Abnormal evening vertical plasma drift and effects on ESF and EIA over Brazil-South Atlantic sector during the 30 October 2003 superstorm

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[1] Equatorial *F* region vertical plasma drifts, spread F and anomaly responses, in the south American longitude sector during the superstorm of 30 October 2003, are analyzed using data from an array of instruments consisting of Digisondes, a VHF radar, GPS TEC and scintillation receivers in Brazil, and a Digisonde and a magnetometer in Jicamarca, Peru. Prompt penetrating eastward electric field of abnormally large intensity drove the F layer plasma up at a velocity $\sim$1200 ms^{-1} during post dusk hours in the eastern sector over Brazil. The equatorial anomaly was intensified and expanded poleward while the development of spread F/plasma bubble irregularities and GPS signal scintillations were weaker than their quiet time intensity. Significantly weaker *F* region response over Jicamarca presented a striking difference in the intensity of prompt penetration electric field between Peru and eastern longitudes of Brazil. The enhanced post dusk sector vertical drift over Brazil is attributed to electro-dynamics effects arising energetic particle precipitation in the South Atlantic Magnetic Anomaly (SAMA). These extraordinary results and their longitudinal differences are presented and discussed in this paper.

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1. Introduction

[2] The earth's ionosphere responds to major magnetic storms by drastic modifications in its dynamics, structure and chemistry, widely manifested in electron density distributions, plasma structuring and plasma drifts. Disturbance electric fields are the major source of ionospheric modification over equatorial and low latitudes. During a storm/sub storm development large polar cap dawn-dusk electric field promptly penetrates to equatorial latitudes until partially balanced by the development of a shielding layer in time-scales of approximately half an hour to several hours [see, e.g., *Kelley et al.*, 1979; *Fejer and Scherliess*, 1998; *Kikuchi et al.*, 1996]. The prompt penetrating (under-shielded) electric field (PPEF) has eastward (westward) polarity on the day (night) side of the equatorial ionosphere, with polarity reversed for the over-shielding electric field that remains at the sub storm recovery. It is also well known that the global thermospheric disturbances originating from the auroral heating produces long duration electric fields, known as disturbance dynamo electric fields (DDEF) [*Blanc and Richmond*, 1980] that dominate the low latitudes with a delay of 4–5 h from the first incidence of the PPEF following the storm onset. These electric fields could last several hours up to one day [*Scherliess and Fejer*, 1997] and have polarity local time dependence that is nearly opposite to that of the under-shielding PPE [*Richmond et al.*, 2003]. The PPEF of eastward polarity can cause large uplift of the day- and evening-side ionosphere resulting in large increase of the total electron content (TEC) as measured by GPS receivers [*Tsurutani et al.*, 2004; *Maruyama et al.*, 2004; *Lin et al.*, 2005a, 2005b]. During such TEC storms the equatorial ionization anomaly (EIA) can expand poleward with the ionization crests displaced to midlatitudes [*Mannucci et al.*, 2005; *Abdu*, 1997]. At low latitudes the eastward PPEF has maximum intensity in the dusk sector [*Richmond et al.*, 2003; *Fejer and Scherliess*, 1998; *Abdu et al.*, 2007], where the prereversal enhancement of zonal electric field (PRE) arising from the F layer dynamo is normally active. Large uplift of the evening F layer can cause the instability growth by Rayleigh-Taylor mechanism leading to the development or intensification of the ESF [*Abdu et al.*, 2003; *Sastri et al.*, 1997]. During seasons of

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low PRE intensity, and hence minimal spread F occurrence, an eastward PPEF present at dusk hours could enhance the conditions for spread F/plasma bubble development. *Abdu et al.* [2003] discussed a case of bubble development due to an eastward PPEF under conditions of southward Bz and AE intensification during the medium intensity storm of August 1998 when the PPEF occurred in-phase with a normally weak PRE of the winter season over Brazil. From DMSP F09 satellite observation during the 4–6 June 1991 storm, *Burke et al.* [2000] observed plasma bubble generation due to disturbance electric field when the vertical ion drift inside the bubbles as measured by the ion drift meter on board the satellite presented supersonic velocities (>1500 ms^{-1}). Little is known about the plasma bubble irregularity development during major/super storm events when the extremely large intensity of an eastward PPEF could drive giant plasma fountain whereby the low latitude ionospheric plasma, lifted up to large heights, could be displaced by forces of diffusion and gravity, to higher latitudes, causing large scale depletion of the TEC in the entire EIA and the low latitude ionosphere, a case for the present investigation.

[3] During the major storm of March 1989, *Batista et al.* [1991] observed from ionosonde measurements large scale F layer uplift with vertical velocity exceeding 200 ms^{-1} in the post dusk hours over the Brazilian south Atlantic longitude sector, while the associated large plasma density depletion at the DMSP altitudes was discussed by *Greenspan et al.* [1991]. During the same storm event large scale TEC depletions at low latitudes with concurrent increase over midlatitude suggested large scale poleward expansion of the post dusk EIA as discussed by *Abdu* [1997]. See also *Abdu et al.* [1995]. Ion drift meter and retarding potential analyzer on board the DMSP and ROCSAT satellites in their orbits at 840 km and 600 km, respectively, detected large scale vertical plasma drifts and plasma density depletions in the post dusk sector ionosphere over the Brazilian-South-Atlantic longitudes during the major storm of July 2000 as discussed by *Basu et al.* [2001], *Lin and Yeh* [2005], and *Lin et al.* [2001]. Ionospheric responses over Brazil to a few intense storms have been discussed also by *Sobral et al.* [1997]. The large poleward expansion of the equatorial anomaly during intense storms has been suggested to be the plasma source for the Storm Enhanced Density (SED) events observed over midlatitudes [*Foster et al.*, 2005; *Lin et al.*, 2007]. During the extended duration super storm event of 30 October 2003 large scale poleward expansion of the EIA was observed in the dayside ionosphere (1400 LT) over Pacific by *Mannucci et al.* [2005] while simultaneous EIA poleward expansion in the post sunset sector (1900 LT) was observed over Brazil-South Atlantic longitude sector which is a focus of discussion in this paper. We present and discuss in this paper the super fast uplift of the equatorial F layer in response to the abnormally large prompt penetrating eastward electric field that occurred during post dusk hours of 30 October over Brazilian East sector and its consequences on the EIA and spread F irregularity developments and on scintillation intensity. The large F layer uplift in the dusk sector caused significant intensification and poleward expansion of the EIA. However, they were found to be severely constraint by poleward directed (cross-equatorial) disturbance thermospheric winds of large intensity as inferred from the latitudinal pattern in the corresponding hmF2 variation. Further, contrary to expectation the large intensity of PPEF did not cause any enhancement in the plasma bubble/spread F irregularities development, and the GPS signal scintillation intensity (S_4 index) over Brazil in general was weaker than its quiet time values.

Table 1.

