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Key Points:
- Solar flare causes equatorial electrojet (EEJ) current near sunrise to flow strongly westward under disturbance dynamo electric field
- Solar flare-induced enhanced *E* layer conductivity longitudinal gradient near sunrise appears to produce large westward electric field
- Overshielding westward electric field during storm recovery causes delay in the EEJ response to flare-induced ionization enhancement

Correspondence to:
M. A. Abdu,
ma.abdu@inpe.br

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Equatorial electrojet responses to intense solar flares under geomagnetic disturbance time electric fields

M. A. Abdu[1,2], P. A. B. Nogueira[3], J. R. Souza[2], I. S. Batista[2], S. L. G. Dutra[2], and J. H. A. Sobral[2]

[1]Instituto Tecnologico de Aeronautica, Sao Jose dos Campos, Brazil, [2]Instituto Nacional de Pesquisas Espaciais, Sao Jose dos Campos, Brazil, [3]Instituto Federal de Educação, Ciência e Tecnologia de São Paulo, Jacarei, Brazil

Abstract Large enhancement in the equatorial electrojet (EEJ) current can occur due to sudden increase in the *E* layer density arising from solar flare associated ionizing radiations, as also from background electric fields modified by magnetospheric disturbances when present before or during a solar flare. We investigate the EEJ responses at widely separated longitudes during two X-class flares that occurred at different activity phases surrounding the magnetic super storm sequences of 28–29 October 2003. During the 28 October flare we observed intense reverse electrojet under strong westward electric field in the sunrise sector over Jicamarca. Sources of westward disturbance electric fields driving large EEJ current are identified for the first time. Model calculations on the *E* layer density, with and without flare, and comparison of the results between Jicamarca and Sao Luis suggested enhanced westward electric field due to the flare occurring close to sunrise (over Jicamarca). During the flare on 29 October, which occurred during a rapid *AE* recovery, a strong overshielding electric field of westward polarity over Jicamarca delayed an expected EEJ eastward growth due to flare-induced ionization enhancement in the afternoon. This EEJ response yielded a measure of the overshielding decay time determined by the storm time Region 2 field-aligned current. This paper will present a detailed analysis of the EEJ responses during the two flares, including a quantitative evaluation of the flare-induced electron density enhancements and identification of electric field sources that played dominant roles in the large westward EEJ at the sunrise sector over Jicamarca.

1. Introduction

Solar flares are impulsive short-duration release of energy by the Sun into interplanetary space. The enormous increase in the electromagnetic radiation spanning from ultraviolet (UV) to EUV bands and to short X-rays intercepting the Earth can produce drastic responses at wide-ranging height regions of the ionosphere and the thermosphere [*Liu et al.*, 2007; *Manju et al.*, 2009; *Nogueira et al.*, 2015]. The ionospheric responses in the form of large increases in the electron density, also known as sudden ionospheric disturbances, manifest themselves in various forms depending upon the diagnostics tools used and height region observed. Increase in the HF radio wave absorption by enhanced *D* region electron density (due to short X-rays) can cause total or partial black out of the echo traces in ionograms recorded by ionosondes [*Sahai et al.*, 2007; *Sripathi et al.*, 2013; *Nogueira et al.*, 2015]. Increase in the *E* layer electron density (due to soft X-rays and UV) can cause large increase in the Hall and Pedersen conductivities, responsible for impulsive changes in the global *Sq* current system known as geomagnetic crochets [*Richmond and Venkateswaran*, 1971] and, especially, for the often spectacular increases in the equatorial electrojet (EEJ) intensity [*Rastogi et al.*, 1997, 1999]. as observed by magnetometers. The flare EUV enhancements produce also large increases in the *F* region electron densities, and the resulting TEC enhancement has been the subject of intensive investigation in recent years, using high-resolution network of GPS receivers [*Tsurutani et al.*, 2005; *Nogueira et al.*, 2015]. The study we report here is, however, restricted to the response of the equatorial electrojet current to intense X-class flares. The impact of a flare on the EEJ current is to cause a sudden increase in the current intensity always in the same sense as that of the pre flare current, to be followed by a decay determined by the decay rate of the ionizing flux. The effect of a flare on the *Sq* current system under normal/quiet conditions is a positive increase in the horizontal component of the geomagnetic field, Δ*H*, (representing eastward current) on the equatorward side of the *Sq* focus and negative change in the Δ*H*, (representing westward current) on the poleward side [*Rastogi et al.*, 1999]. The solar flare effect on the EEJ current system, on the other hand,

Table 1. The Geographic and Magnetic Coordinates of the Stations Used in the Analysis

Station	Geographic Coordinates	Magnetic Dip
Alibag	18.68°N, 72.86°E	25.4°
Piura	5.2°S, 80.1°W	13.53°
Guam	13.58°N, 144.87°E	12.3°
Yap	9.3°N, 138.5°E	3.18 °
Trivandrum	8.48°N, 76.95°E	1.35 °
Jicamarca	12°S, 76.9°W	1.05°
Sao Luis	2.33° S, 44.2°W	−3.71°
Fortaleza	3.9° S, 38.45° W	−13.54°
Vassouras	22.40°S, 43.65°W	−34.75°

involves additional complexity. A few studies have discussed the different aspects of the EEJ responses under varying conditions of the background *E* layer. One such condition is that which drives the counter electrojet (CEJ), a quiet time phenomenon characterized by transient reversal of the EEJ current to westward for durations on the order of 1–2 h, believed to be caused by corresponding westward/downward reversal of the driving zonal/vertical electric field produced by perturbations in local winds within the electrojet region. *Rastogi et al.* [1999, 2013] showed that solar flare enhancement in the ionizing radiation occurring under normal EEJ conditions cause large impulsive increase in the eastward EEJ current, whereas the flare enhancement occurring in the course of a CEJ, or a partial CEJ, produces a westward increase in the EEJ current. In other words, the flare-induced EEJ enhancement is proportional to, and in the same sense as, the immediately preexisting EEJ current, whether directed eastward or westward. Further, the nature of the flare-induced variations in the magnetic field components (ΔH, ΔD, and ΔZ) should be understood considering the fact that the EEJ current flows at a lower height (around 107 km) compared to the *Sq* current, which is situated at 115–120 km, as pointed by *Rastogi et al.* [2013] based on observations from a meridian array of magnetometers.

The nature of the EEJ response to solar flares is fraught with additional complexity when the flares occur sequentially and separated in time sufficient enough for the magnetic storm effects associated with an earlier flare event dominates the low-latitude ionosphere at the time of a later flare events. In other words, depending upon the intensity and phase of the magnetic disturbances that may some times exist during a flare event, the response of the EEJ can turn out to be very complex due to the dominating role of the disturbance electric field in driving the EEJ current. On the dayside where the flare effects occur the disturbance electric field polarity can be eastward or westward for the undershielding or overshielding conditions, respectively, that characterize a storm evolution. Normally under B_z south conditions, the interplanetary electric field (that is, the solar wind electric field) maps to high latitudes in the form of convection electric field that promptly penetrates to low latitudes. This prompt penetration electric field (PPEF) is directed dawn-to-dusk and therefore eastward on the dayside. The convection electric field also drives the Region I field-aligned current (R1 FAC). The subsequent growth of the R2 FAC, equatorward of the R1 FAC, marks the development of the shielding layer, which balances the convection electric field thereby tending to decrease the PPEF intensity to zero. This process may take some time, on the order of half hour to a few hours. However, when a rapid decrease in the convection occurs, often with B_z turning northward, an overshielding effect prevails, and the electric field due to the shielding layer is what dominates the equatorial and low latitudes. This overshielding electric field has westward polarity on the dayside. During much of the night hours the corresponding electric fields are of opposite polarities, but not of our current interest. Regarding the undershielding/overshielding electric fields and their polarity dependence on local time (LT) the readers may see, for example, *Fejer et al.* [2008a], *Abdu et al.* [2009], *Wei et al.* [2015], *Bhaskar and Vichare* [2013], and *Chakrabarty et al.* [2015]. The penetration electric fields are followed (with a delay of a few hours, 3–4 h) by disturbance dynamo electric field (DDEF) (originating from auroral heating) that has westward polarity on the day and evening side with eastward polarity during night hours [*Blanc and Richmond*, 1980; *Fejer et al.*, 2008a; *Scherliess and Fejer*, 1997; *Abdu et al.*, 2006a]. Often, these electric fields may overlap in time in cases of long-duration disturbances, so that the EEJ current response to a flare occurring under such conditions reflects the superposed effects of these different electric fields. In this paper we analyze and discuss two cases of intense X-class flares that occurred during the extended disturbance interval of the October 2003 Halloween storm sequences. The effects of the X17 class flare that occurred at 11 UT on 28 October and also an X-class storm that occurred at 20:40 UT on 29 October are investigated by analyzing the magnetic field *H*-component variations as recorded at South American, Asian, and Indian longitude sectors, and Digisonde data from Peruvian and Brazilian sites. Table 1 shows the stations and their coordinates used in this study.

