamarca. It measures vertical plasma drifts at around 150 km from the Doppler-shifted echoes from daytime irregularities [*Chau and Woodman*, 2004; *Chau and Kudeki*, 2013; *Oppenheim and Dimant*, 2016]. Second, the "geophysical noise level" due to background atmospheric gravity waves and tidal wind-generated dynamo fields is least over Jicamarca compared to other radars in higher latitudes like Arecibo and Chatanika [*Gonzales et al*., 1983; *Earle and Kelley*, 1987]. The Jicamarca Incoherent Scatter Radar (ISR), which estimates the *F* region electric field by measuring plasma drifts, has very high sensitivity of as low as 25 microvolts per meter in electric field measurements, even better than in situ measurements by satellite observations [*Kelley et al*., 2003]. During quiet times, *Chau and Woodman* [2004] showed that the vertical plasma drifts from both radars maintain linear relationship during daytime with very small vertical gradients. *Hui and Fejer* [2015] also confirmed this linear relationship between JULIA and ISR drifts using bimonthly climatological values. It is reasonable to assume that during disturbed times, also JULIA data give very good measurements of vertical plasma drifts and a good estimate of ionospheric electric field as ISR would have measured. This study uses JULIA data to address the contributions of storms and substorms in the penetrating zonal electric fields during geomagnetically disturbed periods.

3. Results

Two space weather events have been presented in this study when a substorm is shown to have played an important role in changing the equatorial vertical plasma drifts. Both events are in the main phase of moderate to minor storms during which substorms also occurred. Figures 1 and 2 summarize the important observations for these two cases.

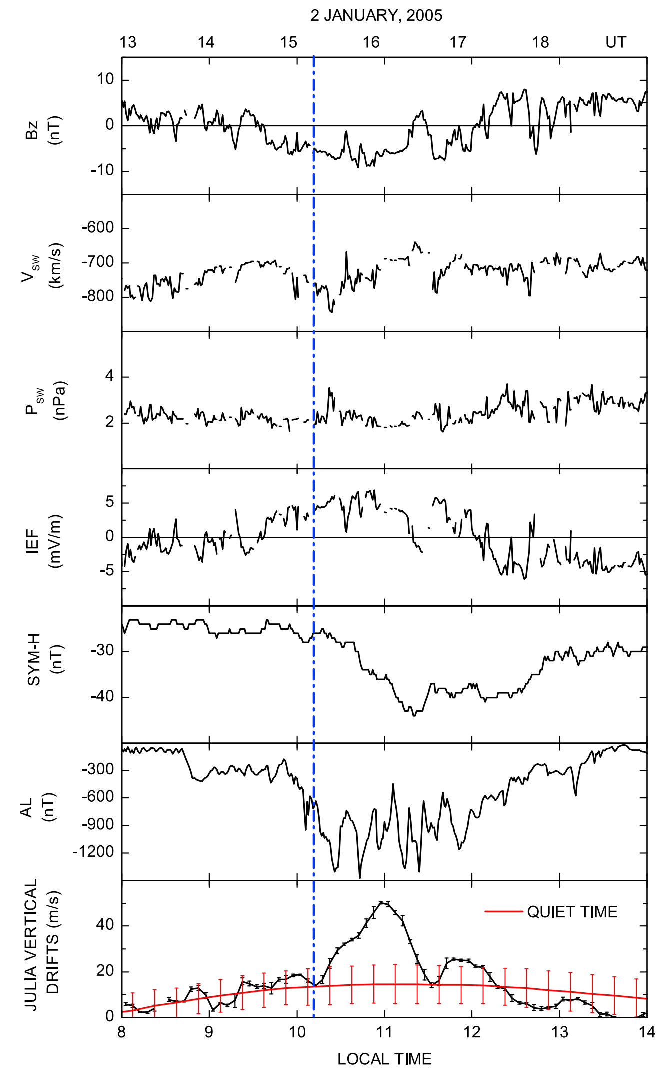

Figure 1. Variations of Jicamarca vertical plasma drifts as a response to changes in solar wind and geophysical parameters on 2 January 2005. From the top are shown (first panel) IMF B_z, (second panel) V_x, (third panel) P_{sw}, (fourth panel) IEFy, (fifth panel) *SYM-H*, (sixth panel) *AL*, and (seventh panel) JULIA vertical plasma drifts. The red line on the bottom panel shows the empirical bimonthly climatological quiet time vertical plasma drifts for non-SSW January–February period from *Hui and Fejer* [2015] along with their standard deviations. The vertical dashed line indicates the commencement time of substorm.