Station	Geog. Longitude	Geog. Latitude	Mag. Dip Angle
São Luís	44.2°W	2.33°S	−2°
Fortaleza	38.45°W	3.9°S	−9°
C. Paulista	45°W	22.6°S	−34°
Jicamarca	76.9°W	22.6°S	1°
Piura	279.3°	5.2°	13.6°

[4] Observational data from multi-instrument diagnostics are utilized in the analysis. F layer height, density and vertical drift were obtained from three Digisondes operated at equatorial and low altitude sites. Plasma irregularity distribution and dynamics were measured at one-minute resolution by a 30 MHz coherent backscatter radar operated at the equatorial site São Luis. TEC and scintillation data were obtained from the Brazilian network of GPS receivers. Magnetometer data from Jicamarca and Piura were used to evaluate the equatorial electrojet intensity variations (as described in section 2.1). The interplanetary magnetic field parameter Bz as measured by the ACE satellite and 1-min Dst as represented by the Sym-H index published by the WDC in Kyoto were used in the interpretation of the ionospheric response features. The coordinates of the stations are listed in Table 1. The ground magnetometer data have 1-min resolution.

2. Results

[5] With the Dst maximum amplitude exceeding 400 nT the 30 October 2003 event was of major storm category. It resulted from the fastest coronal mass ejection (CME) event of the solar cycle 23 [*Gopalaswamy et al.*, 2005] and was preceded by extended duration of intense sub storm/storm activity sequences that began on 29 October. These storms have been investigated from the perspective of the effect they produced in the ionosphere–thermosphere systems at different latitude and longitude regions [see for example, *Abdu et al.*, 2007; *Basu et al.*, 2007, 2005; *Batista et al.*, 2006; *Lin et al.*, 2005a, 2005b; *Mannucci et al.*, 2005; *Sahai et al.*, 2005; *Zhao et al.*, 2005]. Some of these results may be highlighted as follows. Prompt penetration of interplanetary electric field of large intensity caused large intensification and poleward expansion of the equatorial ionization anomaly (EIA) as observed by GPS receivers on board CHAMP satellites in the 1400 LT Pacific longitude sector [*Mannucci et al.*, 2005]. Large scale equatorial plasma depletion in the 840 km DMSP track was observed in the post dusk sector Brazilian- South Atlantic longitudes by *Basu et al.* [2007]. Contrasting/complementary responses of the EIA and F layer heights to disturbance electric field and storm time thermospheric winds in the Asian and Brazilian/south Atlantic longitudes sector were presented by *Abdu et al.* [2007]. TEC response features in the Asian and American longitude sectors during the entire event sequences were investigated

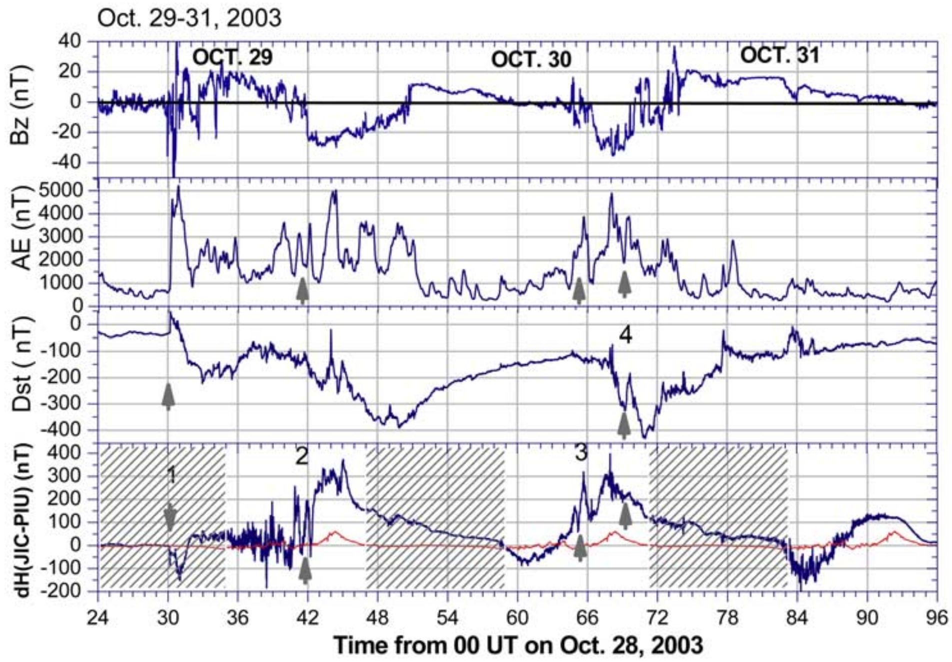

Figure 1. 1-min values of the Interplanetary magnetic field Bz (top) and AE (second from top), Sym-H component (Dst) (third from top) and the $\Delta H_{(JIC-PIU)}$ variation representing the equatorial electrojet intensity (see text) over Jicamarca (bottom), during 29–31October. Also plotted is a reference day $\Delta H_{(JIC-PIU)}$ variation (red curve) over Jicamarca. (Other quiet days considered also show similarly low amplitude of ΔH variations). Night hours over Jicamarca are shown by hatched area.

through observational data from ground-based GPS receiver networks and model simulations by *Lin et al.* [2005a, 2005b], while *Zhao et al.* [2005] discussed the TEC responses based on the ionospheric heights and EEJ intensity variations. Longitudinal comparison of the *F* region responses was presented also by *Sahai et al.* [2005]. Here we limit our discussion to: (1) general features of the disturbance electric field in the American sector during the earlier phases of the storm; (2) the abnormal post dusk *F* layer uplift of 30 October and the consequent EIA poleward expansion, spread F/plasma bubble generation and effects on GPS signal scintillation, over Brazil; and (3) a comparison of the post dusk PPEF intensity over Brazil and Peru, that is, longitudinal variation in the American sector.

