Strong longitudinal difference in ionospheric responses over Fortaleza (Brazil) and Jicamarca (Peru) during the January 2005 magnetic storm, dominated by northward IMF

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[1] In this study we investigate the response of the equatorial F layer to disturbance zonal electric field associated with IMF (interplanetary magnetic field) variations dominated by a strong northward Bz episode during the magnetic storm that occurred on 21 January, 2005. We compared the results obtained from Digisondes operated at Fortaleza, Brazil (Geogr. 3.9°S, 38.45°W; dip angle: −11.7°) and Jicamarca, Peru (Geogr. 12.0°S, 76.8°W; dip angle: 0.64°). A large auroral activity (AE) intensification that occurred at ~1715 UT produced a large F-layer peak height increase (from 300 km to 600 km) over Jicamarca with no noticeable simultaneous effect over Fortaleza. Then the Bz turning northward at ~1940 UT with a rapid change in AE that was accompanied by a large decrease of F layer height and total suppression of the PRE over Fortaleza with no simultaneous effect over Jicamarca. Strong increase in the AE index (from ~400 to 1000 nT) with superimposed oscillations, under Bz North, that soon followed was associated with increases in both the F layer height and the vertical drift velocity over Fortaleza (at 2130 UT), with no corresponding signatures over Jicamarca. These remarkable contrasting responses to prompt penetration electric field (PPEF) as well as to disturbance wind dynamo electric field (DDEF) and other effects observed at the two locations separated only by 2 h in LT in the South American sector are presented and discussed in this paper. Effects on *spread-F* development and foF2 behavior during this storm event are also addressed in this work.

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1. Introduction

[2] During magnetic storms, the ionospheric F-layer height and vertical plasma drifts at equatorial and low latitudes often undergo variations due to the so-called prompt penetration electric fields (PPEF) and disturbance wind dynamo electric fields (DDEF) [*Fejer et al.*, 1979, 2008; *Gonzales et al.*, 1979; *Blanc and Richmond*, 1980; *Batista et al.*, 1991; *Abdu*, 1997; *Abdu et al.*, 2008, 2009; *Sastri et al.*, 1993; *Sastri*, 1988; *Sobral et al.*, 1997, 2001; *Fejer and Scherliess*, 1995; *Kelley et al.*, 2003]. When the IMF Bz suddenly turns to south, convection electric fields become intensified in the magnetosphere and penetrate to low-latitude ionosphere until the plasmasphere is electrically shielded. This penetrating electric field is known as under-shielding electric field, whose polarity is that of the dawn-dusk convection electric field (eastward during the day extending to evening till ~21 LT and westward in night sector). On the other hand, when the IMF Bz turns to north, causing a decline of convection electric fields, a strong over-shielding electric field becomes effective in the plasmasphere that has westward polarity in the day side and eastward in the night side [*Kelley et al.*, 1979; *Abdu et al.*, 2009; *Kikuchi et al.*, 2008]. Another effect observed later in a magnetic storms is the formation of DDEF that can cause significant modifications in the plasma drifts of the equatorial/low-latitude ionosphere. This electric field effects are of long duration and preceded by PPEF effects [*Blanc and Richmond*, 1980; *Abdu*, 1997; *Abdu et al.*, 2006; *Sobral et al.*, 1997; *Sastri*, 1988; *Scherliess and Fejer*, 1997; *Richmond and Lu*, 2000]. The DDEF is westward during the day and till after sunset and turns eastward around 2230 LT, remaining so for the rest of the night [*Huang et al.*, 2005; *Huang and Chen*, 2008; see also *Sobral et al.*, 2006].

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Generally, during daytime hours the DDEF has weak intensity and therefore produces only minor disturbance drifts in the daytime ionosphere [*Fejer et al.*, 2008].

[3] The effects of the PPEF and DDEF are most common to be observed in zonal electric field than in vertical electric field and consequently the observed variations are mainly in vertical plasma drifts, layer height, plasma density etc. During post sunset and pre-sunrise hours, when there is large local time gradient in the E layer conductivity, these disturbance electric fields can cause significant modifications in the ionospheric electrodynamics. Both the PPEF and the DDEF cause large amplitudes of upward drifts and downward drifts near dusk and post-midnight hours, respectively, that can be observed in all the seasons [see also *Richmond et al.*, 2003; *Huang and Chen*, 2008; *Abdu et al.*, 2008; *Sobral et al.*, 2006]. The PPEF can produce also large increase in the daytime upward drifts [see, e.g., *Tsurutani et al.*, 2004, 2008; *Huang et al.*, 2007; *Abdu et al.*, 2007].

[4] In this work, the responses of the ionosphere over Fortaleza and Jicamarca to a geomagnetic storm that occurred in 21 January, 2005, are presented. This event is considered anomalous because the storm main phase was accompanied by a strong northward IMF Bz of long duration. Different aspects of this storm have been studied by several authors [e.g., *Foullon et al.*, 2007; *Orus et al.*, 2007; *Sreeja et al.*, 2009; *Kane*, 2009; *Du et al.*, 2008; *Matthiä et al.*, 2009; *McKenna-Lawlor et al.*, 2010; *Sahai et al.*, 2011]. Our results show evidences of strikingly contrasting response to prompt penetration electric fields during daytime and evening hours over Jicamarca and Fortaleza, two stations separated by only 30° in longitude in the South American sector. The important points that will be discussed in this paper further include: the increase of the F-layer height over Fortaleza caused by an eastward electric field starting at ~2130 UT, when the IMF Bz was northward; oscillations in the F-layer height observed before the beginning of the magnetic storm that was apparently associated with a previous disturbance, and which indicated the presence of gravity wave propagation; and strong sporadic E layer observed over Jicamarca (from 1715 UT to 2015 UT), which indicated intensification of the equatorial electrojet over this region.