Case 1: The first of the two events took place on 2 January 2005 (Ap = 37). Figure 1 shows the variations in different interplanetary and geophysical parameters along with the changes in vertical plasma drifts observed over Jicamarca. The first panel shows the Z component of the interplanetary magnetic field (IMF B_z) followed by solar wind radial velocity (V_x), ram pressure (P_{sw}), Y component of interplanetary electric field (IEFy), *SYM-H*, *AL*, and vertical plasma drifts observed by JULIA. The IMF B_z fluctuates with small amplitude of less than 5 nT, occasionally changing polarity until 0935 LT when it turns southward and remains southward for about the next 2 h (~0935–1120 LT) with its value slowly varying from −5 nT to −8 nT. Throughout this interval, both solar wind radial velocity and pressure change insignificantly (except a jump at around 1025 LT) and do not seem to contribute much to the JULIA drifts (shown in Figure 1, seventh panel). The interplanetary electrical field, IEFy ($= -V_x \times B_z$), which is anticorrelated with IMF B_z, changes sign at around 0935 LT, becomes positive and reaches around +5 mV/m. IMF B_z (IEFy) remains southward (positive) from 0935 to 1210 LT with one northward excursion from 1120 to 1130 LT in between. It is important to note that the southward (or positive) turning of IMF B_z (or IEFy) from 1130 to 1210 also reaches a value of around −8 nT (or 5 mV/m). Following the change of polarity of IMF B_z, at about 0935 LT, *SYM-H* starts becoming more negative, indicating the commencement of a small storm. *SYM-H* increases from about −22 nT to −45 nT during this interval. *AL* starts decreasing to more than −300 nT at 0840 LT and remains steady until 0950 when it starts decreasing rapidly to about −1000 nT at around 1000 LT, soon after the main phase of the storm at 0935 started. *AL* intensifies once more at about 1010 LT just after a substorm starts. Commencement of substorm at about 1006 LT (1506 UT) is confirmed by electron flux data at four energy channels from geosynchronous LANL satellite LANL-97A located at around 145°E in the midnight sector (presented in Figure 3). The nearly dispersionless electron injection at 1006 LT is a clear sign of substorm commencement. As the electron injections reveal multiple jumps before and after 1006 LT, the onset time is also verified with the variations in the H component at 210 MM magnetometer chain of stations. Onset of bay signatures is distinctly evident at ~1006 LT as

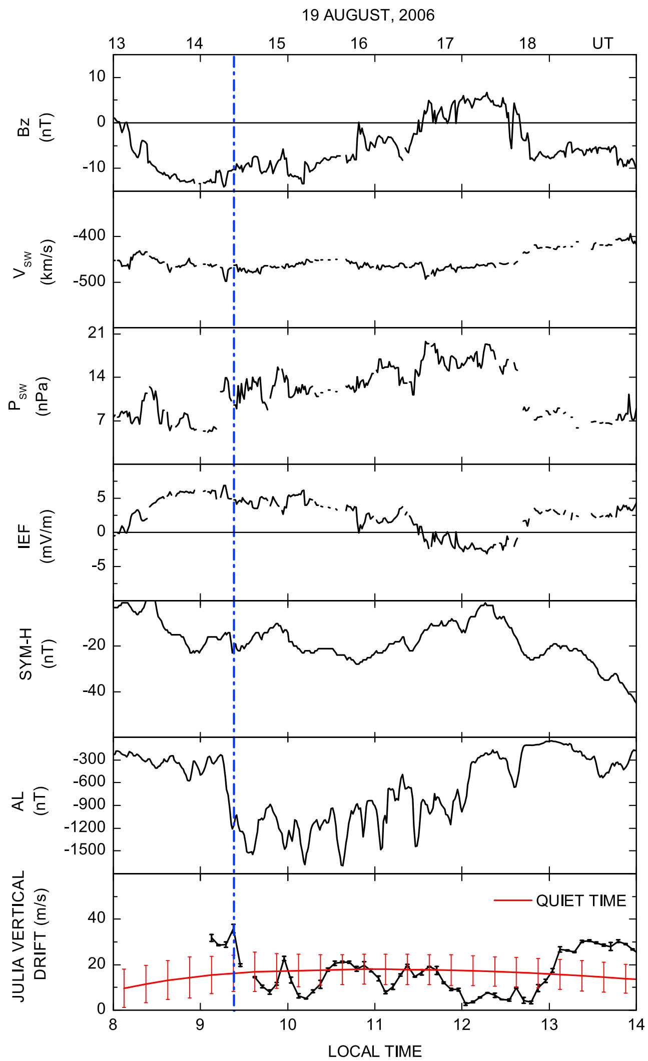

Figure 2. Same as Figure 1 but for 19 August 2006.