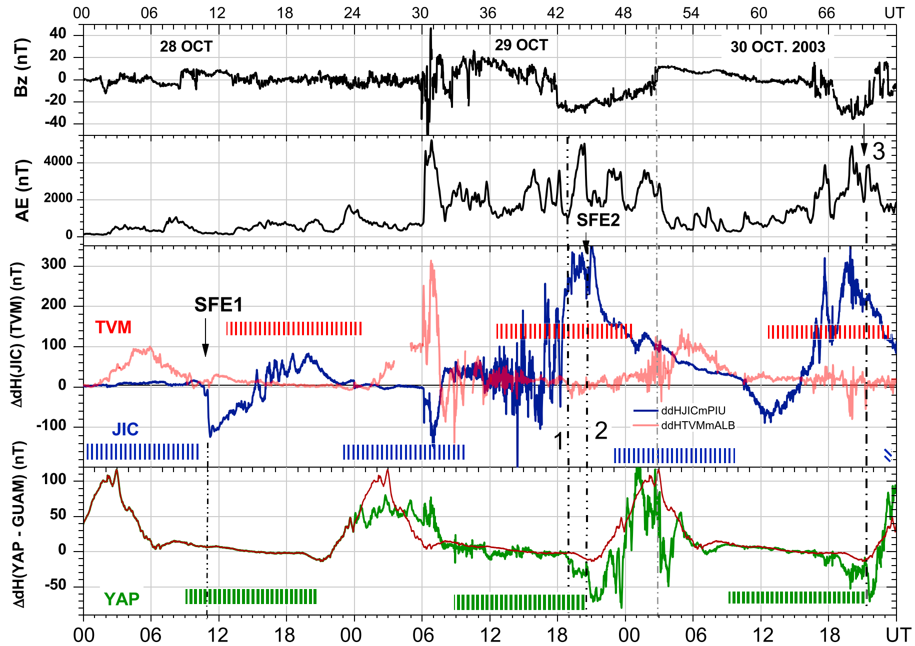

Figure 1. The variations in different parameters during 28 to 30 October 2003. (first panel) The interplanetary magnetic field component B_z and (second panel) the auroral activity index *AE*. (third and fourth panels) The magnetic field *H*-component variation over a dip equatorial station after subtracting the *H* variation over an off equatorial station (denoted as ΔdH), plotted for Jicamarca (navy blue), Trivandrum (red), and Yap (green). The responses to two solar flares are marked as SFE1 and SFE2, at 11 UT on 28 October and 2040 UT on 29 October, respectively. Night hours are indicated by vertical line straps (from the sunrise to sunset at 100 km) in the same color code as that of the data for the three stations. Please note that the UT and LT are related as LT = UT − 5 h for Jicamarca, LT = UT + 5:30 h for TVM, and LT = UT + 9:20 h for Yap.

The two cases of solar flare effects (SFE1 and SFE2) as observed in *H*-component variations at Jicamarca (JIC), Trivandrum (TVM), and Yap that are widely separated in longitude are shown in Figure 1. The *H*-component variations at each station is considered after subtracting its quiet time smoothed midnight value from the total *H* field, the difference being designated as *dH*. The *H* variation due to electrojet current is then obtained by subtracting the *dH* over an off dip equatorial station from that over a corresponding dip equatorial station, resulting in the parameter ΔdH, which is plotted in Figure 1.

The SFE1 occurred when Jicamarca was under the influence of sunrise (LT = UT − 5 h) and the EEJ current, represented by the ΔdH parameter, was negative and large (−125 nT of peak intensity) representing intense westward current that took about 4 h to recover. In the late afternoon hours (1630 LT) over TVM (LT = UT + 5:30 h) the SFE1 produced an eastward increase in the EEJ, but of small amplitude only (~20 nT), and over Yap that was at 20:20 LT (night) (LT = UT + 9:20 h) no effect was observed, as to be expected. The SFE2 produced strong eastward EEJ enhancement (~130 nT of peak intensity) near 16 LT over Jicamarca and strong westward EEJ (~ −50 nT) over Yap, which was close to sunrise (see the vertical line 2 in Figure 1). These and related effects will be discussed in detail in the following sections. There are a number of very interesting aspects of EEJ responses to magnetic storm disturbances (outside of the flare effects) that are not of our present concern as they have been (or will be) discussed elsewhere. The results presented here will clearly demonstrate that the nature of the EEJ response to a solar flare should depend upon the time history of the magnetic disturbances that surrounded the observation of that solar flare effect. In particular, it will be shown that the flare effect reflected the presence of a disturbance dynamo electric field in the morning hours that produced large westward flow of current that decayed at a rate similar to that of the ionizing radiation flux. It is the first time that flare response under the influence of a DDEF is being reported. It will be shown further that in addition to the DDEF, other sources of westward electric fields (such as that associated with quiet time counter electrojet (CEJ) produced by tidal modes and/or that arising from *F* layer dynamo) may have to be invoked to fully account for the strong westward EEJ observed near sunrise. Additionally, using the SFE2, it will be shown for the first time that an over-shielding electric field arising from a substorm recovery phase, occurring at the time of a flare

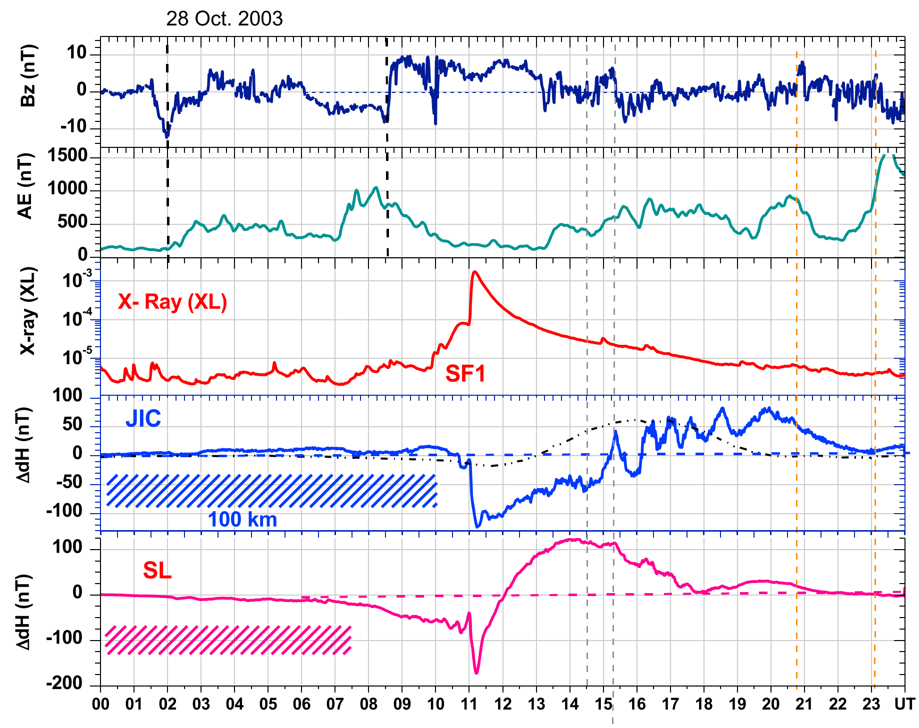

Figure 2. (first panel) The interplanetary magnetic field component B_z and (second panel) the auroral electrojet activity index *AE* variation on 28 October 2003. (third panel) The solar flare X-ray flux variation (in the 0.1–0.8 nm band) is shown. (fourth panel) The EEJ variation over Jicamarca represented by the parameter Δ*dH*, which is the *dH* variation over Jicamarca (at the dip equator) from which the *dH* over the off-equatorial station, Piura, was subtracted. (fifth panel) The EEJ variation over the near dip equatorial station Sao Luis (SL), wherein Vassouras was used as the off-equatorial station. The slant line straps in blue and red for JIC and SL, respectively, indicate night hours ending at the *E* layer sunrise.

enhancement, can cause significant delay in the flare-induced EEJ eastward enhancement, thereby permitting the determination of the Region 2 FAC shielding layer decay time.