2. Experimental Data

[5] The ionospheric parameters used in this study are the true heights (hF) at successive plasma frequencies of the F-layer, the height of the F- layer peak density (hmF2) and the F2 layer critical frequency (foF2) as observed by the Digisondes operated at Fortaleza, Brazil (Geogr. 3.9°S, 38.45°W; dip angle: −11.7°) and Jicamarca, Peru (Geogr. 12.0°S, 76.8°W; dip angle: 0.64°). The Fortaleza and Jicamarca Digisonde data were acquired at a cadence of 10 and 15 min, respectively. The local times at the two sites are given by LT = UT − 3, and LT = UT − 5 h, respectively. The vertical drift velocity deduced from Digisonde data was calculated from true heights at specific plasma frequencies of 3, 4, 5 and 6 MHz by the same methodology as used by *Abdu et al.* [2010]. This methodology has been shown to be valid near sunset and night hours when the F-layer height is near or above 300 km [*Bittencourt and Abdu*, 1981]. In respect to Jicamarca data we also have used the vertical drift inferred from the Jicamarca-Piura magnetometer data following the methodology presented by *Anderson et al.* [2002]. This drift can be considered to be a reliable indicator of the true vertical plasma drifts during the daytime.

3. Results

[6] Figure 1 shows the variations at 1-min resolution, in the SYM-H index (Figure 1a) and in the auroral electrojet activity index AE (Figure 1d); the interplanetary magnetic field components By and Bz in Figures 1b and 1c, respectively (from the ACE satellite database, 4-min resolution) plotted with a time delay of 24 min during the period of 20–22 January 2005. On Jan. 21, at about 1645 UT, the By turned westward and ~30 min later the AE index showed a large increase attaining an intensity of ~3070 nT at 1745 UT. The Bz transitions started as a northward excursion at ~1730 UT followed by alternating southward and northward transitions till ~1940 UT. We may note that at about 1940 UT the Bz turned northward and remained as such for at least 6 h. The initial part of the magnetic storm main phase occurred during ~1940–21 UT when the IMF Bz had turned northward (indicated as shaded area in Figures 1a and 1c). The AE index showed a recovery from 1830 UT up to ~2130 UT, and then a conspicuous increase in its value (from ~400 to 1000 nT) was registered till ~23 UT.

[7] The responses of the equatorial ionosphere over Fortaleza to this geomagnetic storm can be examined in Figures 2 and 3. Figure 2 shows: the By and Bz components, the AE index, the F-layer heights, the vertical drift Vz and the foF2 parameters during 20–22 January. In Figure 2d are shown the variations in true height of the F-layer at successive plasma frequencies (3–10 MHz) (gray lines), the F2 layer peak height hmF2 (red line) and its variation on a reference quiet day, Jan. 25 (green line). Figure 3 shows a blown up picture of the behavior of the same parameters of the Figure 2 from 12 UT/09 LT of January 21 to 12 UT/09 LT of January 22, which will be discussed separately. Duration of the spread-F is indicated by red bars along the time axis.

[8] In Figure 1, we may notice a weak disturbance in SYM-H (of ~40 nT) on 20 January, a day before the storm. Also, a moderate increase in AE occurred starting near midday. Apparently, as a result, in Figure 2d we may notice a small increase in the hmF2 (red line) from its reference quite day pattern. Further a modulation, in the form of a wavelike structure, can be seen in the F layer peak height and in the iso-density contours, during the night hours lasting till morning of 20 January as indicated by the shaded area. These oscillations present characteristics of downward phase propagation thereby suggesting the presence of a large scale TID/gravity waves probably produced during the AE intensification that occurred during the previous day (not shown here).

[9] On 22 January an increase in the F-layer height starting ~0350 UT/0050 LT can be seen in Figure 2d (indicated by a blue arrow). This is most probably caused by a disturbance wind dynamo electric field that has eastward polarity during the pre-sunrise hours [*Fejer et al.*, 2008; *Huang et al.*, 2005; *Huang and Chen*, 2008]. The maximum vertical drift associated with the layer rise was ~40 m/s (Figure 2e) which resulted in spread-F development that

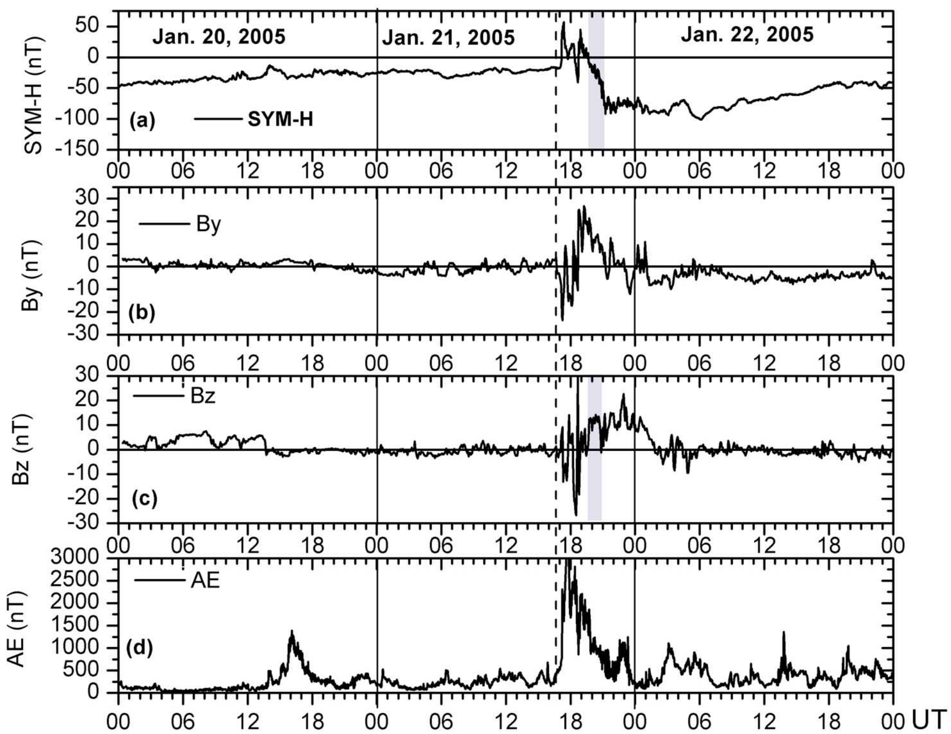

Figure 1. (a) 1 min. values of SYM-H index, (b, c) 4 min. values of the interplanetary magnetic field components By and Bz and (d) AE index during 20–22 January 2005. Between ∼1940–21 UT, the main phase of the storm is related to northward IMF Bz as indicated by shaded area.

lasted till sunrise. This event may be considered to be an interesting evidence on the post midnight spread F development due to a disturbance dynamo electric field. Another interesting aspect to be noted (in Figure 2f) is that the foF2 parameter presented an increase in comparison with the quiet days beginning at 05 UT/02 LT (as indicated by a blue arrow) that lasted till the rest of the day. This increase in foF2 (over the equatorial site) could be produced by an equatorward converging wind that may characterize the storm recovery phase, which was in progress as may be noted in Figure 1; the storm recovery lasted throughout the day of 22 January.