shown in Figure 4a and explained later. *AL* intensifies in strength and reaches a value of up to −1500 nT at around 1040 LT with large and fast fluctuations. It starts weakening slowly from 1120 LT onward soon after IMF B_z starts turning northward and *SYM-H* stops intensifying further. The JULIA vertical plasma drifts in the seventh panel reflect the changes brought about by the IEFy and substorm as it deviates from the quiet time bimonthly average values [*Hui and Fejer*, 2015] (along with their standard deviations shown here in red). The small undulations across the average drifts as seen from 0830 are possibly due to the fluctuations in IMF B_z until it turns southward at around 0935 LT. The vertical drift shows enhancement as IEFy starts increasing during the interval. At around 1010 LT, when IEFy becomes considerably large, the vertical plasma drift suddenly starts increasing enormously and reaches about 50 m/s at 1100 LT from 10 m/s at 1010 LT. This is a significant and unusual increase in comparison with the average climatological drifts expected at this local time. A rapid intensification of *AL* accompanies this fast change in plasma drift at 1010 LT. From 1100 LT the drift starts decreasing at a time when IEFy starts decreasing in strength. Around 1130 LT, IEFy changes polarity and the drift reaches almost 12 m/s, close to climatological values. Once again the drift increases to about 25 m/s as IEFy (IMF B_z) turns positive (southward) and reaches a value of around +5 mV/m (−8 nT). During this time, *AL* starts becoming weaker in intensity and gradually becomes small by 1330 LT. In summary, though the changes in IEFy alters the plasma drifts at low latitudes as expected, the significant increase from quiet time values in the interval 1010 to about 1100 LT corresponds to a large *AL* change (under IMF B_z steadily southward condition) indicating large contribution from substorm activity during this time.

Case 2: The second space weather event being discussed here is on 19 August 2006. The observations of solar and geophysical parameters for this event are shown in Figure 2, which is the same as Figure 1 but for 19 August 2006. IMF B_z in the first panel turns southward at around 0805 LT and remains southward until 1135 LT. IMF B_z attains values of −13 nT at around 0900 LT and −9 nT at around 0940 LT. It then remains relatively steady until 1045 LT and then starts weakening. The solar wind velocity remains nearly steady during this interval. Solar wind pressure shows occasional jumps which might have triggered a substorm at 0922 LT as discussed later. The first jump in solar wind pressure takes place at around 0915 LT. The pressure comes down to initial value of about 7 nPa at around 1245 LT. IEFy turns positive from about 0805 LT and increases to about +6 mV/m with intensifying southward IMF B_z at around 0900 LT. It remains nearly (except a few small and spurious jumps) steady at +5 mV/m until 1020 LT, slowly decays, and then turns negative at around 1135 LT. *SYM-H* turns negative and intensifies to about −25 nT indicating the commencement of a

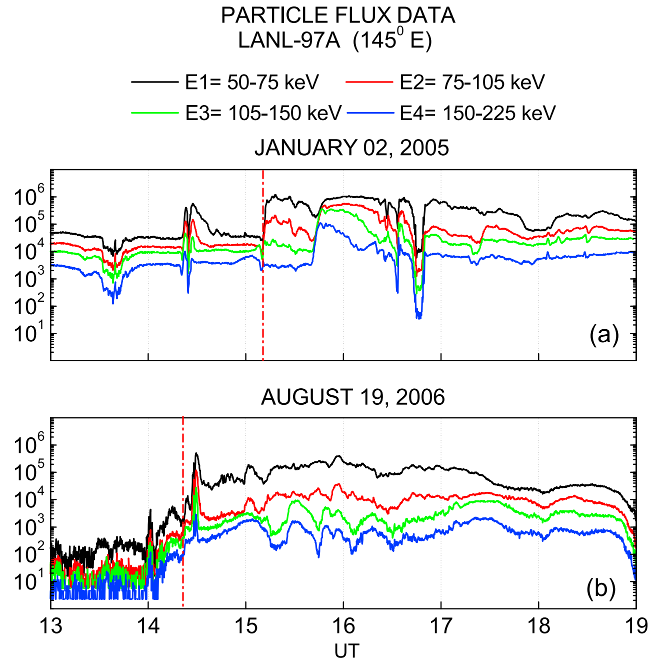

Figure 3. Electron flux (in #/cm^2 s sr keV) data at geosynchronous orbit from LANL-97A satellite in different energy bins for (a, b) both events. The red lines marks the onset time of the substorms.

minor storm and remains around that value throughout the interval when IMF B_z remains southward. *AL* slowly starts intensifying from about −250 nT at about 0800 LT to −300 nT when IEFy turns positive and continues to reach a peak value of +6 mV/m at around 0915 LT. *AL*, in close sync with first pressure jump, then starts intensifying rapidly to about −1500 nT at 0935 LT with a small halt at 0922 LT. With fast, small, and occasional large fluctuations *AL* finally decreases to very small values at around 1245 LT simultaneously when solar wind pressure comes back to the initial values that existed before the substorm. The JULIA plasma drifts data are not available until 0905 when IMF B_z is already southward. From 0905 LT, the drifts have high values, compared to quiet time drifts (shown in red). The drift starts increasing for few minutes from around 0915 in sync with the first jump in solar wind pressure and then