2. Response to Solar Flare Under DDEF

Figure 2 shows the B_z and *AE* variations on 28 October together with the variations in the solar X-ray flux and the corresponding responses in the EEJ intensity over Jicamarca and Sao Luis. The EEJ intensity is represented by the Δ*dH* variation as defined above. The off equatorial stations used to calculate the Δ*dH* for these two stations are Piura and Vassouras, respectively. We note that the B_z turned south at ~01:30 UT and attained maximum negative value (of ~12 nT) at 02:00 UT (indicated by a vertical line). A substorm soon followed with *AE* intensification reaching ~500 nT that lasted several hours. The B_z turned south again at 06:00 UT that again was soon followed by *AE* intensification to ~1000 nT, the recovery of which started with the B_z turning north at 08:30 UT (indicated by a vertical line). This recovery appears to be rapid enough that an associated overshielding electric field must be present at this time [*Kikuchi et al.*, 2003] the polarity of which was a bit uncertain over Jicamarca, which was near-sunrise transition [*Fejer et al.*, 2008a], as can be noted from the Δ*dH* variation over Jicamarca during this time (~08:30–11:00 UT). The uncertainty in the EEJ direction is further compounded by the very low *E* layer conductivity at this local time being close to sunrise.

As a preflare feature, the X-ray intensity presented a "slow" increase starting at ~0950 UT that continued till the 11 UT rapid increase in the X-ray flux that marked the X17 class flare event. During this preflare period the X-ray flux increased from 5E-6 W m^{-2} to 8E-5W m^{-2} and the EEJ showed a westward increase by about 40 nT at Jicamaca and a little higher at Sao Luis. A careful examination reveals a small decrease in the X-ray flux by about 7.4E-06 W m^{-2} (that is, from 8.07E-5 W m^{-2} at 10:48 UT to 7.33E-5 Wm^{-2} at 10:59 UT) that caused (right at 11 UT) a small (but sharp) decrease in the EEJ by about 15 nT at Jicamarca and by 25 nT at Sao Luis.

In Figure 2 a spectacular westward increase in the EEJ (of ~125 nT) can be noted at Jicamarca in association with the sudden increase in the flare X-ray intensity that occurred at 11:00 UT (06:00 LT), which is marked as SF1. The westward directed intense current, instead of a normally expected weak eastward EEJ for this local time (or even a westward EEJ depending upon the polarity of the ambient electric field which is in transition at this time) is a noteworthy feature here. This westward current prevailed for about 4 h, with the polarity turning to eastward near 15:30 UT (~1030 LT) with the ΔdH amplitude fluctuating due apparently to perturbation electric field originating from the disturbances in the B_z and *AE* that continued through the day. The 09 h of the disturbance duration (in the form of the *AE* intensifications) that transpired before the 11 UT flare onset must be sufficient enough for a significant degree of disturbance dynamo electric field to be present at low latitudes [*Scherliess and Fejer*, 1997] at the time of this flare. Thus, the EEJ response to flare enhanced X-ray emission is determined/influenced in this case by the combined presence of a disturbance dynamo electric field (DDEF) as well as possibly by an uncertain overshielding electric field. However, since, as we may note, the westward EEJ (or the reverse EEJ) over Jicamarca lasted relatively longer time (more than 4 h) and was intense enough that we need to conclude that the DDEF (rather than overshielding electric field) may indeed be an important factor responsible for the westward flow of EEJ current during the solar flare. (The peak effect occurring well past the *AE* activity duration is a good indicator favoring the presence of a DDEF.) We will come back to this point later.

Figure 2 (fifth panel) shows the EEJ response recorded over Sao Luis, which is 2 h ahead of Jicamarca in local time. The most striking feature in ΔdH over Sao Luis in response to the 11 UT flare X-ray impulsive increase can be seen as the large impulsive westward increase in the EEJ, which is very similar in magnitude (being close 130 nT) and direction (being westward), to that observed over Jicamarca. But significant differences can be noted in other respects: (a) When the flare X-ray flux was decreasing after its peak intensity the EEJ over Sao Luis reversed to eastward in about 1 h after its peak intensity. This eastward reversal occurred much earlier (by about 3.5 h) than it did over Jicamarca (where such reversal occurred after 4–5 h). (b) The EEJ over Sao Luis was westward beginning from the sun rise till its reversal to eastward at around 12 UT. The aspect (b) shows the presence of westward electric field, due most likely (in large part) to the overshielding electric field mentioned before, and perhaps in part by the DDEF as well (note that the sunrise over Sao Luiz occurs 2 h earlier than it does over Jicamarca). But the DDEF over Sao Luis appears to have decayed by 12 UT as indicated by the reversal of the EEJ to eastward at this time. Here we note that there appears to exist significant longitudinal difference in the DDEF pattern between Jicamarca and Sao Luis (to be further discussed below).

Since the flare occurred close to sunrise over Jicamarca which is also near the local time of the polarity transition of the disturbance electric fields, it is helpful to illustrate, using some observed examples, the nature of the DDEF polarity reversal that should have occurred at this time resulting in the strong reverse electrojet. Although it is known statistically that the DDEF polarity is eastward during presunrise hours and turns westward at sunrise [*Scherliess and Fejer*, 1997], such characteristics is further examined here using case study based on Digisonde data over Jicamarca and Sao Luis plotted in Figure 3**.** This figure shows variations in the *AE* and *SYM-H* (*Dst*) indices together with those of the h_mF_2 values over Jicamarca and Sao Luis during the 29–31 October 2003 storm sequences. Following the development phases of the two successive super storms their respective recovery phases can be noted on 30 and 31 October when it happened to be mostly night hours over the two sites (Sao Luis being ahead of Jicamarca by 2 h in LT). The clear increases in the h_mF_2 in the postmidnight hours of 29–30 and 30–31 October (nights are indicated by shaded area) are indicators of the presence of eastward polarity DDEF that characterizes these hours [*Scherliess and Fejer*, 1997]. It is striking to note that at (or very close to) sunrise the h_mF_2 values decreased rapidly to below their quiet time value on both days, and consistently so at both locations (pointed by arrows) which is a clear indication of DDEF polarity reversal to westward at/near sunrise. The sunrise at 200 km is marked, by the end of the shaded area, at each station. Although the rapid h_mF_2 decrease may have contribution from the photochemical processes that dominate at sunrise, the fact that the lowered h_mF_2 remained consistently less than its quiet time average/reference values (plotted in grey curve) in all the four cases considered here highlights the additional role played by the westward DDEF just after the sunrise. It is important to note that in all these cases, that is, during the two storm recoveries, and at both Jicamarca and Sao Luis, the DDEF morning reversal was completed by around 06 LT, as can be noted from the blue curves crossing downward of the grey curves (at nearly the same local time in all the four cases, as indicated by vertical arrows). This crossing time occurs a little earlier than the nominal morning eastward reversal time for the (quiet time) dynamo electric field that has