[10] We further note that a large-scale oscillation in the F-layer height at higher plasma frequencies occurred from 09 LT to 14 LT on January 22 (see shaded area in Figure 2d). This feature is similar to that observed during the night of 20 January (mentioned earlier) when recovery from a previous magnetic disturbance was taking place. Thus it appears that the presence of propagating large scale TIDs/gravity waves is a frequent feature over Brazil during a storm recovery phase, at least during this observational period, which is an interesting topic for further study.

[11] Figure 3 shows as mentioned previously that Bz turned northward around 1940 UT/1640 LT on January 21 and the AE index showed a rapid recovery, decreasing from 1700 to 870 nT. At this time, just before sunset, a decrease of the F-layer peak height over Fortaleza (from 400 km to 300 km) with corresponding decrease in almost all the iso-density contours was observed. This occurred just before the start of the quiet time prereversal enhancement in the vertical drift, PRE, (as can be verified from a comparison with the quite day Vz pattern, plotted in green). This height decrease appears to have been caused by an electric field of westward polarity, which is an over-shielding electric field, associated with the northward IMF Bz turning at ∼1940 UT/1640 LT. As regards the prereversal enhancement in the vertical drift/zonal electric field, we note that, in comparison with the quite day pattern, its development was totally suppressed by the penetration electric field from the over-shielding process. The possibility of a DDEF (due to strong auroral activity observed before the PRE occurrence time) which is also westward at this local time may be raised, but the clear association of the height decrease with the Bz turning north, with the simultaneous rapid AE decrease appears to overwhelmingly favor the over-shielding electric field as mainly responsible for the total suppression of the PRE on this evening. In this respect this PRE suppression event is very similar to the cases previously reported by *Abdu et al.* [2009] in which also total PRE suppression occurred.

[12] It may be noted that the variations in the F-layer height and foF2 parameters are anti correlated during this episode as seen in Figures 3d and 3f. The rapid height decrease at 1940 UT/1640 LT (indicated by dotted vertical line 2) by an over-shielding electric field resulted in the compression of the F2 layer as indicated by the closing-in of the plasma frequency iso density lines that started at this time (see Figure 3d). As a result the foF2 became enhanced. With the lifting up of the layer that followed, the foF2 decreased, as to be expected due to the plasma fountain diffusion, thus resulting in the observed anti correlation between the heights and the foF2.