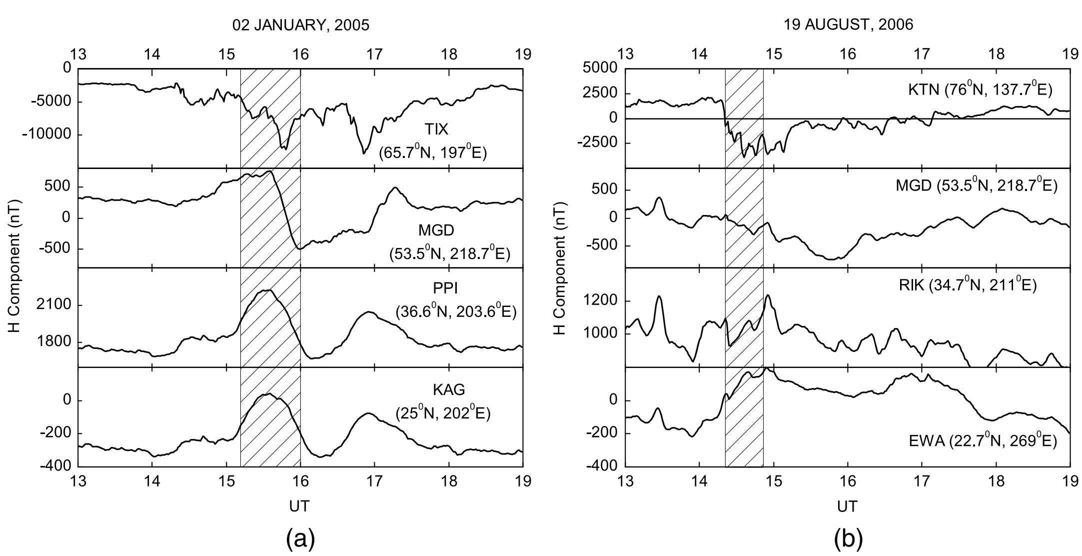

Figure 4. Variations in the H component of Earth's geomagnetic field to confirm the onset of substorms during the (a, b) two events.

suddenly starts decreasing from around 0920 LT. This decrease in drift starts soon after *AL* intensification indicating prompt penetration effects due to the substorm. At this time IMF B_z is steadily southward. This clearly shows a westward induction electric field after 0920 LT (the drift data has 5 min temporal resolution) due to the substorm. The onset of a substorm at 0922 LT has been verified from LANL satellite particle flux data similar to Case 1 and is shown in Figure 3b. The onset of a substorm at 0922 LT is also verified from the 210 MM chain of magnetometers (Figure 4b). It seems that the *AL* intensification from 0922 LT gets contribution from the substorm onset. The present communication will only address the sharp reduction in drift occurring at 0922 LT (reflected in drift values after 0920 LT) over Jicamarca in tandem with sharp changes in *AL* and geosynchronous electron injection. The fluctuations in drifts after 0935 LT are believed to be not directly related to the substorm and will be investigated in a separate work.

3.1. Interpreting the Observations and Substorms' Contributions

The two substorm events addressed here take place during storm times when IMF B_z remains southward so as to rule out any major storm-induced transient prompt penetration electric field during the substorm periods. On 2 January 2005, we notice that the storm starts at around 0935 when IMF B_z turns southward and by 0955 it becomes quite steady. An increase of upward drift or an enhancement of eastward electric field is expected during this local time. The drifts in Figure 1 during this time do show increased values compared to bimonthly climatological quiet times. Earthward nearly dispersionless electron injection at geosynchronous orbit recorded by LANL-97A satellite at around 1506 UT (1006 LT) is an indication of the onset of a substorm. The *AL* starts intensifying during this time and from about 1010 LT the substorm-induced electric field enhances the upward vertical plasma drifts or eastward electric field. The drifts increase to a peak value of 50 m/s in 30 min and then decrease to preonset values in the next 30 min. This total ~60 min period is consistent with the typical duration of substorm expansion phase and is also consistent with the findings of *Huang* [2012]. The IMF B_z effects become more pronounced once again from 1130 LT when IMF B_z turns back to southward condition. This is why the overshielding field, which may have helped in the decrease of drift values during the northward incursion of IMF B_z just prior to this, could not make a longer impact and the drifts start increasing once again in response to southward turning of IMF B_z. No substorm is seen in this period and thus the induced electric field due to substorm is absent. Thus, the excess drift over tidal or quiet time drifts from 1130 LT to 1210 LT is only because of IEFy-induced prompt penetration field. So it is clear that the high drift values of plasma drifts from 1010 LT to 1130 are due to the superposition of additional substorm-induced electric fields over storm time and tidal wind-generated fields.