2.1. Some Features of the Disturbance Electric Fields in the American Sector

[6] Figure 1 shows in the first three panels the interplanetary magnetic field component B_z, the auroral electrojet activity index AE and the Dst index (1-min Sym-H) variations during 29–31 October 2003. In a recent paper *Abdu et al.* [2007] discussed the possible effects of the different phases of the Bz, AE and Dst variations during these extended event sequences in terms of the PPEF and the DDEF associated with them vis-a-vis some outstanding ionospheric response features observed in the Brazilian and Asian longitude sectors. The abnormal vertical drift of the post dusk sector *F* region, the main focus of this paper, is found to present significant variation within the American longitude sector, with larger intensities over Brazil, as verified by comparing the data over Jicamarca and the Brazilian stations to be discussed later. There is growing consensus that the relatively larger PPEF and the associated vertical drift mostly observed in the post dusk hours over the Brazil- East sector may be a unique feature of the longitude of the South Atlantic Magnetic Anomaly [*Abdu*, 1997; *Abdu et al.*, 2005; *Basu et al.*, 2001, 2007] under the influence of a modified ionospheric conductivity distribution in this region. [see also, *Abdu et al.*, 1998; *Lin and Yeh*, 2005]. It is not clear if the presumably enhanced PPEF in the SAMA region is a unique feature of the post dusk hours, or it could occur also at other local times. For a better perspective of the effects of the PPEF at other local times we will first briefly examine some outstanding response features noted during the extended storm interval that preceded the 30 October event. In the bottom panel of Figure 1 is shown the equatorial electrojet (EEJ) intensity variation over Jicamarca (JIC) during the entire disturbance period. Here the EEJ strength is represented as $\Delta H_{(JIC\text{-}PIU)}$ which is $\Delta H_{JIC} - \Delta H_{PIU}$, the difference in the ΔH variation obtained by subtracting the ΔH variation over Piura, an off-equatorial station, from that over the dip equator, Jicamarca. ΔH is the geomagnetic field horizontal component variation with reference to its midnight values at each station. The first B_z southward turning can be noted at 0610 UT which caused (within the 1-min data resolution) a prompt onset of AE intensification and D_{st} increase (representing the storm sudden commencement-SSC) on 29 October indicated by the Arrow 1 in Figure 1. During this initial phase of the storm when it was local midnight sector over Peru a strong prompt penetrating electric field of westward polarity produced an intense westward EEJ current (with peak intensity of −150 nT) that lasted through the duration of the AE intensification, from 06:10 UT to ~07:30 UT. Such PPEF induced nighttime EEJ westward

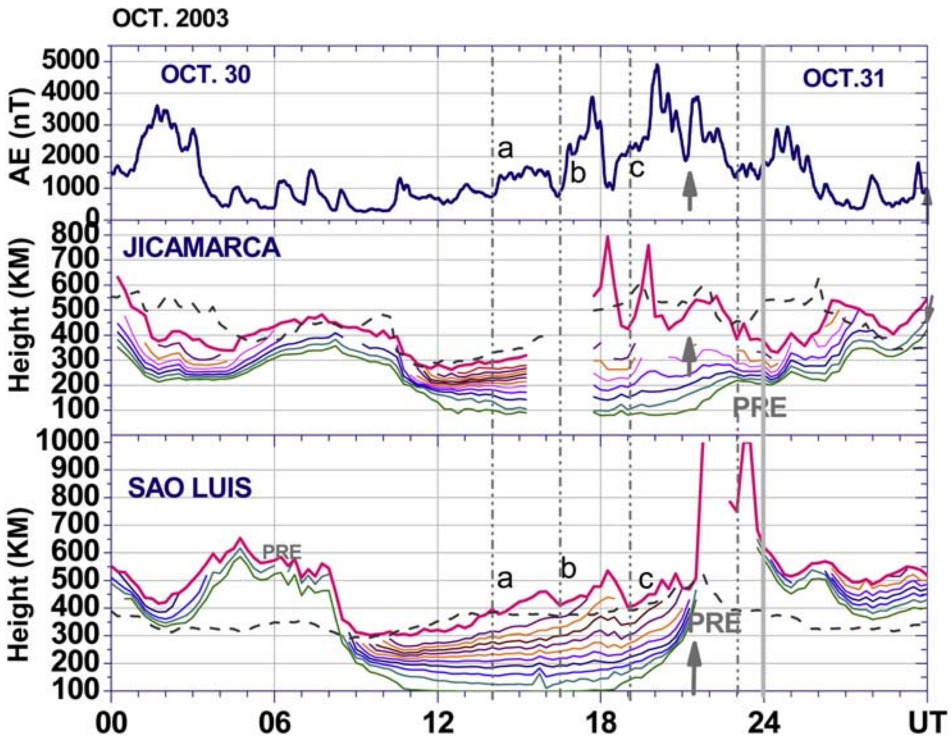

Figure 2. 1-min values of AE index on 30–31 October, the F layer heights at specific plasma frequencies at 1 MHz interval (starting at 3 MHz) and the hmF2 over Jicamarca (middle) and São Luís (bottom). Note the large and rapid rise of the heights over São Luís corresponding to a rapid AE intensification at ~21:10 UT/18:10 LT indicated by arrows. The dashed vertical lines "a", "b", and "c" mark some specific AE intensification phases for which hmF2 increases over Sao Luis are identified. (hmF2 response over Jicamarca is also evident). A grey vertical line at 24 UT indicates the division of the UT day.

current related to B_z southward turning and AE intensification was observed also in the Pacific sector on two succeeding nights of this storm sequence, which has been discussed by *Abdu et al.* [2007]. Assuming a quiet midday value for the zonal electric field over Jicamarca of the order of 0.6 mV/m [based on the vertical plasma drift measurements by *Fejer et al.*, 1991] and electron density values assumed to be comparable to the daytime conditions, the peak westward current over Jicamarca (near 7 UT/02 LT) can be estimated as corresponding to a prompt penetrating westward electric field of ~2 mV/m. Simultaneous F layer downdraft due to a westward electric filed was observed over São Luis with a peak drift velocity (near 07 UT/04 LT) of 130 m/s, as estimated by running the SUPIM [Sheffield University Plasmasphere-Ionosphere Model, *Bailey et al.*, 1993], which corresponds to a westward electric field of ~3 mV/m [*Abdu et al.*, 2007; *Batista et al.*, 2006]. The relative magnitudes of these PPEFs at Jicamarca and São Luis, (the former being 2 h in LT behind the latter), appear to be consistent with the PPEF LT variation as per the TIEGCM model results by *Richmond et al.* [2003] (see the result at time C in their Figure 4). Additional cases of discrete EEJ responses over Jicamarca to episodes of AE intensification and recovery may be noted during day time hours (examples indicated by the Arrows 2, and 3 in Figure 1) of 29–30 October. The corresponding responses over São Luis, registered in the hF variations, were very weak on 29 October (not shown here). The hmF2/hF variations shown for 30 October in Figure 2 does show somewhat clear response features around 14–20 UT over São Luis (marked "a", "b", and "c"). Jicamarca presents some data break and slightly different responses in hF/hmF2. The discrete EEJ response identified by Arrow 3 in Figure 1 appears to have a clear signature in hF variation over Jicamarca around 18 UT in Figure 2. Notwithstanding the dominating role of the daytime photo-chemistry the hF variations over São Luis do not appear to represent a disturbance electric field variation of larger intensity than that caused the increases in hF, and the $\Delta H_{(JIC\ -\ PIU)}$ variation (of the order of 150–200 nT), over Jicamarca. The conspicuous AE increase at ~2110 UT (1810 LT) indicated by the Arrow 4 (Figure 1) was responsible for the abnormally large F layer uplift to be discussed later. It is of interest to note further that, besides the discrete responses to some specific AE fluctuation episodes, the eastward EEJ shows a general increase of intensity that is significantly larger than its quiet time reference values, which appears to correspond to southward Bz conditions and periods of elevated background levels of the fluctuating AE variations. Such long duration disturbance EEJ might suggest that the Region II field aligned current presents only a partial shielding for long duration polar cap electric field penetrating to equatorial latitudes. The eastward EEJ continues into the night hours of 29 October and 30 October even after the Bz turned northward and when the

Dst was in the recovery phase. The disturbance dynamo electric field (DDEF) is expected to turn eastward during premidnight period when (on these two nights) the Dst recovery was in progress, remain eastward and turn back to westward in the morning hours according to the model results by *Richmond et al.* [2003]. Thus it appears that the eastward EEJ decreasing in intensity during the later part of the night followed by a rather intense and slowly varying westward EEJ that is consistently present in the morning hours of 30 October and 31 October is driven by a disturbance wind dynamo electric field. We will not be discussing these effects further; instead we will proceed to discuss the unusually large F layer uplift on the evening of 30 October.