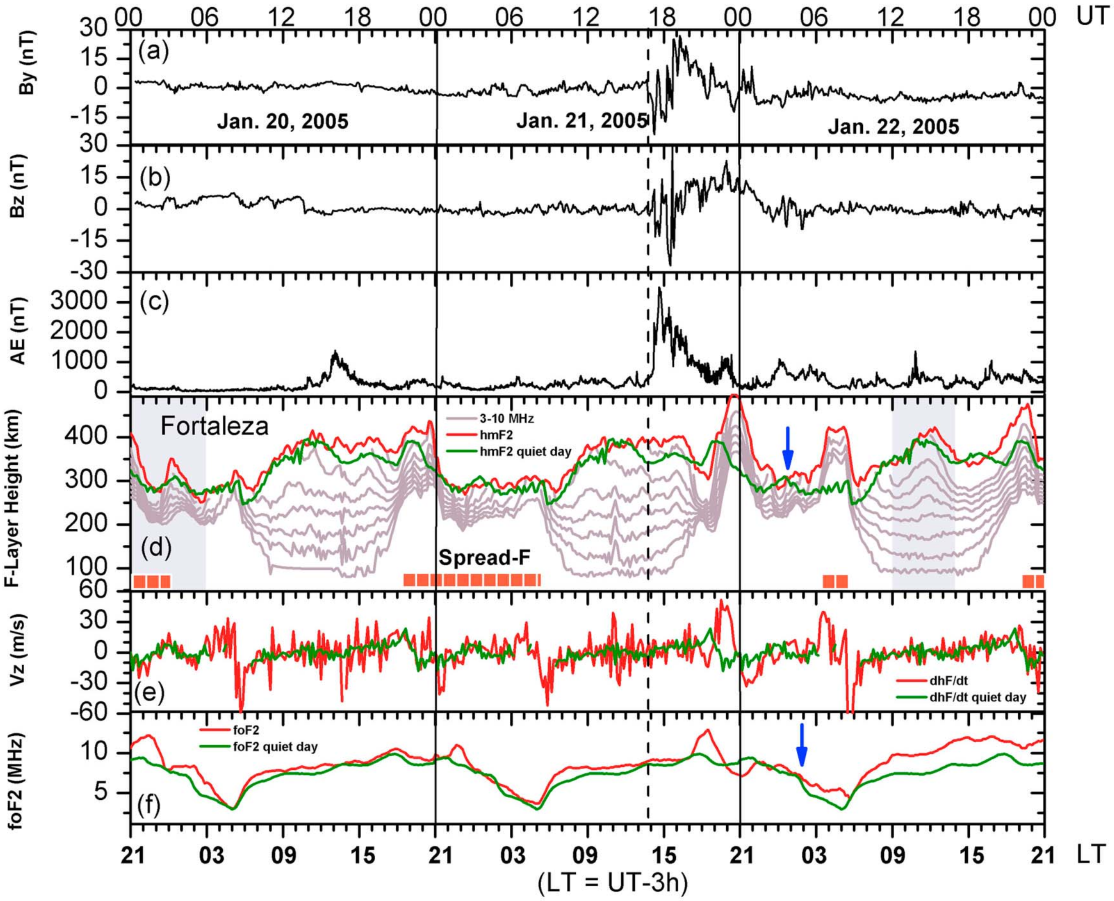

Figure 2. (a, b) Plots during 20–22 January of the interplanetary magnetic field components By and Bz; (c) the AE index; (d) the ionospheric F region heights at specific plasma frequencies at interval of 1 MHz starting at 3 MHz till foF2 (gray curves), and the hmF2 (red curve) as obtained from the SAO explorer of the Digisonde at Fortaleza, with duration of spread-F indicated by horizontal red bars; (e) the ionospheric vertical drift Vz that was calculated using the F-layer bottomside true heights (hF) at specific plasma frequencies as d(hF)/dt and (f) the foF2 parameter. Average quiet days are represented by a green curve, the dashed vertical line indicates the beginning of the storm, and the blue arrow and shaded area make an important variation observed in foF2 parameter and in the F-layer height, respectively (see text).

[13] A strong increase in the F layer heights in Fortaleza starting at ~2130 UT/1830 LT (the hmF2 increasing from 300 to 500 km) can be seen in Figure 3d, as indicated by dotted vertical line 3. This increase corresponds to a large vertical drift that attained a peak values of ~50 m/s (Figure 3e) which corresponds to an eastward electric field of ~1.5 mV/m [*Fejer and Scherliess*, 1995]. We may note that the By component showed a rapid change (at 2130 UT) that was accompanied by an increase of the AE index (from ~400 to 1000 nT). It is possible to consider that this uplift of the F-layer was caused by a penetration electric field due to magnetic reconnection. Although the Bz component was northward at this time it appears that the magnetic reconnection did occur possibly by the mechanism discussed by *Gonzalez and Mozer* [1974]. It may be noted that the large vertical drift due to the eastward PPEF occurred at a time when the quiet time PRE must have been in its downward drift phase. Thus the actual vertical drift due to the PPEF alone may, in fact be, larger than what is obtained from the time rate of change of the F layer heights that is plotted in the figure. In other words, the eastward PPEF was >1.5 mV/m.

[14] Although the F-layer peak height increased from 300 km to 500 km, the development of spread-F was not observed. In this case, it appears the electron density gradient did not increase sufficient enough with the layer up lift (as indicated by the nearly same rate of increase at all the frequencies) to cause the spread-F. If there are other factors, besides the bottom side density gradient that might have contributed to the suppression of spread F development, they need to be investigated from further analysis of the data, which is beyond the scope of the present paper.

[15] The results for Jicamarca are presented in Figure 4. In response to the sudden onset of the storm initiated by the rapid AE increase at 1715 UT (1215 LT in Peru), the F layer heights exhibited a large increase with the peak height hmF2 increasing from 300 km to 600 km as shown in Figure 4d. The vertical drift inferred by the Jicamarca-Piura magnetometer data (blue line) attained a value of ~45 m/s at

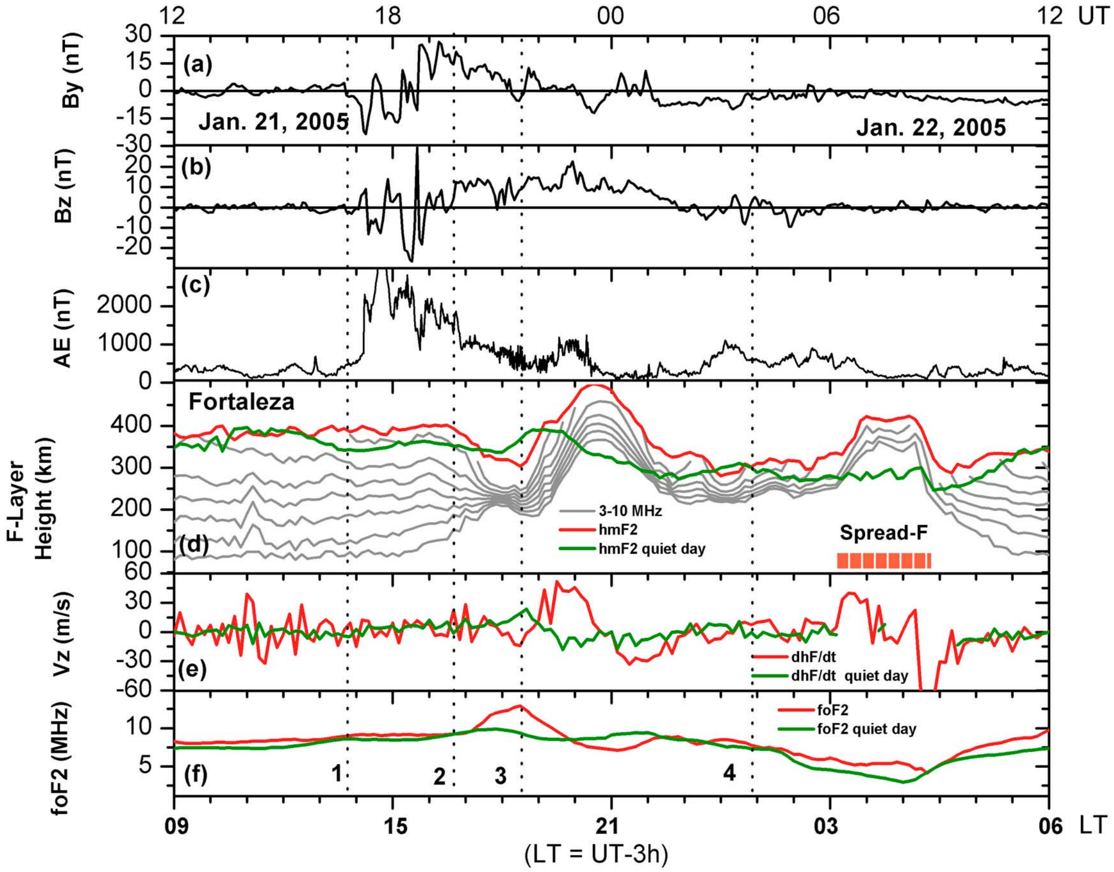

Figure 3. The same plots as those in Figure 2 but from 12 UT of 21 January 2005 to 12 UT of January 22. The dotted vertical lines make some important points that are discussed in the text.