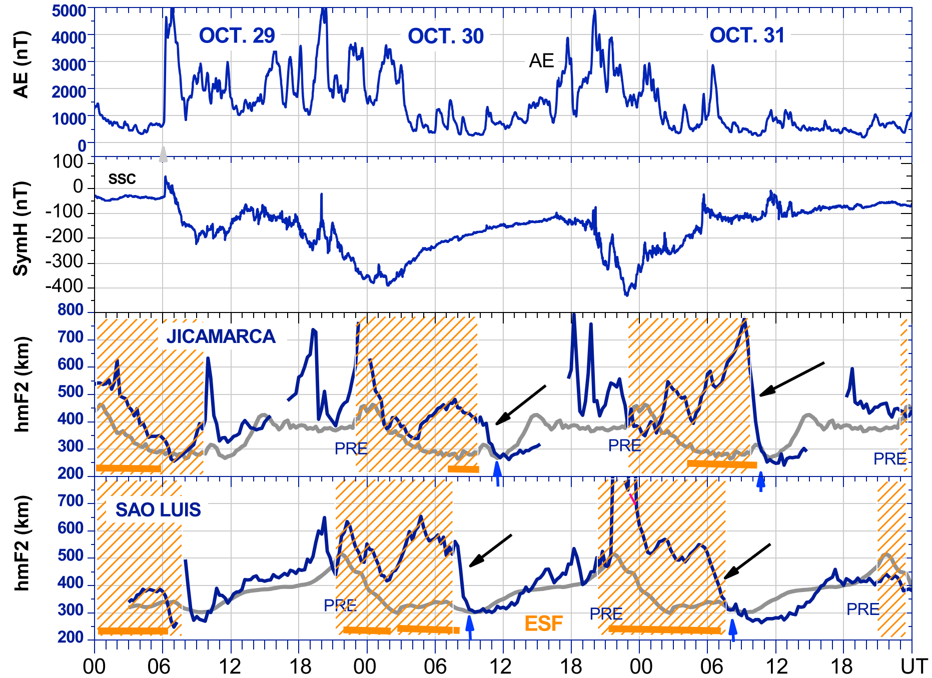

Figure 3. (first panel) Auroral activity (*AE*) index and (second panel) *SYM-H* (*Dst*) index variations during 29–31 October 2003. The *F* layer peak height (h_mF_2, blue curves) over (third panel) Jicamarca and (fourth panel) Sao Luis. The arrows point to the abrupt height decrease marking the DDEF polarity reversal to westward, consistently observed at both stations under the storm recovery phase on 30 and 31 October 2003. The grey curve represents the quiet time reference for h_mF_2. The orange shaded intervals represent night hours, and the horizontal orange bars indicate the occurrence of spread *F*.

been observed to be ~06–07:00 LT for equinoctial conditions over Jicamarca [for example, *Fejer et al.*, 2008b]. The flare radiation enhancement occurred just around the time expected (or a bit later) for the DDEF to fully turn westward, thereby accounting (at least partially) for the large westward EEJ enhancement that followed (Figure 2). Figure 3 shows also different other types of the h_mF_2 responses to disturbance electric field that are not our present concern as they have been discussed elsewhere [see, for example, *Abdu et al.*, 2007].

It is important to point out here that although the DDEF polarity reversal at sunrise is clear and consistent in all the cases, the same cannot be said about the intensity of the DDEF, which seems to vary from case to case as to be expected. But more curiously the DDEF pattern (represented by the h_mF_2 variation) shows significant difference between Jicamarca and Sao Luis, confirming the existence of a significant longitudinal difference in its variation as also reported previously [see, for example, *Abdu et al.*, 1997]. Concerning the present case, the characteristics just discussed above could help explain the difference between the EEJ response over Sao Luis and that over Jicamarca that was noted in Figure 2. The DDEF that was present at SL appears to have dissipated a few hours earlier than it did over Jicamarca.

Additional evidences on the role of DDEF in the ionospheric responses to this flare may be noted in Figures 4a and 4b, which presents the isolines of *F* layer heights at a number of sequential plasma frequencies, together with the h_mF_2 variation, over Jicamarca and Fortaleza, respectively. Fortaleza is located some 600 km east of Sao Luis. The results on 28 October, the day of the flare, are compared with those of 27 October that was a quiet day. In Figure 4a the onset of the X-ray increase at ~09:50 UT (that is, the preflare intensity increase, indicated by an arrow) marks the beginning of the gradual build up of the flare enhancement that coincided with the sunrise just reaching down to ~100 km over Jicamarca. The larger h_mF_2 during the presunrise hour of 28 October, as compared to the previous night (represented by dashed curve), is a rough indicator of the influence of an eastward DDEF at these hours. Its transition to a westward electric field (indicated by the rapid descent of the layer) occurred also when sunrise was near 100 km, which happened to coincide with the first increase in the flare X-ray enhancement (at ~10 UT). The rapid fall of the h_mF_2 and the entire layer with it, by ~200 km in less than a period of 1 h, is a clear indication of the combined presence of a downward plasma drift due to a westward electric field and the sunrise related possible photochemical effects that began at this

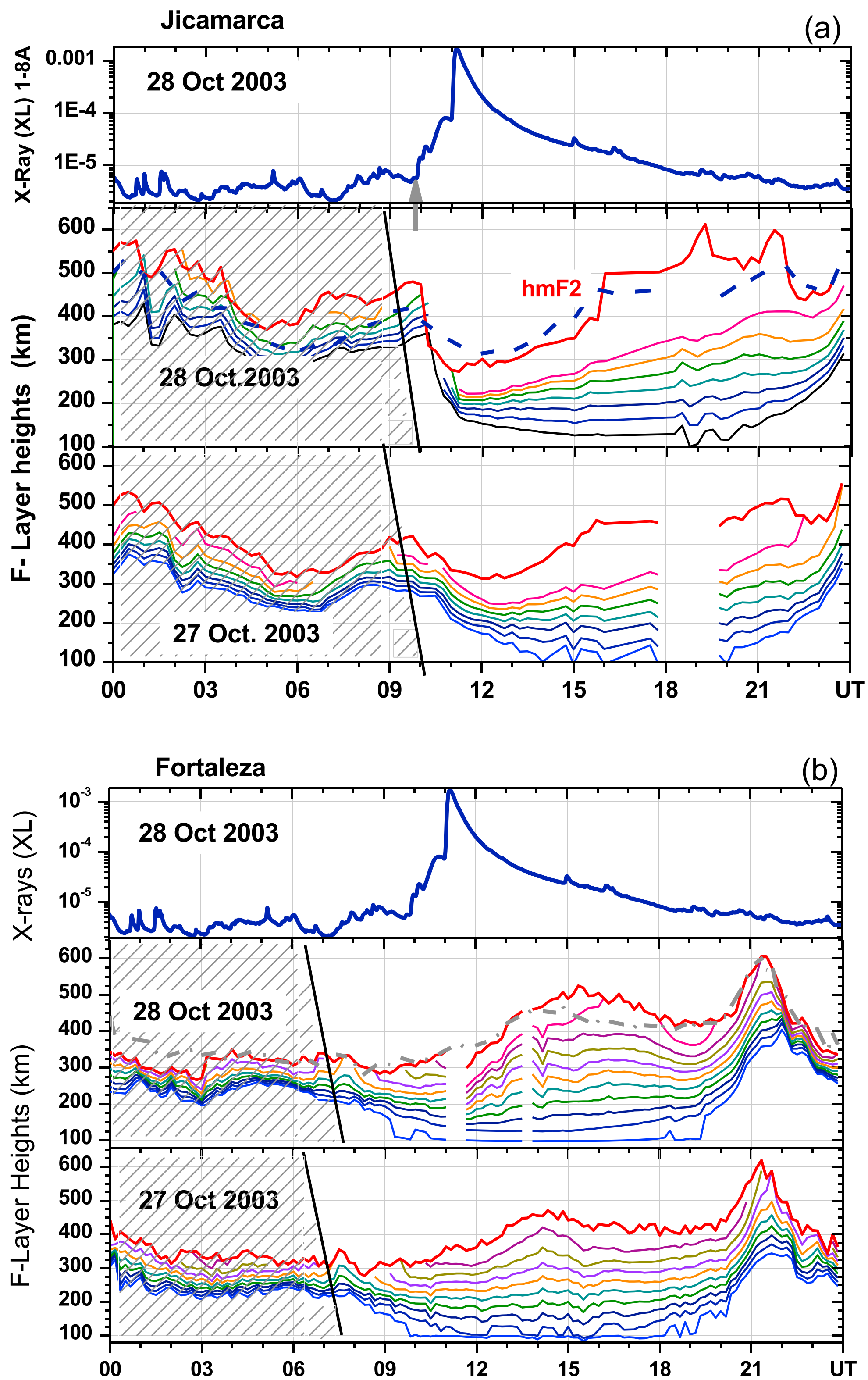

Figure 4. (a). The X-ray flux variations and the F layer heights at a number of sequential plasma frequencies, at 1 MHz interval, and the h_mF_2, over Jicamarca on 28 October 2003, and on 27 October (a quiet day). (b) Similar plots for Fortaleza. The vertical slant line defining the end of the shaded region indicates the sunrise time as a function of height. The h_mF_2 on 27 October (dashed curve) is compared with that of 28 October in the middle plots for the respective stations. There is a data gap from 17:50 UT to 19:50 UT on 27 October at Jicamarca and at 1345 UT on 28 October over Fortaleza.

time. The contribution from the latter process can be assessed from the corresponding sunrise transition observed on the previous morning. Thus, in comparison to the previous morning the dominating presence of a westward turning electric field on this morning can be easily noted.