2.2. Abnormal Post Dusk Vertical Drift Over São Luis

[7] Figure 2 shows the UT variations in hmF2 and the F layer bottom-side electron density/plasma frequency isolines over São Luís ((2.6°S, 44.2°W) in the bottom panel, and the corresponding variations over Jicamarca in the middle panel for 30–31 October, together with the AE index in the top panel. Immediately following the ∼21:10 UT sudden intensification of the AE the hmF2 over São Luis showed a very rapid rise from ∼500 km to beyond 1100 km (indicated by an arrow) within the 15 min sounding interval. Range spreading F layer trace was set in by 21:30 UT (not shown here) which caused only small uncertainty in the hmF2 values. The local time of the layer uplift (21:30 UT/18:30 LT) coincided with that of the prereversal enhancement in the vertical drift indicated as "PRE" in Figure 2. This layer uplift corresponded to a vertical drift velocity of >700 ms^{-1} (determined as dhmF2/dt) and was accompanied by large decrease of the F2 peak density (with foF2 reaching down to ∼4 MHz, Figure 6). The corresponding F layer height rise over Jicamarca (middle panel, Figure 2) was very small, not exceeding that corresponding to a vertical drift velocity of 40 ms^{-1} as determined from the time rate of change of the F layer peak height (dh_mF/dt). The velocity indicated by the rate of change of height at specific bottom-side plasma frequencies (dhF/dt) is significantly less than 40 m/s however. Following an irregular AE recovery, starting at ∼21:30 UT the hmF2 reached a background disturbed level by 24 UT that was significantly higher than its quiet time values (plotted by dashed line) over São Luis. Over Jicamarca the corresponding hmF2 was less than its quiet time value. This different conditions of the hmF2 relative to their reference values at São Luis and Jicamarca would point to the different degrees of dominance of the PPEF and DDEF at this phase of the storm at the two sites.

[8] The Range-Time-Intensity (RTI) and Range-Time-Velocity (RTV) maps obtained by the 30 MHz VHF backscatter radar at São Luis are presented in Figure 3. The development of 5-m plasma irregularity structures was evident starting at ∼21:30 UT (18:30 LT). Within less than the next 15 min their heights shot up to beyond the 1300 km range of the radar, causing the echo patch to reappear near 300 km (before 22:00 UT) by range aliasing. The vertical velocity near 21:30 UT as determined from the steep slope of the fast rising irregularity trace in the RTI map is ∼1200 ms^{-1}, which agrees with the velocity determined from the RTV map as well. We note that the 1-min resolution radar data provide a more accurate estimate of the irregularity vertical drift than that was obtained from the 15-min resolution ionograms which represents only a lower limit for such velocity. This is clearly the highest velocity ever measured of equatorial plasma irregularity vertical drift by radio sounding technique. Precursor signature for ESF development, in the form of ionogram multiple F layer traces was evident in the ionogram taken at 21:15 UT (18:15 LT) when the hmF2 was 468 km over São Luís (not shown here). Thus the rapid layer uplift due to the PPEF seems to have occurred during an ongoing ESF instability development that apparently did not suffer additional enhancement due to the disturbance electric field. In the ionogram the F-layer trace presented reduced range spreading (not shown here) than that is typical for quiet conditions which suggested that the ESF development under this extremely large eastward PPEF (and F layer vertical uplift) was reduced in intensity. This point can be further verified from Figure 4 wherein the scintillation S_4 index during 18–24 LT interval as observed from the GPS receiver network in Brazil is plotted in geographic latitude versus longitude. The scintillation intensity distribution in the quiet night of 28 October shows that the S_4 index is downward of 0.5 (as per the color code) around the latitude of São Luis while it has higher values (upward of 0.5 and approaching 0.9) at latitudes farther away from equator. Thus we note that the scintillation intensity increases toward the latitude of larger background electron density of the EIA as compared to its smaller values around the equatorial density trough region. The general pattern of the S_4 distribution is similar on the night of 30 October as well (lower panel of Figure 4). However, the S_4 values are generally weaker in the equatorial as well at the EIA crest latitudes on this night, which corroborates the results from the Digisonde and VHF radar at São Luis. Thus it appears evident that the unusually large post dusk F layer uplift of 30 October was accompanied by irregularity development of less than normal intensity.

[9] Figure 5 shows the vertical total electron content (VTEC) derived from 20 GPS stations (14, RBMC/Brazil and 6, IGS South American Network) for October 28 and 30 at 20–21 UT (17–18 LT) and 22–23 UT (19–20 LT). The quiet day post sunset development of the EIA in the Brazilian East sector can be verified from the 22–23 UT (19–23 LT) TEC map on 28 October in the lower left panel. (The post dusk EIA presents some degree of North–South asymmetry on this day). In comparison, we note that the EIA was already more intense at 20–21 UT (17–21 LT) just prior to the large uplift of the ionosphere on 30 October. Around one hour into the uplift, the TEC map for the 22–23 UT (19–20 LT) interval shows, a large depletion in the Brazilian East (Atlantic) sector with the EIA crest displaced to higher (southern) latitudes. Such plasma depletions have been observed over the Brazilian-Atlantic region during previous intense storms as well [*Batista et al.*, 1991; *Greenspan et al.*, 1991; *Abdu*, 1997; *Abdu et al.*, 1995; *Basu et al.*, 2001]. The very weak intensity of the L-band scintillation over the equatorial anomaly crest region (in Figure 4) is a result of the weak ESF development on this night, mentioned earlier, as well as the result of the large plasma depletion that dominated the low latitude ionosphere over Brazil (as seen in Figure 5). The TEC depletion, together