~1245 LT. This vertical drift and the consequent F layer rise near midday over Peru should be caused by the action of an eastward directed PPEF from under-shielding effect that characterized the storm development phase. The action of this penetration electric field is evident in the intensification of the equatorial electrojet (EEJ) in Figure 4f (dotted vertical line 1), which corresponds to an intensification in eastward electric field. At about 30 min after this increase, the EEJ and hence the vertical drift values show a decrease which are coincident with a recovery in the AE index (from ~3000 nT to 1700 nT) and Bz turning to the north. This decrease in eastward electrojet and in vertical drift associated with Bz north and AE recovery can be an evidence of over-shielding electric field acting over Jicamarca region [see also *Shume et al.*, 2011]. At about ~1815 UT, we may note a strong increase in vertical drift (blue line) that attained a peak of 105 m/s (Figure 4e) which is equivalent to an eastward directed disturbance prompt penetration electric field of ~2,62 mV/m. This intensification in the velocity and the EEJ was coincident with Bz turning to southward as showed in Figure 4b. It is interesting to note that the corresponding F layer response as registered by the Digisonde over Fortaleza (Figure 3d), which is two hours ahead of Jicamarca, (that is, near 15 LT), was nearly inexpressive. This difference in response between the Jicamarca and Fortaleza appears to be due to the local time dependence of the PPEF which is largely in agreement with LT pattern of this electric field in the equatorial region as obtained from simulation studies by *Richmond et al.* [2003] and *Maruyama et al.* [2011] and from ROCSAT-1 observations by *Fejer et al.* [2008]. The local time variation of the ionospheric conductivity and its longitudinal gradient at these two nearby longitudes might play a role in such behavior of the PPEF.

[16] In Figure 4g the variation in foF2 parameter showed an anti correlation with the F-layer height variation due to the PPEF effect (1215 LT/1715 UT to 1450 LT/1950 UT), which is somewhat similar to the anti correlation between the two parameters observed over Fortaleza in response to the over-shielding electric field episode. The large F layer rise over Jicamarca was caused by the strong eastward PPEF that produced a super fountain by which the plasma was removed from the equator, resulting in the large foF2 decrease over Jicamarca. *Veenadhari et al.* [2010] also showed a case in which the penetrating electric fields from high latitudes caused a strong EEJ at the equator region. This disturbed electric field was responsible by a decrease in foF2 parameter over an equatorial station due a strong EIA (Equatorial Ionization Anomaly) enhancement associated with a super fountain effect.

[17] Earlier to the start of this storm there was an increase in foF2 during 03–13 LT/08–18 UT in comparison with the quiet days. This might be the result of a DDEF from the previous disturbances (mentioned earlier). Later on, well into the recovery phase of the storm on 22 January, the foF2

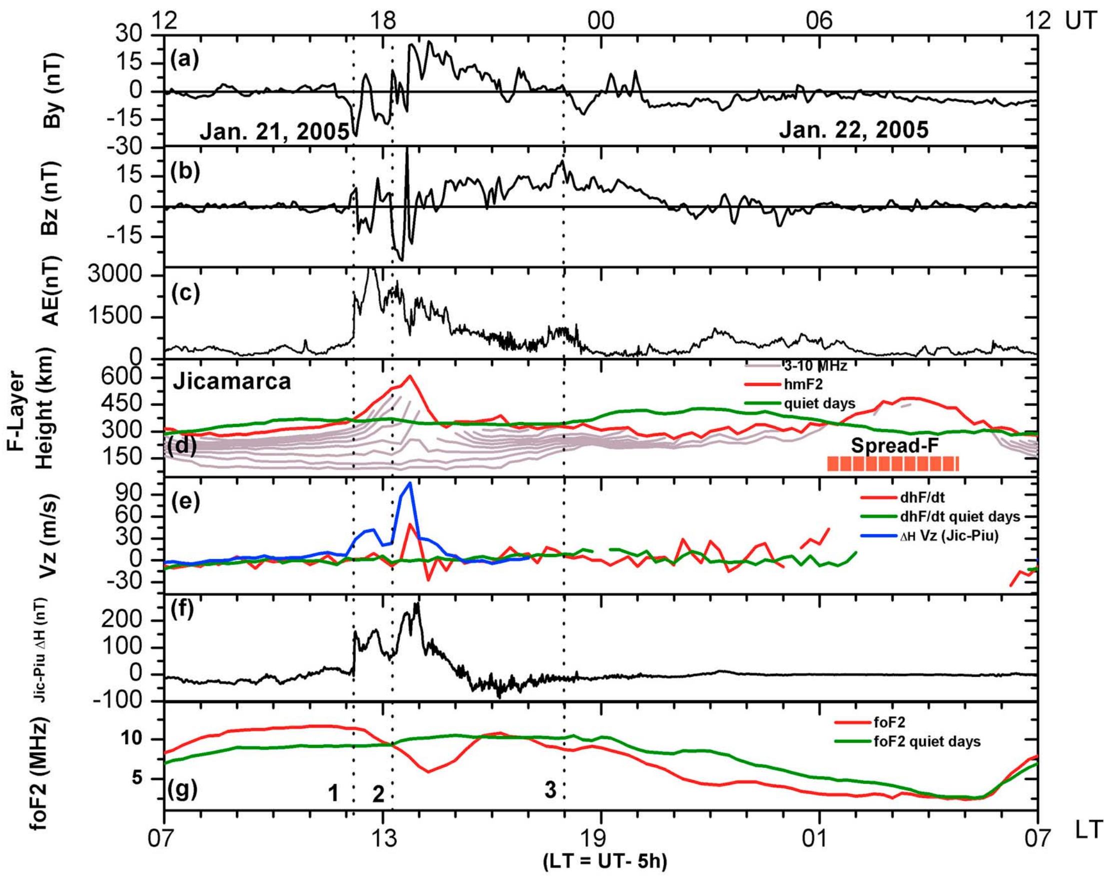

Figure 4. (a, b) Variations of the interplanetary magnetic field components By and Bz and (c) AE index from 12 UT of 21 January to 12 UT of 22 January. (d) F region heights at specific plasma frequencies at interval of 1 MHz starting at 3 MHz (gray curves) and the hmF2 variation (red curve) as obtained from the Sao explorer of the Digisonde at Jicamarca with the durations of spread-F indicated by horizontal orange bars. (e) The ionospheric vertical drift Vz derived from Digissonde (dhF/dt) as indicated by red and green lines and also the vertical drift inferred by Jicamarca-Piura magnetometer data (blue line). (f) The EEJ effect on the ground deduced from variations of the H component of the Earth's magnetic field measured by magnetometers in Jicamarca and Piura is shown and (g) the foF2 parameter. Average quiet days are represented by a green curve, the dotted vertical lines indicates make some important variation observed in By, Bz, AE and the responses of the ionosphere over Jicamarca to a geomagnetic storm studied here (see text).