The penetration efficiency of disturbed time magnetospheric electric fields to low-latitude ionosphere is not very clearly understood. In this investigation, the favorable conditions encouraged for a small exercise to quantify the substorm contribution to the penetrating field. For Case 1, if a simple and reasonable assumption is made that the efficiency of penetrating IEFy remains the same during the period when substorm dominates (1010–1130 LT) and around 1140 LT when only IEFy dominates, the comparable magnitudes of IEFy during these two intervals give an opportunity to compare the effects of IEFy and susbstorm-induced electric fields on the vertical plasma drifts over Jicamarca. It can be noted that IEFy peak value from 1015 to 1050 LT is around +5 mV/m which is also the IEFy value at around 1140 LT. So, if +5 mV/m of IEFy at 1140 LT causes a resultant vertical plasma drift of about 23 m/s, the same magnitude of IEFy can be assumed to make similar contribution in plasma drifts during the interval when substorm dominates (1010–1130 LT). Thus, at around 1100 LT, when the plasma drifts reach peak value of around 50 m/s and IEFy is ~ +5 mV/m, the difference (50 m/s − 23 m/s = 27 m/s) needs to be accounted by the substorm-induced field only as tidal wind-generated fields can be assumed to be almost the same during 1100 LT and 1140 LT.

It is important to note that there was magnetic activity on the previous night prior to the event. *SYM-H* became negative at around 1300 LT on the previous day and remained around −25 to −40 nT until this event. In case of any disturbance dynamo, a westward electric field during the event is expected [*Fejer et al.*, 2008]. But instead, an enhancement in the eastward electric field is seen. Moreover, the magnitude due to disturbance dynamo is expected to be only a few m/s [*Fejer et al.*, 2008; *Yamazaki and Kosch*, 2015]. A small reduction of upward plasma drift is possible throughout this event due to DD. Thus, it can be safely concluded that the minimum contribution due to substorm is around 27 m/s for this event, which is greater than the tidal and IEFy-induced upward drifts combined.

During the second event, on 19 August 2006, IMF B_z turned southward at 0805 LT when the Jicamarca drift is expected to increase, but unfortunately, the radar drift data were available only after 0905 LT. The magnetometer data (not shown here) show the expected change for this IMF B_z turning. Around 0850 LT, IMF B_z is steady at around −13 nT and remains steadily southward with a few occasional dips at around −9 nT value till 1045 LT. The drift values at 0905 LT are about 30 m/s, which is higher than the quiet time values, probably due to IEFy-induced eastward electric field at this local time. A sudden rise in solar wind pressure at around 0915 LT is believed to have triggered a substorm accompanied by rapid intensification of *AL* which continues to fluctuate for the next 2 h. The sudden change in solar wind pressure, if effective in inducing a direct electric field at low latitudes through dayside compression of the magnetosphere, is expected to increase the drifts or induce eastward electric fields at the low latitudes [*Huang et al*., 2008]. It seems that the small rise in drifts at 0915 LT is probably a response to this pressure jump. This is followed by a sudden decrease of drifts as seen from 0920 LT (remember, the plasma drift data has 5 min temporal resolution), which is suggested to be due to the substorm-induced westward electric field. Any disturbance dynamo-generated westward field is ruled out because the *SYM-H* values for the previous 2 days were very small and no major geomagnetic perturbation was seen. As a southward IMF B_z or positive IEFy is expected to increase the upward vertical plasma drifts, a sudden decrease in drifts below bimonthly quiet time values is anomalous. The drift values reduce so much that they fall to about 8 m/s at 0945 LT, much below quiet time drifts associated with tidal electric fields. This clearly indicates that the substorm has induced a westward field at low latitudes that opposed IEFy, pressure induced (if any), and tidal fields resulting in a sudden decrease in plasma drifts. Similar to the previous event on 2 January 2005, if it is assumed that the penetration efficiency of IEFy to equatorial ionospheric electric field remains constant throughout the event, then similar values of IEFy at 0920 LT (before substorm onset), 0945 LT (substorm dominated), and a slightly smaller value at around 1330 LT (after substorm is over) should produce around 25 to 30 m/s of vertical drift over Jicamarca. It is interesting to note here that the jump in solar wind pressure might have increased the drifts from 0915 to around 35 m/s for the next few minutes until substorm starts dominating. This increased pressure can modulate the penetration efficiency of the high-latitude electric fields to low latitudes as described later. Keeping this in mind, it is meaningful to compare drifts under similar elevated pressure conditions during IEFy- and substorm-dominated times. Thus, if drifts at 0920 LT (the peak value just before substorm starts dominating) and at 0945 LT (when substorm is dominating) are compared, it can be seen that at 0945 LT, the substorm is contributing a westward field which produces around −27 m/s (8 m/s–35 m/s) of vertical drifts, and the resultant being about 8 m/s.