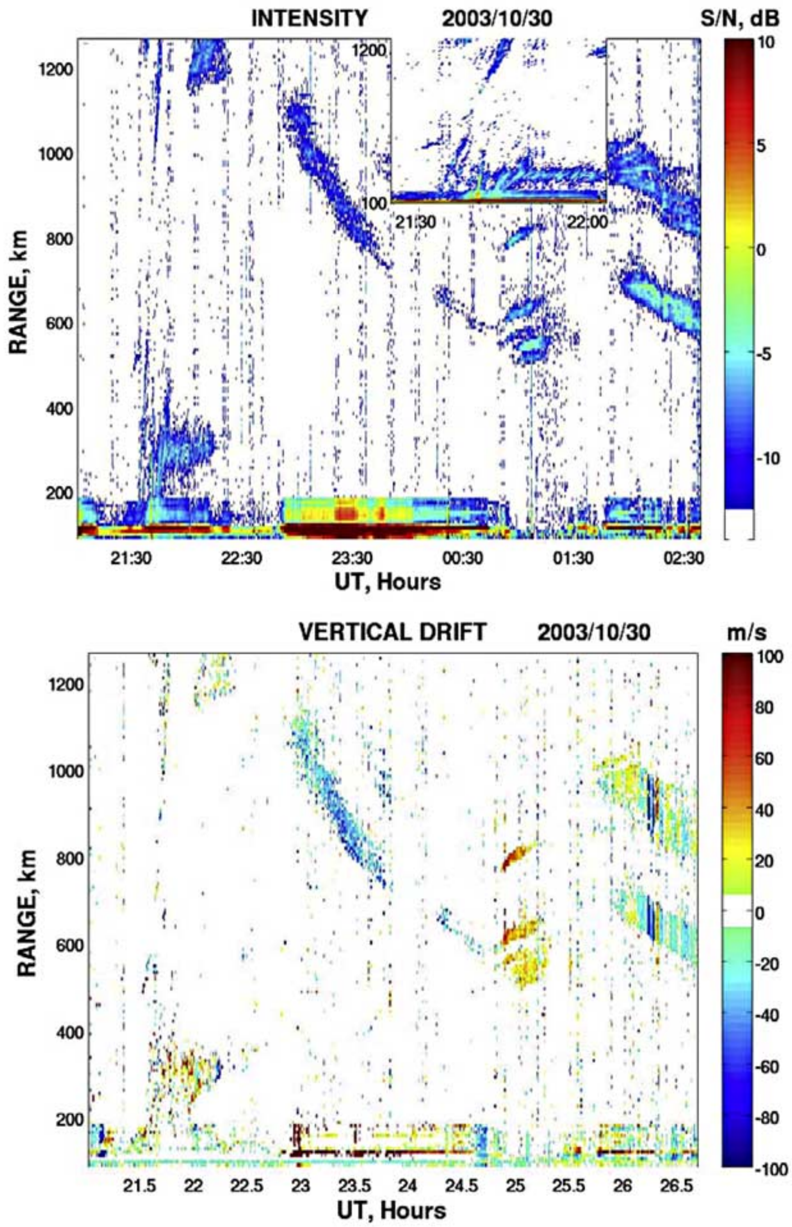

Figure 3. RTI (upper) and RTV (lower) maps from a 30 MHz coherent backscatter radar at São Luís on the night of 30 October. Note the rapid uplift of the 5-m irregularity echo patch near 21:30 UT (18:30 LT) (amplified in the inset). The vertical velocity of the uplift is calculated as ~1200 m/s. The radar echo is weak on this night.

with very low foF2 values (shown in the lower panel of Figure 6) suggests the action of a giant plasma fountain responsible for a poleward displacement of the EIA. The poleward displacement of the EIA in Figure 5 and in the data presented by *Lin et al.* [2005a, 2005b], however, appear to be significantly more limited than that observed on this day in the eastern Pacific longitude sector between 20:12 and 22:04 UT (12:30–13:30 LT) by *Mannucci et al.* [2005].

3. Discussion and Conclusions

[10] Different signatures of the equatorial ionospheric response to a PPEF of unusually large intensity are presented above. One of the striking aspects concerns the fact that the large zonal electric field near sunset that occurred nearly in phase with the prereversal zonal electric field did not cause any enhancement in the intensity of a developing ESF event, which looks to be quite unexpected and surprising. A combination of circumstances appears to be responsible for such a situation. The nonlinear vertical growth velocity of a bubble instability (under the R-T mechanism) is of the order of 100–200 ms^{-1} under quiet/non storm conditions [e.g., *Zalesak et al.*, 1982]. The layer uplift occurring immediately after the ESF instability initiation appears to be responsible for confining the instability development to the bottomside of the rapidly rising F layer. Additionally the rapidly evolving vertical density gradient