over Jicamarca showed significant decrease (with respect to the quite day curve) starting at ∼17 LT and lasted till post midnight hours (∼04 LT). This is likely caused by a DDEF of westward polarity as indicated by the hmF2 decrease at these hours (that is, from 17 LT to 01 LT in Figure 4d). The F layer remaining at lower height (<300 km) for a longer time, and subject to the recombination loss of plasma, lead to the foF2 decrease. Later the foF2 depletion appears to show a slow recovery possibly by the continuing DDEF whose polarity reversed to eastward after midnight remaining so till sunrise (as can be noted in Figure 4d).

[18] The PRE was totally suppressed over Jicamarca on 21 January as can be verified by comparing the vertical drift with its quite day reference values around 18–19 LT, in Figure 4e (it may be noted that the quiet time PRE was very small any way). This PRE suppression appears to have been caused in part by an over-shielding westward electric field due the AE recovery (under Bz north) that occurred at 18 LT (Figure 4c) and in part by a DDEF of westward polarity that appears to have just set in at this time. As a result, post sunset spread-F did not occur on this evening. It should be remembered that normally on a typical quite day of January the spread-F develops immediately after the PRE [*Abdu et al.*, 2009]. The westward electric field that suppressed the PRE, and hence the spread-F, continued till its reversal to eastward just after midnight which then continued till sunrise. The F layer heights as well as the vertical drift (Figures 4d and 4e) presented oscillations of significant amplitude, of ∼1-h period from 21 LT to midnight. At ∼0110 LT, the vertical drift attained value of 40 m/s which resulted in spread-F development as indicated by the red horizontal band in Figure 4d) that persisted till morning hours (Vz was not calculated during the period of spread F). This case was similar to that of Fortaleza where also the spread-F development occurred in response to DDEF.

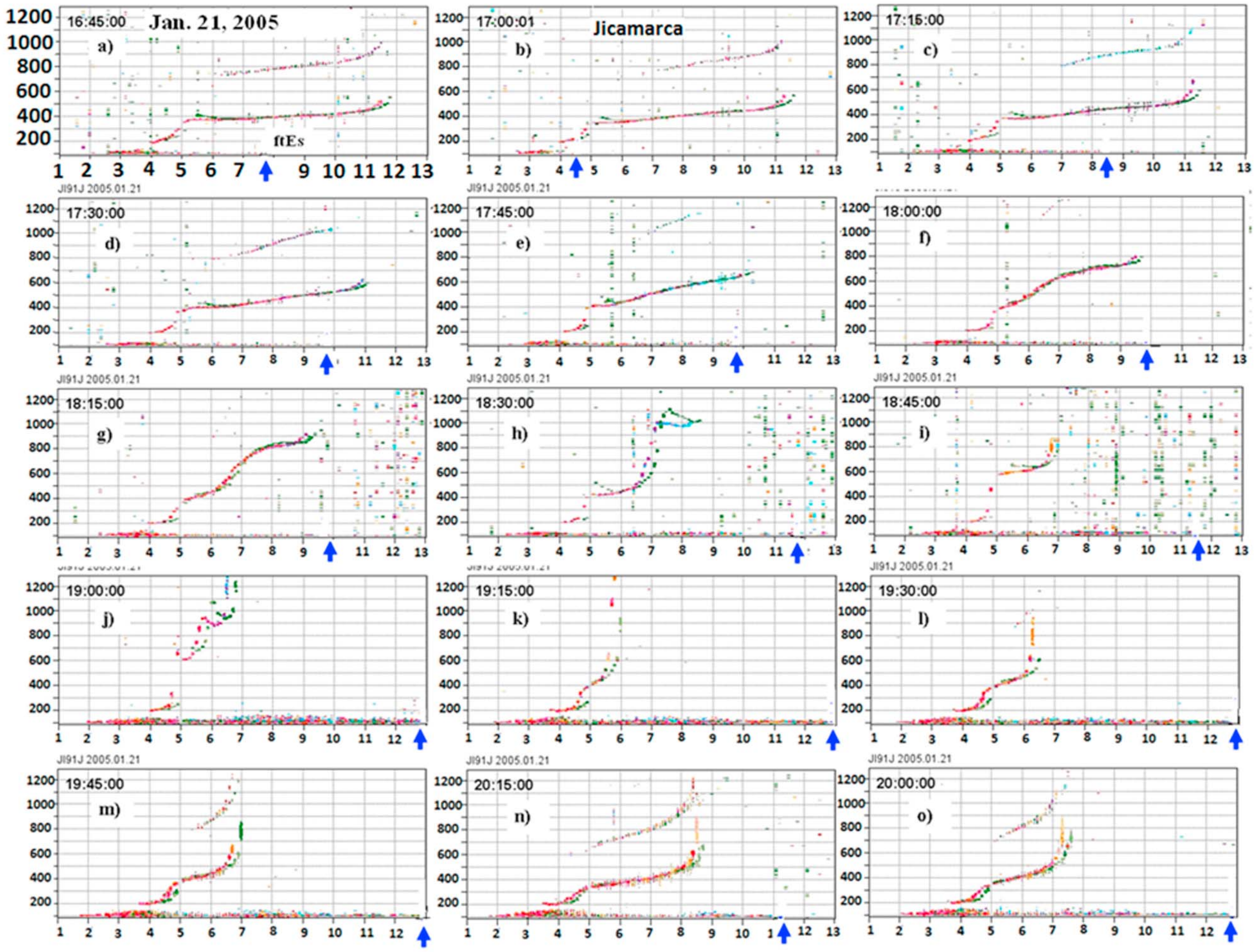

Figure 5. Sequential ionogram over Jicamarca for 1645 UT to 2000 UT on Jan. 21. The blue arrows represent the Es layer critical frequency. A strong increase can be seen in the equatorial electrojet through intensification in the Esporadic layer between 19 and 1945 UT in the ionograms in Figures 5j, 5k, 5l, and 5m. This was a response to strong prompt penetration electric field observed at 1715 UT.