The commencement of a substorm is marked by "dispersionless" particle injection from the magnetotail toward the Earth [e.g., *Reeves et al*., 2003]. Such injection of particles can be detected at geosynchronous orbits by LANL (Los Alamos National Laboratory) satellites. Figures 3a and 3b show the electron injection data in different discrete energy channels for the two events from satellite LANL-097A that was located at nightside during both events. The almost dispersionless injection of electrons for the Case 1 at 1506 UT (1006 LT) is shown with a dotted line in Figure 3a. Similarly, Figure 3b shows the commencement of a substorm at 1422 UT (0922 LT) for the second case. To remove any ambiguity in the interpretation of LANL data in the presence of two more particle injection signatures before and after substorm onset in Case 1, the 210 MM chain of magnetometers data [*Yumoto, K., and the CPMN group*, 2001] are used to confirm the occurrence of substorm at around 1506 UT (1006 LT). Figure 4 shows variations in the H components of geomagnetic field over four different stations spanning from high to low latitudes in the Northern Hemisphere. The data shown for Case 1 are from stations: Tixie (TIX, geomag: 65.7°N, 196.9°E), Magadan (MGD, 53.6°N, 218.7°E), Popov Island (PPI, 36.6°N, 203.6°E), and Kagoshima (KAG, 25°N, 202°E) and for Case 2 are from stations: Kotel'nyy (KTN 69.9°N, 201°E), Magadan (MGD, 53.6°N, 218.7°E), Rikubetsu (RIK, 34.7°N 210.8°E), and Ewa Beach (EWA, 22.7°N, 269.4°E). At the onset of a substorm, magnetic bays with opposite polarities are expected at high and low latitudes [*Sastri*, 2002; *Chakrabarty et al*., 2008]. The shaded region shows negative bay at highest latitudes, whereas positive bay in the low latitudes. Such variations are not seen during the two other apparent particle injection events in Figure 3a, which can be seen before and after the substorm onset and thus confirms that the substorm at 1506 UT only could recognizably affect/reach up to the low latitudes. To ascertain the onset of substorm further, Pi2 pulsation data from Moshiri (MSR 37.6°N, 213°E), RIK, and KAG are also looked into but not shown here for brevity. For Case 1, the rapid Pi2 pulsation can be observed from about 1506 UT, which is consistent with particle flux data and magnetometer bay data. The substorm onset for Case 2 at 1422 UT similarly is confirmed with 210 MM data as shown in Figure 4b. For this case also, renewed Pi2 pulsation activity can be seen to get triggered at 1422 UT.

4. Discussions

The effects of substorms on magnetospheric and global ionospheric convections have been known for quite some time but a great controversy remains about the exact electrodynamic processes that follow the substorm onset and how the substorm onset affects the convection. While many studies reported an enhancement of high-latitude convection on substorm onset, many others observed a decrease in convection processes [e.g., *Lyons et al.*, 2003; *Bristow and Jensen*, 2007; *Kamide et al.*, 1996, *Miyashita et al.*, 2008]. The effects of substorms on low-latitude electric fields were similarly contradicting. *Gonzales et al.* [1979] and *Sastri et al.* [2003] reported westward penetrating field on substorm onset, whereas *Huang et al.* [2004] and *Huang* [2009, 2012] reported eastward enhancements of electric field over low latitudes caused by substorms. *Hsu and McPherron* [2003] pointed out that isolated substorms often take place during northward turning of IMF B_z. A northward turning of IMF B_z may also induce a westward overshielding field on the dayside low-latitude ionosphere [*Kelley et al.*, 1979; *Fejer et al.*, 1990]. *Huang* [2009] suggested that the observed westward penetrating fields during a substorm onset, reported by many, may result from the accompanying overshielding fields and not because of the substorm itself. He further showed, using sawtooth-type substorms during steady southward IMF B_z condition to remove any transient penetrating electric field changes due to IMF orientations, that substorm onset alone can cause an enhancement of the eastward electric field on the low-latitude ionosphere. In a subsequent study, using large number of such sawtooth-type substorms during steady southward IMF B_z, *Huang* [2012] concluded that substorms induce an eastward penetrating field on the low-latitude ionosphere. Also, along with this ambiguity about polarity of substorm-induced electric field on low latitudes, previous studies do not delineate quiet time dynamo field due to tidal winds, storm effects, and substorm effects.