An effect due to the 11 UT rapid flare radiation enhancement that manifested itself as the spectacular reverse EEJ (Figure 2) appears to be perceivable in the *F* layer heights as well; in that, the isolines showed some degree of more rapid layer descent at this time (as compared to the corresponding behavior on 27 October). We note further that the $f_{min}F_2$ values (in the ionograms) suffered significant increase (not shown here separately) around the time of peak X-ray intensity. Over Fortaleza where the flare radiation enhancement started some 2 h after sunrise, the plots in Figure 4b clearly show the total blackout of the HF echo traces in the ionograms, for about 40 min (as evident in the discontinuity in the plasma frequency plot during 1100–1140 UT). (Please note that the break in the isolines at 1345 UT at Fortaleza on 28 October is due to missing ionogram at this time and not a flare effect.) The impact of a DDEF appears unnoticeable during much of the day over Fortaleza, which testifies to the longitudinal difference in the DDEF briefly mentioned earlier.

An examination of the isolines of plasma density of Figure 4 shows that the total HF blackout in ionograms observed over Fortaleza was absent over Jicamarca. This contrasting feature would suggest that the flare radiation incident at a larger zenith angle over Jicamarca was not sufficient to produce the *D* layer density enhancement required for causing total absorption of the HF signals, whereas the smaller zenith angle over Fortaleza could results in a larger flare-induced incremental ionization, which was added to a larger background ionization, so that the resultant ionization increase was sufficient to cause total absorption of the HF radio waves used by the ionosonde.

3. EEJ Response to Flare Radiation in the Presence of an Overshielding Electric Field

In the summary plots of Figure 1 the event marked as SFE2 on the ΔdH variation (in third panel) is a very interesting episode which offers a rare opportunity to understand the characteristics, such as the time scale and evolution, of an overshielding electric field that happened to be present at that time and shaped the EEJ response to the solar flare. This X-class flare occurred at 2040 UT on 29 October when the super storm activity was in progress, having been preceded by a sequence of severe activity, marked by rapid *AE* intensification and decay phases, for around 14 h (as can be noted in the figure). The storm/substorm activity had its initiation with the 06 UT B_z southward turning, and large *AE* intensification exceeding ~5000 nT, when an undershielding penetration electric field caused large eastward EEJ current intensification of $>$200 nT over TVM near midday and a smaller-amplitude EEJ intensification of ~50 nT at YAP in the late afternoon hours, the details of which will not be discussed here.

A notable B_z southward turning with large intensity occurred at 18 UT on 29 October that was soon followed by a large *AE* intensification by ~3500 nT (beginning at the vertical lines 1 in Figure 1). Fluctuating disturbance electric fields must be responsible for the large variations in the EEJ that is noticeable during much of the daytime of 29 October over Jicamarca. These electric fields should be arising from the imperfect shielding condition provided by the inner magnetosphere through the dynamics of the Region 2 FAC, as well as by the disturbance wind dynamo that must have developed due to the extended event sequence. The 18 UT southward turning of the B_z and the subsequent *AE* intensification caused an undershielding electric field of eastward polarity that dominated the equatorial region. This PPEF caused a large EEJ intensification (of ~300 nT) in the afternoon over Jicamarca, as indicated by the vertical line 1. Simultaneous electric field intensification was observed also on the nightside, but of westward polarity, as evident in a moderately strong westward fluctuations in EEJ (of ~40 nT) near midnight over TVM (red curve) and a westward EEJ also of moderate intensity (~30 nT) at predawn hours over Yap (green curve) [see, also *Abdu et al.*, 2007]. These features are also indicated as beginning with the vertical line 1.

The variations in the relevant parameters together with that of the flare X-ray flux are plotted in expanded time scales in Figures 5a and 5b. Starting at 2020 UT the *AE* presented a rapid decay, which ended at ~2037 UT (see Figure 5b) after which the activity was relatively stable for about 2 h. The rapid increase in X-ray during SF2 started at 2040 UT right at the end of the *AE* decay. The rapid *AE* decay (by ~3500 nT in about 12 min) starting from line 2 in Figures 5a and 5b, when the B_z south was decreasing at a slow rate, produced

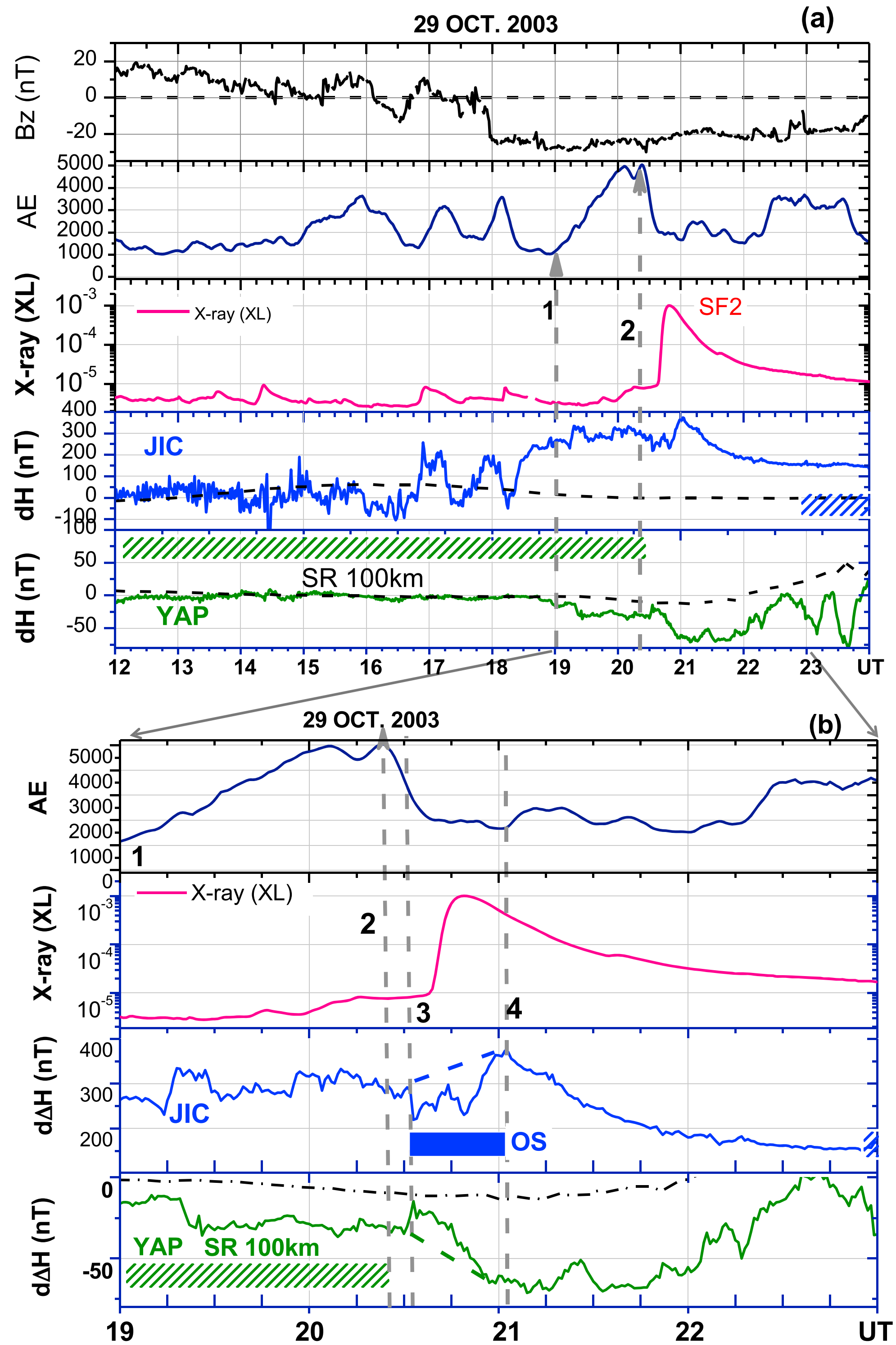

Figure 5. (a) The variation during 12–24 UT on 29 October 2003 of the B_z, *AE* index, X-ray intensity (0.1–0.8 nm band) (first to third panels) and ΔdH over Jicamarca and Yap (fourth and fifth panels). (b) The same parameters as above plotted in a more expanded time scale during 19–23 UT. The dashed curves in bottom two panels in Figure 5a represent the quiet day curves for Jicamarca and Yap. The dash-dotted curve in the bottom panel of Figure 5b is the quiet day curve for Yap.