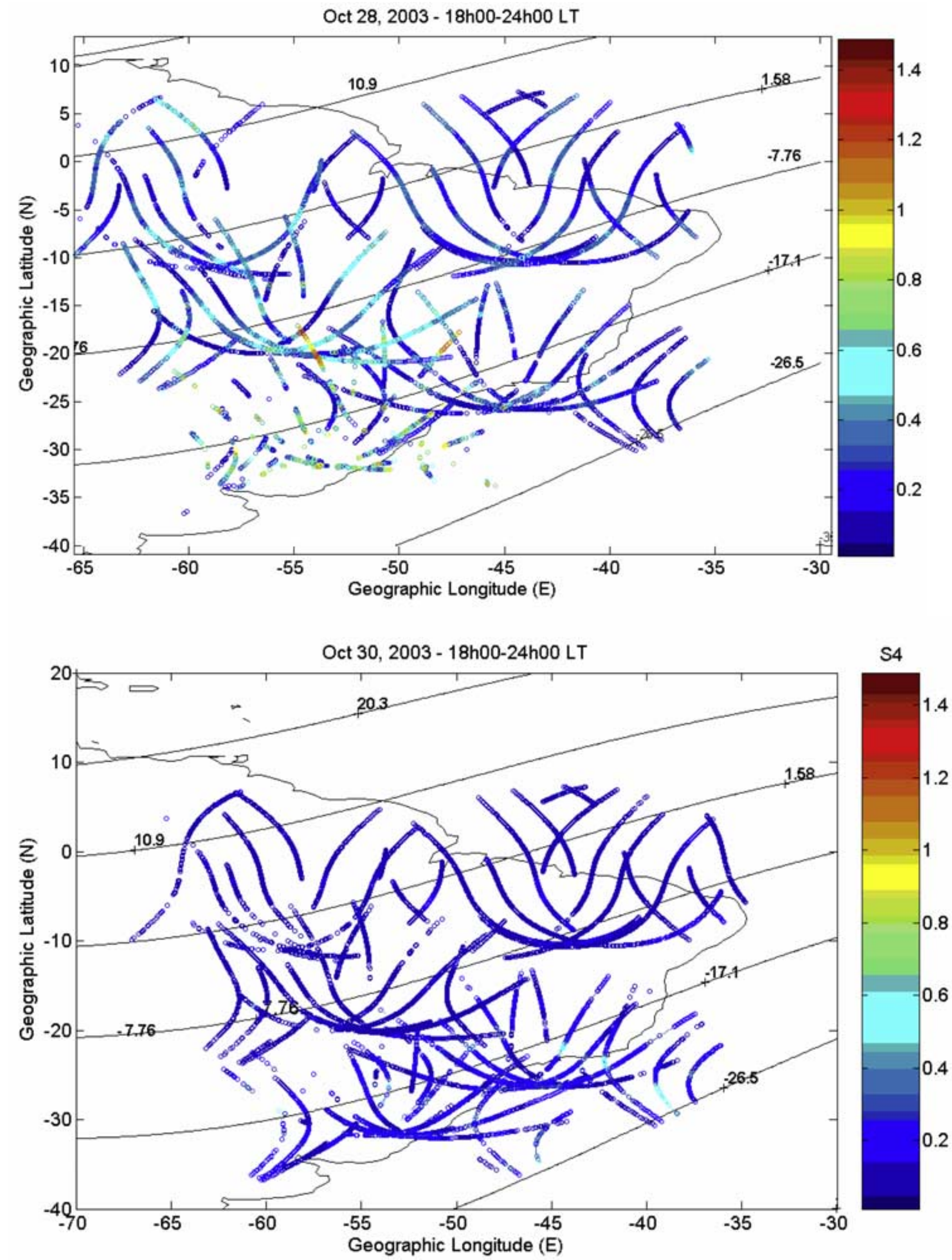

Figure 4. GPS Scintillation S4 index distribution in geographic latitude versus longitude on 28 October (reference day) and on 30 October. The S4 intensity is represented by the color code on the GPS orbital segments according to the color scale shown on the right.

in the depleted plasma background might be insufficient to be conducive for an enhanced instability growth. Another factor that can contribute to a suppressing effect on the bubble growth could be the presence of strong meridional/transequatorial wind that could enhance the integrated conductivity of an unstable flux tube [*Maruyama*, 1988; *Abdu et al.*, 2006]. We may examine this possibility with the help of the results in Figure 6 which shows the hmF2 and foF2 variations, respectively in the upper and lower panels, over São Luis (dip:$-2°$), Fortaleza (dip:$-9°$) and Cachoeira Paulista (dip:$-34°$). The hmF2 plot shows the fastest F layer uplift (highest vertical drift velocity) over São Luis with systematically lower vertical drifts over Fortaleza and Cachoeira Paulista. It is clear that the F-layer uplift near 21 UT indicates a systematic decrease of the vertical drift velocity with the increase of the station latitude, a feature that points to the role of an intense poleward wind to drive the layer downward against the force of electric field to induce large upward drift. By comparing the vertical drifts (measured as dhmF2/dt) over Fortaleza and Cachoeira Paulista that are $\sim$370 ms^{-1} and $\sim$100 ms^{-1} respectively, and assuming uniform winds in the longitude region of the two stations the poleward wind can be estimated to be of the order of 400 ms^{-1} near 21:30 UT/18:30 LT. Such strong poleward wind over low southern latitudes should be part of a trans-equatorial wind, directed from northern to southern

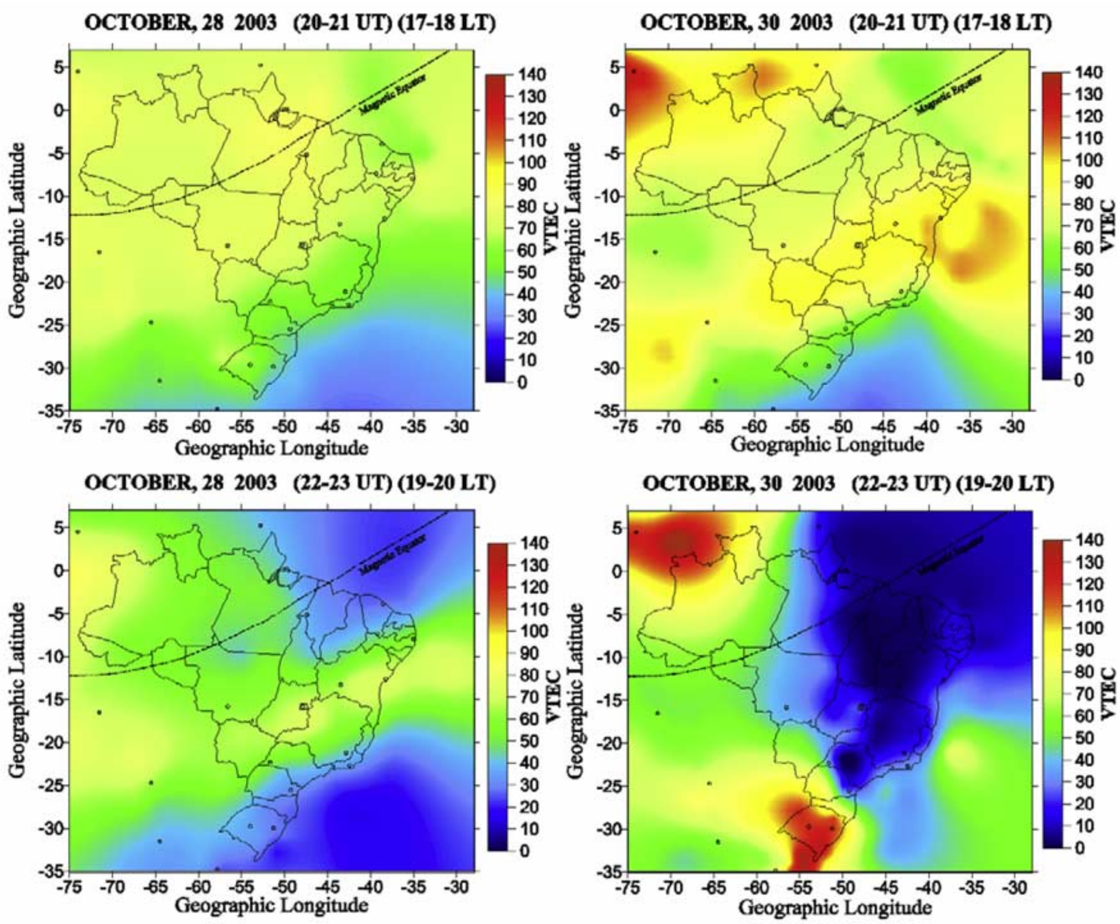

Figure 5. Vertical Total Electron Content (VTEC) distribution in latitude versus longitude over Brazil on 28 October (reference day) and 30 October for 20–21 UT/17-28 LT and 22–23 UT/19–20 LT intervals. Note the large TEC depletion in the eastern part of Brazil in the 22–23 UT interval of 30 October (the TEC enhancement in the South Atlantic may not be real due the GPS station network over Brazil covering only the land area).

hemisphere [see also, *Abdu et al.*, 2007]. A comparison with the vertical drift over São Luis would yield still larger poleward/transequatorial wind. The validity of such meridional winds would strongly dependent on the validity of the assumption of a uniform wind being present in the wide geographic region covered by these stations. However, since we have no appropriate data sets to verify the validity of such an assumption, no attempt was made to perform a detailed calculation of the precise magnitude of these large winds. Nevertheless the wind calculated as 400 m/s by comparing the hmF2 variation over Fortaleza and Cachoeira Paulista and possibility of still higher winds as suggested from comparison of the hmF2 variation over these stations with that over São Luis does seem to give an idea of the intensity of the poleward wind that must have been present over low latitudes during this major storm event. Considering the large *F* layer height and the vertical drift that characterized the event, we believe that a poleward wind even as intense as estimated here may not have been a key factor in suppressing the ESF development. This problem merits further investigation.