Kelley et al. [2003] suggested that the disturbed time equatorial electric field is about 7% of the incoming IEFy at the high latitudes. *Nicolls et al.* [2007] used a ratio of 15:1 between IEFy and electric field over Jicamarca. *Huang et al.* [2007] found a factor of 10 as suitable for such prompt penetration cases. Also note that the difference between factors of 10 and 15 will be pronounced only when IEFy is large and will be very close when electric field values are small. Each of the present two events is a minor storm event with the peak value of IEFy around 5–6 mV/m and IEFy/15 is close to and less than the quiet time values. A factor of 10 in the present cases shows clear enhancements due to IEFy effects from quiet time values. Though both linear transfer theory and any scaling factors are debatable, a comparison of the present observations is made with such models to understand the role of substorms better. Although the reported efficiency factor varies, in general, from 7 to 10% on event-by-event basis, by assuming a maximum contribution from storms (10%) in the present investigation, minimum contributions of substorms are determined. Moreover, for a given event, assuming that the penetration efficiency does not change much between intervals with and without the presence of substorm (which are spaced within an hour), it is attempted to find the excess fields induced by substorms. Over Jicamarca vertical plasma drift of 40 m/s represents an electric field of 1 mV/m. For tidal electric field estimations, the climatological drift values from *Hui and Fejer* [2015] are used. It is important to note that the day to day variability of these drifts are large [*Hui and Fejer*, 2015] and thus an order of 1 σ variability across the mean climatological values are included in the estimation of substorm contributions. The σ values for the events are about 0.21 and 0.16 mV/m, respectively. On 2 January 2005 event, comparing electric fields estimated from radar data at 1100 LT (substorm dominated) and 1155 LT (only IEFy dominated), an additional 0.3–0.7 mV/m additional contribution from substorm over IEFy/10 during this period was found. Thus, in this case, we see that the substorm-induced field is comparable to the IEFy-induced fields and is added constructively with both the IEFy and tidal fields resulting in enhancement of eastward electric field over Jicamarca. In Case 2, an approximate estimate of the substorm-induced field can be made if we assume that the IEFy/10 at 0920 LT (only IEFy dominated) and 0945 LT (substorm dominated) is around 0.4 and 0.5 mV/m, but the actual radar measured fields are about 0.9 mV/m at 0920 LT and 0.2 mV/m at 0945 LT indicating a field of around -0.46 to -0.8 mV/m contributed by substorm alone at around 0945 LT. In this case, the substorm-induced field was added destructively with the tidal and IEFy fields. As the contribution due to DD is shown to be westward during this local time [*Fejer et al.*, 2008], the contribution due to substorm (when eastward as in Case 1)

Table 1. A Comparison of Different Model and Measured Electric Fields Over Jicamarca During the Two Events Brings Out the Competitive Contributions of Substorms[a]

	Quiet Time Field [*Hui and Fejer*, 2015] (mV/m)	Max Storm Contribution [IEFy/10] (mV/m)	Measured Field From JULIA (mV/m)	Min Range of Substorm Contribution (mV/m)	Comments
2 January 2005					
1100 LT	0.36 ± 0.21	0.37	1.24	0.3–0.7	Substorm contribution could be underestimated due to DD which is of the order of a few m/s
1155 LT	0.35 ± 0.21	0.4	0.62		substorm absent
19 August 2006					
0920 LT	0.27 ± 0.16	0.5	0.9		Substorm absent
0945 LT	0.32 ± 0.16	0.5	0.2	−0.46 to −0.8	Westward electric field due to substorm

[a]Note that the errors in JULIA radar measurements are 1 order less than the 1 σ values of climatological drifts and thus not shown in the table.

will increase the value if one removes the contribution due to DD. However, it may be noted that the minimum contribution due to substorm remains unchanged. Case 2 (wherein westward contribution from substorm is observed) is not affected by DD.

From the above discussions, it can be clearly seen that at times, substorms can produce much stronger fields compared to IEFy and tidal fields put together. This gets support from the comparison of substorm-induced drift values estimated in previous section from direct radar measurements when no climatological comparison or linear transfer approximations were made for tidal and IEFy-induced drifts, respectively. Table 1 summarizes the comparison of electric fields from model and radar observations during substorm- and IEFy-dominated times. A maximum storm contribution with 10% penetration efficiency is used so as to bring the minimum range of substorm contribution, whenever significant (comparable to IEFy/10). Note that during both the intervals for a given event, the climatological and IEFy-induced drifts are almost equal. The errors in JULIA radar measurements (~ ±0.05 mV/m) are 1 order less than the standard deviations of climatological drift values and are thus neglected. It can be seen from the table that the excess fields at times cannot be explained by tidal (including 1 σ variations) and IEFy fields combined. So the excess contributions must come from the accompanying substorms at those times.