an overshielding electric field of westward polarity over Jicamarca (on the dayside) as indicated by the sudden EEJ decrease by about 80 nT marked by the vertical line 3 (at 2032 UT) in Figure 5b. At the same time the overshielding electric field had eastward polarity over Yap in the sunrise sector, as indicated by the EEJ increase over there by about 15 nT (also indicated by the vertical line 3). It is important to note that even though the signature of an overshielding westward electric field is evident over Jicamarca the background electric field was eastward, which in fact is the net result of the simultaneous presence of three electric fields (from three distinct sources), that is, a disturbance wind dynamo electric field of westward polarity expected from the several hours of the preceding *AE* activity, the overshielding electric field also of westward polarity (just mentioned above), and the imperfectly shielded prompt penetration electric field of eastward polarity being the most dominant one. Under the action of the net eastward electric field, a sudden increase of flare X-ray flux (that should produce a sudden increase of the *E* layer ionization) should have caused a large and rapid increase in the eastward EEJ current, similar to the rapid EEJ response (although of westward current) that occurred over Jicamarca and Sao Luis during the 28 October flare (shown in Figure 2). But such an expected sharp increase in the EEJ current (eastward current in this case) was not observed on 29 October over Jicamarca as can be clearly noted in the plots in Figures 5a and 5b. After some degree of uncertain response at the beginning of the X-ray flux increase (shaped by the changing overshielding electric field) the EEJ eastward intensity started a steady increase at 2050 UT that continued till 2100 UT even while the X-ray intensity during this period was decreasing from its peak intensity (that it had attained at 2045 UT). After attaining a peak at 21 UT the EEJ intensity decreased accompanying the concurrent decrease in the flare X-ray flux (as is evident from Figure 5b). We may attribute the delayed steady EEJ increase (to attain its 21 UT peak) to the decay of the overshielding electric field that had set in at ~2032 UT (soon after the start of the *AE* decay). On this basis the peak in the EEJ intensity may correspond to the end of the decay of the overshielding electric field. Thus, we note that the total duration of the overshielding electric field may be delineated by the vertical lines 3 and 4, the corresponding time difference being 28 min (marked by a horizontal blue bar in Figure 5b). The delayed response of the EEJ over Jicamarca to an X-class flare (in this case) therefore provides a measure of the decay time of the overshielding electric field. A linear scale plot (not shown here) revealed that the X-ray flux continued its decay at a significantly faster rate than did the EEJ whose decay rate reflected the approaching sunset condition.

Over Yap that was in the sunrise sector the overshielding electric field occurred exactly at an electric field polarity transition phase. A reverse/westward EEJ (green curve) due to an undershielding electric field was in progress (Figures 5a and 5b, bottom) starting at ~1900 UT due to the *AE* intensification that had started near this time and that continued till ~2025 UT (as mentioned before). This reverse EEJ should have become intensified further at sunrise due to the action of a (prevailing) disturbance dynamo electric field that should be turning westward at this time. But we note that the EEJ presented a rapid eastward increase due to the overshielding electric field of eastward polarity (at the vertical line 3; Figure 5b), which appears to have decayed by 21 UT (as indicated by an interpolated dashed baseline). The eastward polarity of the overshielding electric field starting around 0630 LT (2030 UT) over Yap is consistent with the results form ROCSAT data on disturbance vertical drift published by *Fejer et al.* [2008a] that showed (in their Figure 1) that the undershielding electric field polarity remains westward till ~08 LT in morning when it reverses to eastward (in equinoctial months). (We know that the polarity of the overshielding electric field is opposite to that of the undershielding electric field.) The duration of the overshielding electric field over Yap is about the same as that found over Jicamarca, being delineated between the lines 3 and 4.

The large degree of EEJ fluctuations on 30 October under the combined influences of a PPEF associated with the *AE* activity with the B_z south, and the DDEF (due to the preceding extended *AE* activity), during much of the daytime over Yap, can be noted in Figure 1. The EEJ response to the overshielding electric field showing its polarity to be westward (eastward) in the afternoon (sunrise) sector, as found here, is consistent with the existing observational and theoretical results [*Fejer et al.*, 2008a; *Wei et al.*, 2011; *Richmond et al.*, 2003].

4. Discussion

The EEJ response to the 28 October flare, that is, the SFE1, highlighted the strong westward current, suggesting the presence of strikingly large westward electric field apparently favored by the flare occurrence being close to sunrise, as explained below. The typical local time of the (quiet time) dynamo electric field reversal

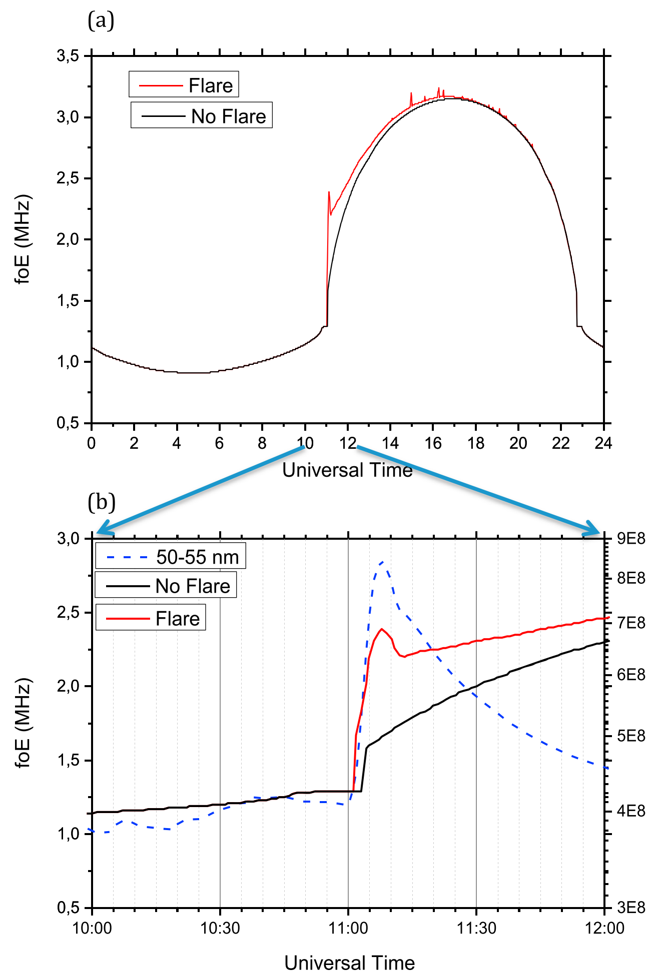

Figure 6. (a) SUPIM-INPE simulation of f_oE over Jicamarca on 28 October 2003. The red curve represents the f_oE variation when the ionizing radiation fluxes include those due to the X-class flare radiation, while the black curve represents the f_oE diurnal variation unaffected by the flare. The spiked peak in f_oE at 11 UT due to the flare may be noted. (b) An expanded time scale plot highlighting the f_oE increase due to the flare extra ionization. The flare emission variation in wavelength band 50–55 nm is also shown using rightside scale for which the axis values are photons cm^{-2} s^{-1}.

from its nighttime westward to daytime eastward polarity over the longitude of Jicamarca, under equinoctial condition, is found, statistically, to be at 07 LT according to ROCSAT-1 vertical drift data analyzed by *Fejer et al.* [2008b]. The flare X-ray peak occurred near 06 LT when that electric field should be westward. In this scenario one expects the EEJ response to start as a westward current intensification as indeed observed, but its expected reversal to an eastward current within about 1 h did not happen over Jicamarca. The intense EEJ continued westward well into the morning hours till about 10 A.M./15 UT, which strongly suggests the presence of strong westward electric field starting from the beginning of the flare intensification (or even a bit earlier to that), thereby supporting the presence of a DDEF with polarity reversed to westward by 06 LT. This is evident also in the example of the *F* layer height variations under storm recovery conditions at both Jicamarca and Sao Luiz shown in Figure 3, in which the average LT of the DDEF morning reversal to westward was noted to be 05–06 LT. An intriguing aspect of the EEJ response in Figure 2 is the large amplitude of the Δ*dH* (~125 nT) under the small background *E* layer ionization typical of the sunrise condition, though intensified to some degree by the flare radiation. This feature might demand relatively large zonal electric field to account for the observed EEJ amplitude, which will be examined below.