[19] Figure 5 shows a sequence of ionograms for Jan. 21 that shows the response of the ionosphere over Jicamarca to this storm. Here we may note the manifestations of the disturbance electric field simultaneously in the F layer heights and in equatorial electrojet plasma irregularities. It is well known that the equatorial sporadic E layer (Q-type Es layer) is a manifestation of the presence of plasma irregularities arising from the gradient drift instability process operating in the electrojet region. The top frequency reflected/backscattered by the Es layer (that is, ftEs) can be considered to be representative of the irregularity strength and hence an approximate measure of the electric field intensity. Before the beginning of the storm ($\sim$17 UT), the ftEs (indicated by blue arrow) in Figure 5a shows a value of $\sim$7.8 MHz and later this value decreases to $\sim$4.5 MHz. Then, in the ionogram sequence taken after the storm onset this value steadily increases to $\sim$13 MHz. This increase indicates that a strong eastward electric field was responsible for the intense electrojet represented here by the decameter size irregularities that constituted the intense sporadic E layer. The Es layer and/or electrojet irregularity intensification under storm time electric fields have been reported before [see, e.g., *Rastogi*, 1973; *Abdu et al.*, 2003; *Sahai et al.*, 2011]. Here the simultaneous responses both at the F layer heights and in the Es layer confirm the role of the PPEF extended in a wide height region of the equatorial ionosphere.

4. Discussion and Conclusions

[20] In this paper we have analyzed the responses of the equatorial ionosphere during the intense geomagnetic storm of 21–22 January 2005, using data from Digisondes operated at two nearby longitudes (separated by 30°), in Brazil and Peru and also from magnetometers in Peru. The results show that disturbance electric fields play crucial roles in the variations of the F-layer heights and vertical drift, which, during daytime, are mainly caused by PPEF, while during nighttime both PPEF and DDEF play crucial roles. Striking contrast in the response features is noted between the two sites that are separated only by 2 h in LT. Among the major points of our results concern the effects of prompt penetration (under-shielding) eastward electric field under Bz South as well as Bz North conditions and in association with AE intensifications, large contrasts in the storm time response

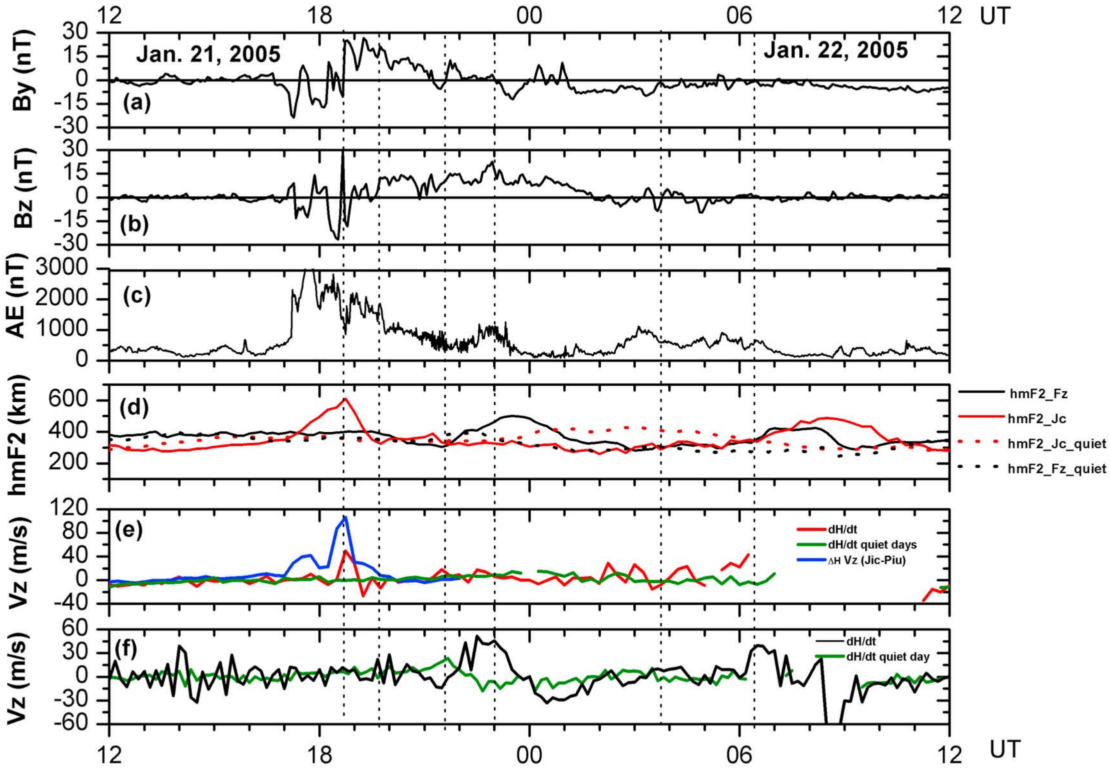

Figure 6. (a, b) Variations of the interplanetary magnetic field components By and Bz and (c) AE variations on 21–22 January. (d) Comparison between the hmF2 parameter from Jicamarca and Fortaleza, (e) vertical drift of Jicamarca and (f) vertical drift of Fortaleza. The vertical drifts in green and red lines were deduced from Digissondes and the vertical drift in blue line was inferred by the Jicamarca – Piura magnetometer data.

features between Fortaleza and Jicamarca, modulation of the F-layer by large scale gravity waves observed during the storm recovery phase especially in the Brazilian longitude sector, and the intensification of the equatorial electrojet irregularities (in the form of Es layers) observed at Jicamarca.