It is interesting to note that in the second case, the choice of "only IEFy dominated" time of 0920 LT instead of more stable drift values with similar IEFy values like 1350 LT for comparison calls for some attention. The reason for this is that the ratio of the IEFy to equatorial zonal electric field depends on the ratio of the size of the magnetosphere to the length of the line between IMF and the Earth's magnetic field [*Kelley et al.*, 2003]. The size of the magnetosphere changes with the changing solar wind pressure. So, it is the similar solar wind pressure condition which made 0920 LT more suitable than 1350 LT when comparing with substorm-dominated drift at 0945 LT. It is also important to mention here that such substorm-induced electric fields may change due to the relative changes of the measurement location with respect to the substorm current wedge [*McPherron*, 1991] and also with local time as well as intensity of the substorm, penetration efficiency, and MI coupling. Needless to say that the present estimations can change depending on the above conditions, and comprehensive investigations are needed to model these estimates.

Huang [2012] pointed out that most westward penetration of substorm-induced fields reported by many were accompanied by northward turning of IMF B_z, and he suggested that these observed westward penetrating fields were possibly because of overshielding effects and not substorms as were generally perceived. Here, Case 2, an event where no northward turning of IMF B_z was present, the substorm induced a very strong westward penetrating electric field. It is to be noted that this may not qualify as a sawtooth-type event as described by *Huang* [2009, 2012], as this substorm may have been externally triggered by solar wind pressure. *Huang et al.* [2008] reported that a solar wind pressure impulse can cause an eastward enhancement of equatorial electric field directly through dayside compression of the magnetosphere, but here in this case, a substorm triggered by solar wind pressure impulse is observed to cause a strong westward penetration over equator. So, this clearly indicates that the westward induction of electric field at low latitudes is possible even without change in IMF orientation.

Kikuchi and Hashimoto [2016] suggested that the penetration electric field is a competition between the convection electric field driven by Region 1 current system and the shielding electric field driven by

Region 2 current system. It is the imbalance of these two current systems which decides the polarity and strength of the induced electric field at the low latitudes. When a southward IMF B_z is expected to increase Region 1 current and thus the dayside eastward electric field (upward plasma drifts), the dominance of the shielding field will decide if the eastward field (upward plasma drifts) will enhance or decrease. The shielding field originates whenever the partial ring current increases at the onset of a substorm and due to enhanced convection from the nightside [*Kikuchi et al.*, 2003]. In their work, on a particular event, they observed substorm-induced eastward fields over high latitudes whereas westward fields in the subauroral latitudes. In this study, we see two events where we observe both eastward and westward fields over low latitudes soon after the substorm onset. *Hashimoto et al*. [2011] showed that substorm can drive both Regions 1 and 2 current systems. It may have so happened that in Case 1 the substorm enhanced the Region 1 current system more than the Region 2 current system and we observed a resultant-enhanced eastward field; whereas in the second event, soon after the substorm, the Region 2 currents started dominating, resulting in an overshielding-like situation which gave rise to a strong westward electric field over the equator. *Wei et al.* [2009] observed intensification of penetration westward fields over low latitude, whereas *Huang* [2009, 2012] observed eastward enhancement during sawtooth events over low latitudes. Interestingly in Case 2, the westward-induced field was not strong enough to cause a counter electrojet over the equator. So it still remains a mystery how the susbstorm-induced field will impact the low latitudes in terms of polarity. It is suggested that measurement or close estimation of Regions 1 and 2 currents can provide a clue to solve this riddle.

5. Summary

Two cases of storm time substorm events over Jicamarca sector are presented in this study. The IMF B_z, during both cases remains southward and thus any contribution from ovsershielding fields can be ruled out. The unusual nature of the vertical plasma drifts measured by JULIA on both occasions under southward IMF B_z condition helped to bring out the intriguing role of substorms. In one occasion, we observed a large eastward penetrating field for about an hour, whereas on the other, substorm induced a strong westward electric field. This investigation unambiguously shows that substorms can generate westward penetrating electric fields even in the absence of IMF B_z turning northward. An order of magnitude calculation of minimum contribution due to substorm is carried out by taking 10:1 penetration efficiency of IEFy to equatorial zonal electric field. It was found that the substorm-induced electric fields are ~0.3–0.7 mV/m (eastward) and ~0.5–0.8 mV/m (westward) for the two cases under consideration. The present investigation thus provides important examples of estimates of substorm-induced electric fields on equatorial ionosphere over South American sector.

The present investigation also shows that the puzzle over polarity of substorm-induced electric fields remains unsolved and that the substorm contribution to the penetrating electric field during storm time can be at times quite significant. This has direct implication on how storm time magnetospheric electric field penetration effects are evaluated at equatorial and low latitudes.

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