The role of an overshielding electric field associated with the *AE* recovery that had set in at ~08:15 UT (on 28 October) is unlikely to influence the EEJ response over Jicamarca. This is because as we have determined from the SFE2 event, such electric field must have decayed in about 30 min, whereas ~1 h 45 min elapsed after the *AE* decay had set in before the EEJ response beginning at 11 UT. A realistic estimate of the zonal electric field during the flare peak intensity can be made by comparing the Δ*dH* value at this time with that of its quiet midday value. The latter can be represented as

$$\Delta dH_1 \ \alpha \ I_1 \ \alpha \ J_{\O 1} = E_{\O 1} \sum\nolimits_{C1} \qquad (1)$$

where the suffix "1" is used to denote midday values. I_1 is the total current in the EEJ at midday, $J_{\O 1}$ is the corresponding current density at the EEJ center, $E_{\O 1}$ is the zonal electric field, and $\sum_{C1}$ is the field line integrated Cowling conductivity at the EEJ center. By using a suffix "*F*" to denote the corresponding parameters at the flare maximum, we have

$$\Delta dH_F \ \alpha \ I_F \ \alpha \ J_{ØF} = E_{ØF} \sum\nolimits_{CF} \tag{2}$$

Taking the ratio of equation (2) to equation (1) we have

$$\Delta dH_F / \Delta dH_1 = E_{ØF} \sum\nolimits_{CF} / E_{Ø1} \sum\nolimits_{C1} \tag{3}$$

We know that $\Sigma_{C1} \ \alpha \ n_{e1} \ \alpha \ (f_oE_1)^2$ and $\Sigma_{CF} \ \alpha \ n_{eF} \ \alpha \ (f_oE_F)^2$, where n_e represents the *E* layer peak electron density, and f_oE is the *E* layer critical frequency. Thus, from equation (3) the electric field during the flare peak can be represented as

$$E_{ØF} = E_{Ø1}(\Delta dH_F / \Delta dH_1) \ (foE_1)^2 / (foE_F)^2 \tag{4}$$

The parameters of equation (4) required for estimating the $E_{ØF}$ were determined as follows: ΔdH_1 was calculated as the mean of seven quietest days of the month (October 2003), in each case the midday values over Piura being subtracted from that of Jicamarca ($dH_{1JIC} - dH_{1PIU} = \Delta dH_1$). The mean value of ΔdH_1 was 65 nT, with significant day-to-day variations with the maximum being 80 nT. The value of $E_{Ø1}$ was calculated from the vertical drift velocity V_d, which in turn was obtained from its statistical relationship with ΔdH_1, given by $\Delta dH_1 = 3.19 \ V_d - 15.97$, as derived by *Anderson et al.* [2004] based on the Jicamarca JULIA radar vertical drift data and magnetometer data for the month of October 2003. Here $V_d = E_{Ø1}/B$, and *B* is the geomagnetic field intensity. The value of f_oE_1 was obtained from Jicamarca Digisonde ionograms as mean of seven quiet day values during October 2003.

The *E* layer critical frequency during the flare peak at 11 UT (f_oE_F) could not be determined from ionogram due to the HF black-out caused by the underlying enhanced *D* layer absorption arising from the flare-induced X-ray extra ionization. Therefore, the f_oE_F was calculated through a simulation of the extra ionization using the Sheffield University Plasmasphere-Ionosphere Model (SUPIM) [*Bailey et al.*, 1997]. The SUPIM-Instituto Nacional de Pesquisas Espaciais (INPE) version that was used has its lower limit of calculation extended to 90 km (from the120 km limit of the original SUPIM), and the result obtained for the E layer over Jicamarca on the flare day are presented in Figure 6. This figure shows the f_oE variation on 28 October resulting from all the ionizing radiation including the flare radiation (red curve), which is compared to its variation in the absence of the extra flare radiation (black curve). We may notice the f_oE_F occurring as a spike at 11 UT right at the flare peak (Figure 6a), the detailed characteristics of which is being presented more clearly in the expanded time scale plot in Figure 6b. The midday value of the f_oE (that is, f_oE_1) calculated by the SUPIM-INPE may be noted as 3.20 MHz in Figure 6a, whereas its observed value as obtained from Jicamarca ionograms is 3.65 MHz, which is higher by a small factor of 1.125. The SUPIM-INPE-calculated f_oE_F is 2.35 MHz as may be noted in Figure 6b. The expected observational value of f_oE_F can be obtained by applying the above factor (1.125) to its calculated value. Thus, we get a more realistic value of this parameter as $f_oE_F = 2.7$ MHz.

Using the above parametric values corresponding to equation (4), we may estimate the zonal electric field during the flare peak, ($E_{ØF}$), to be limited between 2.13 and 2.22 mV/m, respectively, for the maximum (80 nT) and the mean (65 nT) value of ΔdH_1 used as the midday reference for this calculation, the corresponding midday value of the zonal electric field being 0.65 mV/m and 0.75 mV/m, respectively (see Table 2). Based on these results, we may consider that the zonal westward electric field that drove the reverse EEJ at the flare peak was at least of 2 mV/m. The closeness of this value to reality is dependent on (1) how accurately we have represented the quiet time midday electric field as well as on (2) the SUPIM simulation of the f_oE. The item (2) does not contribute to any uncertainty to the real f_oE values since its modeled value was normalized to the observation near midday. The item (1) may involve some degree of uncertainty due to the possibility that the "quiet time" EEJ intensity is subject to variations due to forcing from upward propagating atmospheric waves such as tidal modes and planetary/Kelvin waves [e. g., *Forbes*, 1995; *Abdu et al.*, 2006b]. An underestimation of the ΔH_1 used in equation (4) could lead to an overestimation of the flare peak electric field ($E_{ØF}$), which appears to be a possibility in our study. However, this aspect does not seem to affect the main point of focus in this study as will become clear from the discussion below.

We note that the value of the electric field at the flare peak (estimated above as at least 2 mV/m) is significantly larger than its quiet midday values whose upper limit is about 0.75 mV/m. To account for this significantly larger value of the flare time zonal electric field ($E_{ØF}$) we may examine the possible contributions to it

Table 2. The ΔdH Values During the Solar Flare of 28 October 2003 With 8 Days Mean and Maximum Values, the Corresponding f_oE Values, and the Calculated Electric Fields

ΔdH_1 (nT)	ΔdH_F (nT)	$E_{Ø1}$ (mV/m)	f_oE_1 (MHz)	f_oE_F (MHz)	$E_{ØF}$ (mV/m)
65 (Mean)	125	0.65	3.65	2.35	2.22
80 (Max.)	125	0.75	3.65	2.35	2.13

arising from different sources as (1) the westward disturbance dynamo electric field mentioned earlier ($E_{ØDD}$); (2) the electric field associated to a possible presence of an ongoing CEJ ($E_{ØCEJ}$), known to be driven by local wind, when the response to a flare is found to be an enhancement in the westward EEJ current (as discussed by *Rastogi et al.* [1999]; (3) the possibility of a flare-induced enhancement in the longitudinal/local time gradient in the *E* layer conductivity gradient at sunrise causing zonal electric field enhancement through the involvement of *F* layer dynamo process ($E_{ØFD}$). In other words, the flare time electric field in the case of the present flare, which occurred in the recovery phase of a minor storm, in the possible presence of a CEJ, and near sunrise, can be represented as

$$E_{ØF} = E_{ØDD} + E_{ØCEJ} + E_{ØFD} \tag{5}$$

As regards the item 1, the $E_{ØDD}$ turns westward typically near 06 LT as discussed before (from its nighttime eastward polarity), and as shown by *Scherliess and Fejer* [1997] it has a magnitude on the order of 0.25 mV/m (corresponding to an *F* region plasma downward vertical drift of 10 m/s) for the case of a typical magnetic storm. This is a statistical value and can vary from case to case. Concerning the item 2, the mean ΔdH variation (representing seven quiet days), plotted in Figure 2, does show the presence of CEJ, with a magnitude of 18 nT, peaking near 11:30 UT (close to the flare peak time). The corresponding zonal electric field was calculated by using an equation equivalent to equation (4), in which the corresponding f_oE values were based on SUPIM-INPE simulation results in Figure 6. This resulted in $E_{ØCEJ} = 0.6$ mV/m. Considering that the estimated value of $E_{ØF}$ is on the order of 2 mV/m, we need to account for yet an additional electric field on the order of 1. 15 mV/m. The third term in equation (5), that is electric field due to *F* layer dynamo, represents the only other source that we can think of as having the potential to contribute to complete/improve the picture.