[21] An interesting aspect of the present observations is the different degree of ionospheric responses over Fortaleza and Jicamarca to the same event. We noted that over Jicamarca (Figure 4) an intensification in the equatorial electroject irregularities occurred along with a strong increase of the F-layer height around midday (~1715 UT/1215 LT), but over Fortaleza such effects were not observed; any fluctuations in the F-layer height was nearly imperceptible and there was no indication of Es layer irregularities. We believe that this may be caused by the difference in the ionospheric conductivity and its local time/longitude gradient between the two locations. Over Jicarmarca, at about 12 LT, the conductivity was increasing, while over Fortaleza (~17 UT/14 LT) it is high but its local time gradient is different from that over Jicamarca, and consequently the effect of the under-shieling electric field can be higher over Jicamarca resulting in the observed larger height increase/vertical drift than over Fortaleza. The sense of local time variation in the intensity of the PPEF as obtained from other observations and as predicted by model simulation studies [e.g., *Fejer et al.*, 2008; *Richmond et al.*, 2003] is in conformity to that found in our results.

[22] As another aspect of the differing degrees of responses at the two locations, we may note in Figure 6 that the F-layer height over Fortaleza decreased at ~1940 UT/1640 LT on 21 January (Figure 6d), which was due to an over-shielding electric field as suggested from the decreasing AE index at this time. This feature was not seen over Jicamarca (at the same time) where the F layer descent (the downward vertical drift) occurred at 1845 UT/1345 LT due to an over-shielding westward electric field. It is to be noted that the F layer rise (upward vertical drift) due an under-shielding eastward electric field that usually precedes the over-shielding phase did not occur over Fortaleza in contrast to its occurrence over Jicamarca. Thus we note that during a long duration AE recovery phase, with the Bz remaining progressively northward, the penetration electric field effects, both from the under-shielding eastward and over-shielding westward phases, are drastically different at the two locations separated in longitude only by 30 degrees (two hours in local time). A striking difference may again be noted further ahead in the fact that the Fortaleza F-layer height and vertical drift increased in association with the AE intensification starting at ~2130 UT (most likely due to an under-shielding electric field) whereas no such effect was observed over Jicamarca (see Figure 6d). The subsequent recovery of this AE intensification occurred when it was 18–19 LT/23–24 UT

over Jicamarca which is also the local time of the quiet time PRE, and the PRE was totally suppressed (as can be noted in comparison with the quiet day curve). Such PRE suppression may be attributed to a westward electric associated with the over-shielding effect from the 23 UT AE recovery under the Bz north conditions [see also *Abdu et al.*, 2009]. The beginning of the downward vertical drift over Fortaleza at about 23 UT (Figure 6f) also appears to be caused by the over-shielding/westward electric field associated with this AE recovery. Thus it appears that there is correspondence/similarity in the effect of over-shielding westward electric field over Jicamarca and Fortaleza when it occurs at or after the sunset hours. This may be due to a possible first order similarity in the post sunset conductivity LT gradient at the two longitudes.

[23] The DDEF effect usually sets in after a delay of a few (∼5–6) hours from the storm onset [*Scherliess and Fejer*, 1997]. During the present storm the first clear indication of the DDEF appears during the post midnight hours of 22 January (Figure 6d). (Possible causes of the lower than normal hmF2 from near 00 UT till ∼06 UT over Jicamarca, as also the effects of the fluctuating AE index during this same period on the hmF2 over the two stations, are not clear to us so far.) What looks like a clear signature of the DDEF appears in the form of height increase beginning first over Fortaleza (near 0350 UT) and a little later over Jicamarca (near 0630 UT). Additionally the height increase was modulated by a simultaneous rise near 0630 UT apparently resulting from an over-shielding eastward electric field associated with the general AE decrease that was occurring at this time (Figure 6c). As a result of the height increase spreads F developed simultaneously over both Fortaleza and Jicamarca (Figures 3 and 4). It is interesting to see that the height decrease indicating the DDEF polarity reversal to eastward, associated with the sunrise, occurred first over Fortaleza and later over Jicamarca as to be expected from the sunrise sequence at these stations. The height variations during the night, in general, appears to suggest a stronger DDEF over Jicamarca where the disturbance height departure from the quiet day variation is more striking than it is over Fortaleza.

[24] As previously mentioned, this geomagnetic storm is special because a part of the main phase occurred when the Bz was directed northward. *Du et al.* [2008] suggested some possible scenarios about this phenomenon. One of them is that this event can be the result of an accumulation of solar wind energy in the magnetotail. Another possibility is related to the magnetic reconnection involving the contribution of viscous interaction. Independent of the magnetospheric processes, our results show that the F-layer height over Fortaleza underwent significant decrease during the Bz northward turning and AE recovery (1940 UT/1640 LT), but over Jicamarca the height variation was almost similar to that of the quiet days. The over- shielding effect of height decrease over Jicamarca appears to have occurred somewhat earlier (by ∼1 h). It was pointed out that, still under the Bz north condition the increase in the F-layer height over Fortaleza near 2130 UT (1830 LT) was caused by an under-shielding electric field (due an AE intensification) and the different behavior in Jicamarca was due to a balance between this under-shielding electric field and the disturbance dynamo electric field. The DDEF effect did not dominate over Fortaleza as it appears it was over Jicamarca, which might suggest the presence of a longitudinal/local time dependence in it. *Abdu et al.* [2008] also noted different responses of hmF2 parameter between São Luis (near Fortaleza) – Brazil and Jicamarca – Peru during 30 October 2003 superstorm. They pointed out that this difference could be due to different degrees of the storm phase dependent dominance of the PPEF and DDEF at the two locations. The increase of the F-layer heights over Fortaleza starting at ∼0350 UT/0050 LT on January 22 (Figure 6d) and similar increase starting at 0630 UT/0130 LT over Jicamarca are typical cases of disturbance dynamo effects apparently modulated in a small degree by an over-shielding eastward electric field. In both cases, spread-F development occurred due to the height increase in response to DDEF.

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