[11] The intense poleward wind on the other hand seems to have played a role in causing the asymmetry in the EIA latitudinal structure and in limiting/reducing the intensity of the crest and its latitudinal expansion. Numerical simulation of the anomaly development for intense storms by *Lin et al.* [2005a, 2005b] has shown that a storm-time equator-ward wind could cause intensification of the EIA by acting to slow down the fountain associated downward plasma diffusion. Conversely a poleward wind could displace the plasma further downward to regions of enhanced recombination thus reducing the EIA intensity. The strong asymmetry in the EIA in the Brazilian eastern sector during 22–23 UT of 30 October (Figure 5) could be the result of the strong transequatorial wind (poleward in the Southern Hemisphere) indicated by the hmF2 latitudinal variation near this time in Figure 6 just discussed above.

[12] It was pointed out that the scintillation intensity distribution has a latitudinal variation characterized by its S_4 values increasing toward the equatorial anomaly latitude of increasing back ground electron density. From a study of nonlinear three-dimensional evolution of an equatorial spread F bubble, using a time dependent equatorial fountain model, *Keskinen et al.* [2003] showed that the effect of finite parallel conductivity is to slow down the linear and nonlinear evolution of the plasma bubble. Further, at the

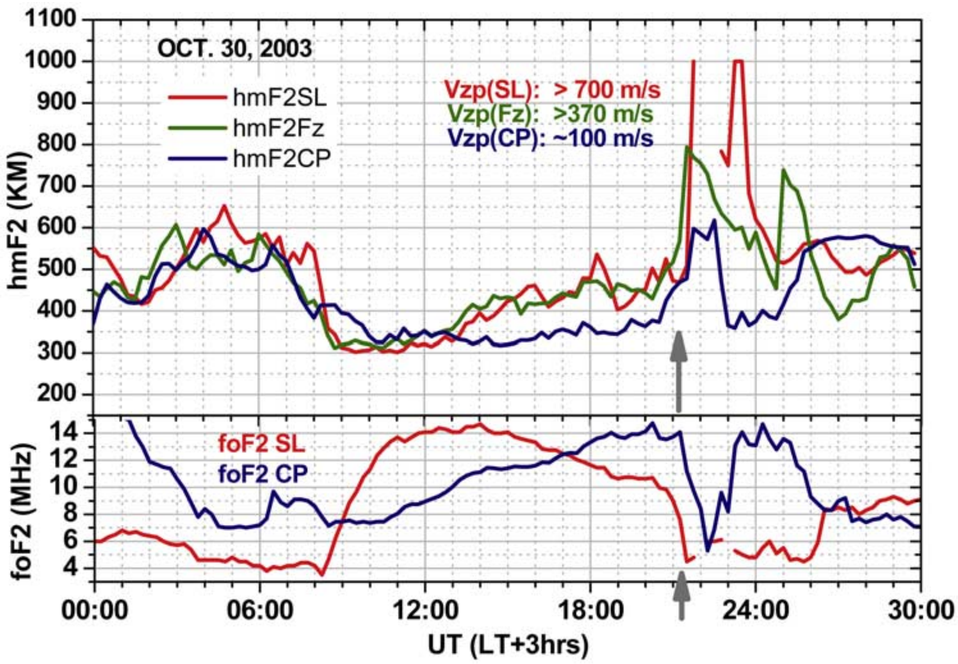

Figure 6. (upper) the hmF2 and (lower) foF2 over SL (São Luís), Fz (Fortaleza), and CP (Cachoeira Paulista) on 30–31 October. Note the large hmF2 increase near 21:30 UT and the associated large decrease of foF2 at Sao Luis and C. Paulista indicated by arrows. Over Fortaleza, the spread F in the ionogram did not permit reliable scaling of the foF2 which therefore is not shown.

anomaly crest latitude of enhanced electron density their model results showed that, although the R-T instability growth may be slightly weakened compared to that over the dip equator, ESF structures can be generated with extremely steep density gradients. Such enhanced gradients could be a cause of the enhanced scintillation over the anomaly latitude for a quiet day (28 October 2003) verified in the present results. It is not clear if and how the 3D development of the R-T mechanism could have operated under these extreme conditions of the disturbance electric field of the 30 October. However, we believe the TEC depletion of the post dusk hours (19–20 LT) of 30 October (evident in Figure 5) must have contributed to the generally reduced S_4 index values arising from an already weaker ESF irregularity generation that marked this evening.

[13] A very significant difference in the intensity of the prompt penetration electric field can be noted between São Luís and Jicamarca in Figure 2. As compared to the super fast vertical drift over São Luís ($\sim$1200 ms^{-1}) the vertical drift over Jicamarca was very small indeed, being of the order of 40 ms^{-1} (or even less, as discussed below) as determined from the time rate of the *F* layer height rise registered at this time. A vertical drift of 40 m/s over Jicamarca corresponds to an eastward electric field of 1 mV/m [*Fejer et al.*, 1991]. The PPEF caused also EEJ increase over Jicamarca (indicated by the Arrow 4 at $\sim$21:10 UT of 30 October in Figure 1) which was perceivably of small intensity, the ΔH being of the order of 25 nT which would correspond to an incremental PPEF of the order of 0.15 mV/m only. This EEJ response intensity would suggest that the F layer vertical drift estimated as 40 m/s from dhmF2/dt (from ionograms) over Jicmarca is an upper limit for the disturbance drift. It is to be noted that the PRE (indicated as such in Figure 2) occurs at $\sim$18:30 LT over both São Luis and Jicamarca. The PPEF event of $\sim$21:30 UT occurred when it was $\sim$16:30 LT, and therefore around 2 h behind the LT of the PRE, over Jicamarca. In contrast, we note the near simultaneous incidence of the two electric fields over São Luís (which is two hours in LT ahead of Jicamarca). According to the result of simulation of equatorial disturbance electric field based on coupled Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation model by *Richmond et al.* [2003], the penetration electric field has maximum intensity near 19 LT (which is close to the LT of the PRE), the intensity being weaker by a factor of $\sim$3 at a local time $\sim$2.5 h earlier. Thus we expect the ratio of the disturbance zonal electric field intensity over São Luis to that over Jicamarca for this case to be $\sim$3. However, considering the observed drift velocity of 1200 m/s over São Luis and the observed upper limit of 40 m/s for the vertical drift over Jicamarca we obtain a factor 30 as a lower limit for the ratio of the PPEF over São Luis to that over Jicamarca. Thus it appears we have here a case of large enhancement of the disturbance electric field in the Brazilian Atlantic (South Atlantic) longitude sector. We may attribute this to the large scale conductivity spatial gradient produced by energetic particle precipitation in the South Atlantic Magnetic Anomaly (SAMA). From measurements of *F* layer vertical and zonal drifts over Fortaleza by a digital ionosonde *Abdu et al.* [1998] showed that large scale enhanced conductivity structures arising from energetic particle precipitation in the SAMA during magnetic storm conditions could influence the electrodynamics of the nighttime equatorial ionosphere under spread F conditions. It was shown that large meridional electric field could be generated by Hall conduction induced by an imposed zonal PPEF in