Based on the *F* layer dynamo theory [*Rishbeth*, 1971] it is expected that during/close to the day/night transition period the zonal electric field can become enhanced due to the action of zonal thermospheric wind blowing across the terminator in the presence of the large longitudinal gradient in the *E* layer integrated conductivity that exists at this time. The evening/postsunset enhancement in the zonal electric field, under such conditions, that is the prereversal enhancement in the zonal electric field (PRE)/vertical drift in the *F* region, has been demonstrated by using theoretical and model calculations by several authors [see, for example, *Heelis et al.*, 1974; *Farley et al.*, 1986]. Especially, the longitudinal gradient in the *E* layer conductivity across the sunset terminator has been shown to control in a significant way the PRE vertical drift [*Batista et al.*, 1986; *Abdu and Brum*, 2009]. Depending upon the direction of the thermospheric zonal wind, the longitudinal gradient in *E* layer conductivity is expected to produce vertical drift modification near sunrise as well, which however, has not been investigated in any detail so far. In the present study we note that the solar flare-induced *E* region electron density enhancement that occurred just around sunrise over Jicamarca should amount to a significant increase in the longitudinal gradient in the *E* layer conductivity around the morning terminator (see Figure 6) that could provide the condition for causing an enhanced westward electric field, that is, an increase in downward plasma drift. The precise contribution to an enhanced vertical drift needs to be quantified by using a model/simulation study, which is beyond the scope of the present investigation. An important point to verify in this context is that such an extra source of zonal (westward) electric field is highly unlikely to be present/evident over Sao Luis where the flare occurred at a later local time, 2 h after sunrise as can be noted in Figure 2, and therefore, well removed from possible sunrise influence on *F* layer dynamo electric field. Equation (4) was used again to obtain an estimate of the $E_{ØF}$ over Sao Luis. Based on calculation by the SUPIM-INPE the value of f_oE_F was found to be 3.8 MHz, which was almost the same as that of the quiet day mean f_oE_1 observed by Digisonde over Sao Luis (that was 3.84 MHz). Also, it can be noted in Figure 2 hat the values of ΔdH_F and ΔdH_1 are approximately of similar magnitude. Therefore, it is possible to make a rough assessment that the zonal electric field over Sao Luis during the flare peak is comparable to its value near midday, which is reasonable to expect. This is an important result that strongly supports our finding that additional electric field from *F* region dynamo source could be present over Jicamarca due to the flare occurring close to sunrise over that location.

The EEJ response to the X-class flare of 29 October (SFE2) was a unique event (under a rare circumstance) in that the flare occurred at a time exactly when the *AE* was recovering from its large intensification (by about 3500 nT) that occurred during 19–20 UT (14–15 LT at Jicamarca). This recovery took less than 10 min to complete so that it can be qualified as a "rapid" recovery. This rapid recovery produced a strong overshielding electric field of westward polarity as indicated by the negative deviation in ΔdH by ~80 nT (see Figure 5) over Jicamarca. The overshielding electric field occurred even when the B_z was southward (but slowly decreasing). Previous studies have shown [for example, *Wei et al.*, 2011] that the typical solar wind condition in which the interplanetary magnetic field (IMF) suddenly turns northward after a prolonged southward orientation is neither a necessary nor a sufficient condition for overshielding. Such overshielding signatures, observed even under stable southward IMF conditions, have been reported [*Fejer et al.*, 2007; *Ebihara et al.*, 2008], as it indeed seems to be the case also in the present observation.

The shielding layer, constituted by the Region 2 FAC, starts development with the convection growth so that it becomes effective in the late main phase [*Kikuchi and Hashimoto*, 2016], which, in the present case, is represented by the large *AE* increase during the 19–20 UT interval when eastward electric field dominated at low latitudes. The rapid decrease in *AE* starting at 20:25 UT, representing the recovery phase, marked the onset of the overshieling electric field of westward polarity. Here it is to be noted that during the extended duration *AE* activity, convection electric field continued to penetrate to low latitude due to imperfect shielding conditions as pointed out by *Huang et al.* [2005] [see also, *Richmond et al.*, 2003], but the precedence of extended period of activity has also resulted in the simultaneous presence of DDEF, the net electric field during the flare time being of eastward polarity. It is interesting to note that under such conditions it is still possible to identify the signature of an overshielding electric field due to the very rapid change in the EEJ that it caused (as indicated by the vertical dashed line 3 in Figure 5b). As pointed out by various authors the time constants for the build up of the shielding layer (Region 2 FAC) and for the subsequent decay of the overshielding electric fields are important information because of their well-known controlling effects on various low-latitude phenomena, such as the development of the equatorial anomaly, plasma bubble irregularities, and on the EEJ current system (studied here) [see, for example, *Abdu et al.*, 2007, 2009]. They also control the decay of the ring current in the storm recovery phase as pointed out by *Kikuchi and Hashimoto* [2016].

The occurrence of an X-class solar flare coinciding with a clean case of a storm decay phase resulted in a unique event of suppression of a prompt EEJ response to flare-induced increase in the *E* layer ionization, which we note is the first observation of this kind. This suppression caused effectively a delay in the EEJ response that permitted us to identify the role of a westward electric field present at the time, that is the overshielding electric field associated with the storm recovery. The decay time of the overshielding electric field obtained from this event, as 28 min, is in excellent agreement with the theoretical model simulation results obtained by *Peymirat et al.* [2000] as 32 min. The present result may therefore represent the first experimental determination of the overshielding decay time based on a clean event.

5. Conclusions

The present investigation on the EEJ response to two X-class solar flares has revealed some new and unique aspects of the electrodynamics of the equatorial electrojet and the low-latitude ionosphere under disturbed conditions, especially relating to disturbance electric fields, in the form of imperfectly shielded penetration electric field, disturbance dynamo electric field, overshielding electric field, electric field of quiet time CEJ, and electric field that can arise from sunrise transition process. The rare nature of the occurrence of these flare events under the unique circumstances in which they were observed has limited the present investigation to only two cases. The main conclusions of the study may be summarized as follows:

1. During an intense (X-class) solar flare, the equatorial electrojet near sunrise over Jicamarca undergoes strong westward intensification, suggesting the presence of abnormally intense westward electric field. The precedence of the event by several hours of magnetic disturbance of moderate intensity (marked by B_z south and *AE* activity conditions) suggested a significant role of disturbance dynamo electric field in the EEJ response.

2. Being close to the local time of the DDEF polarity morning reversal to westward and under the presence of a morning counter electrojet (CEJ), the flare-induced EEJ response over Jicamarca suggested dominance of westward electric fields from both these two sources. A possible third source of electric field is proposed to be arising from the *F* layer dynamo under the sunrise transition. The *E* layer conductivity local time gradient enhanced by the flare ionization near sunrise may contribute to the generation of zonal electric field by *F* region dynamo at sunrise.
3. The EEJ response features over Jicamarca, where the flare occurred closer to sunrise, suggested the presence of westward electric field whose intensity was larger than over Sao Luis where the flare occurrence local time was 2 h later. Such comparison appears to support the proposed presence of an enhanced *F* layer dynamo-induced westward electric field (the third source mentioned above) near sunrise over Jicamarca.
4. A rapid recovery in the storm time *AE* activity during an X-class flare can cause delay in the EEJ response to that flare. The delay can arise from the action of an overshielding electric field of westward polarity that, thereby, permits the determination of the decay time of the associated overshielding electric field. The overshielding decay time so deduced is found to be in good agreement with theoretical model simulation results.

Study is being pursued to elucidate further on the detailed nature of the different sources of electric fields that can exist during solar flares occurring at local times of varying ionospheric electrodynamical conditions and under magnetically disturbed periods.

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