the presence of an enhanced conductivity structure presumably produced by energetic particle ionization in the SAMA region [see also *Abdu et al.*, 1981, 2003, 2005]. *Greenspan et al.* [1991] observed large scale plasma depletions and vertical plasma drift in the post dusk DMSP track over Brazilian-South Atlantic region during the major storm of 12 March 1989. For the major storm event of 16 July 2000, *Basu et al.* [2001] showed that the large scale equatorial plasma depletions in the 840 km post dusk sector DMSP track was more pronounced in the Brazilian eastern longitude than in tracks further away (eastward) from it which they attributed to possible influence of energetic particle precipitation in the SAMA region. A recent study by *Basu et al.* [2007] using the DMSP database for the present super storm (of 30 October 2003) also showed large scale density depletions in the DMSP orbits over Brazilian eastern sector which was attributed to possible post dusk enhancement of the prompt penetration electric field in the South Atlantic Anomaly longitude. During the July 2000 major storm event *Lin and Yeh* [2005] measured large scale plasma depletions in the 600 km orbit of the ROCSAT-1 which they modeled to show that a disturbance electric field imposed on electron density/conductivity enhanced regions such as that produced by particle precipitation in the SAMA could be modified in such a way that the electric fields could be intensified at the conductivity enhancement-depletion boundary, decreasing with increasing distance away from it. Inside the conductivity enhancement itself the electric fields can be represented by the following relationships:

$$\frac{E_Y}{E_o} = \frac{\Sigma_H}{\Sigma_P}; \tag{1}$$

$$\frac{E_X}{E_o} = \frac{\Sigma_P^o}{\Sigma_P^i}; \tag{2}$$

$$\frac{E_Y}{E_X} = \frac{\Sigma_H^i}{\Sigma_P^i} \tag{3}$$

E_0 is the back-ground electric field which, in this case, is the disturbance zonal (prompt penetrating) electric field, E_Y is the Hall conduction electric field induced by E_0, Σ_H and Σ_P are the field line integrated conductivities. Equation (1) was based on the assumption of a slab of conductance enhancement due to energetic particle precipitation in the E region over the SAMA region and for negligible contribution from neutral wind and vertical current to E_Y [see *Abdu et al.*, 1998]. Assuming a circular geometry for the enhanced conductance region wherein the field line integrated conductivities are much larger than their outside values ($\Sigma_H^i \gg \Sigma_H^0$, $\Sigma_P^i \gg \Sigma_P^0 > \Sigma_H^0$) *Lin and Yeh* [2005] obtained the equations (2) and (3). Here the superscript "i" and "o" indicate "inside" and "outside" respectively of the conductance enhancement region. E_X and E_Y are the zonal and vertical/meridional electric fields inside the enhanced conductance. E_X and E_o are responsible for the vertical plasma drift and E_Y is responsible for the westward plasma drift at the F region heights and higher up. We note from equations (1) and (3) that the Hall electric field (E_Y) can be larger than its causative zonal electric field (E_X or E_o) by a factor by which the integrated Hall conductivity is higher than the Pedersen conductivity. Further, we note from equation (2) that the zonal electric field inside the enhanced conductance region is less intense than its outside value, and that inside a depleted conductance region the zonal electric field is higher than its outside value. On the basis of these relationships we may visualize the following scenario in which the large scale zonal electric field enhancement responsible for the abnormal vertical drift could be taking place. The disturbance zonal electric field causing the vertical drift has a longitudinal modulation on it that is imposed by the enhanced conductivity structure at E region heights (produced by particle precipitation) as mentioned before. Large vertical plasma drift is responsible for the large scale TEC depletions in the EIA region and the plasma density depletions observed in the DMSP and ROCSAT orbits. The larger zonal electric field just at the edge and outside of the conductance enhancement region would cause larger F region vertical drift and hence plasma depleted flux tubes outside the conductance enhancement region. The resulting decrease in the integrated conductivity of the plasma depleted flux tubes would enhance the intensity of the driving zonal electric field inside the plasma depleted flux tubes (according to equation (2)), that in turn would contribute to enhanced vertical drift intensifying further the degree of the plasma depletion, a situation that could lead to an unstable growth of the zonal electric field [see also *Lin and Yeh*, 2005]. The meridional/vertical electric field E_Y that drives the plasma westward (E_Y being induced by an eastward E_o or E_X) is also modulated longitudinally and hence could cause westward drifting plasma density modulations across the flux tubes thereby contributing to control the integrated conductivity and hence the growth of the zonal electric field inside plasma depleted flux tubes. A detailed time dependent modeling that takes into account the relevant controlling factors, such as the ionization balance and related electrodynamics processes could clarify the nature of zonal electric field enhancement. The present considerations, though qualitative in nature, do seem to suggest that large zonal electric field enhancement corresponding to the abnormal vertical drift could occur close to conductance enhancement regions presumably produced by energetic particle induced ionization in the SAMA region. The relatively weaker geomagnetic field intensity of the SAMA could also contribute to larger vertical drifts.

[14] The main conclusions from the present study may be stated as follows: (1) While prompt penetrating eastward electric field occurring in the post dusk sector could, in general, enhance the ESF/plasma bubble development processes, in the case of very intense eastward electric fields/super fast vertical drift such enhancement may not occur; (2) Equatorial TEC depletion and associated EIA poleward expansion due to super fountain effect present latitudinal asymmetry and reduced crest intensity when accompanied by intense trans-equatorial winds; (3) The intensity of storm-time prompt penetrating electric field occurring during post dusk hours over Brazil- Atlantic sector appears significantly enhanced which may be recognized as a feature peculiar to the South Atlantic Anomaly region

where enhanced conductivity spatial structures can be produced by energetic particle precipitation during magnetic storms. (4) Prompt penetrating electric field of westward polarity during night hours can produce westward EEJ of large intensity.

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