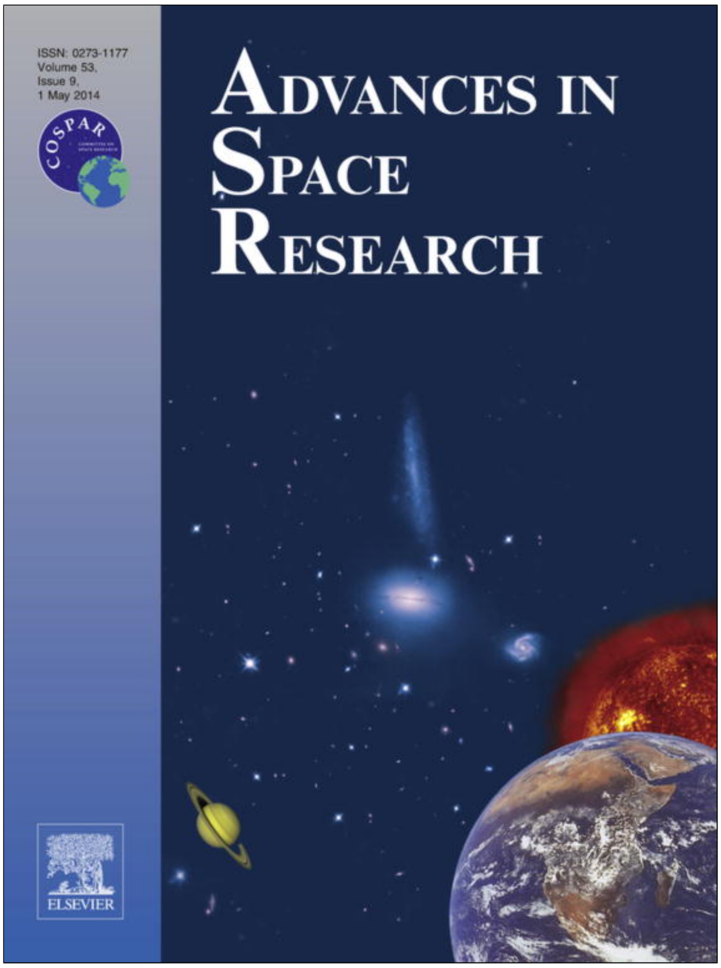
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Some ionospheric storm effects at equatorial and low latitudes

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Abstract

In this paper, the response of the equatorial and low latitude ionosphere to three intense geomagnetic storms occurred in 2002 and 2003 is reported. For that, critical frequency of F2-layer foF2 and the peak height hmF2 hmF2 for the stations Jicamarca (11.9°S), Ascension Is (7.92°S) and Tucuman (26.9°S) are used. The results show a "smoothing" of the Equatorial Anomaly structure during the development of the storms. Noticeable features are the increases in foF2 before the storm sudden commencement (SC) at equatorial latitudes and the southern crest of the Equatorial Anomaly. In some cases nearly simultaneous increases in foF2 are observed in response to the storm, which are attributed to the prompt electric field. Also, positive effects observed at equatorial and low latitudes during the development of the storm seem to be caused by the disturbance dynamo electric field due to the storm-time circulation. Increases in foF2 above the equator and simultaneous decreases in foF2 at the south crest near to the end of a long-duration main phase are attributed to equatorward-directed meridional winds. Decreases in foF2 observed during the recovery phase of storms are believed to be caused by composition changes. The results indicate that the prompt penetration electric field on the EA is important but their effect is of short lived. More significant ionospheric effects are the produced by the disturbance dynamo electric field. The role of storm-time winds is important because they modify the "fountain effect" and transport the composition changes toward low latitudes.

Keywords: Geomagnetic storms; Equatorial anomaly; Ionosphere

1. Introduction

It is well known that during quiet magnetically conditions the F2 layer in the magnetic equator is characterized by a depression in the electron density or "trough" and two peaks (crests) at about 15°–20° latitude (Stening, 1982). This is the so-called Appleton or equatorial anomaly (EA).

Changes in the mentioned structure are produced in association with geomagnetic storms (usually referred as ionospheric storms), which have been a topic of extensive studies for many decades. However, in spite of large number of case studies and a few morphological studies on the storm related changes of various ionospheric parameters, our understanding of the ionospheric storms at the EA area still remains unsatisfactory (e.g. Abdu et al., 1991; Zhao et al., 2005).

The studies of the response of the ionosphere to geomagnetic storms are important for understanding the energy coupling process between the Sun and the Earth and for forecasting space weather changes.

Geomagnetic storms are caused mainly by solar wind transients from the coronal mass ejections (CMEs) and solar flares or by the corotating interaction regions (CIRs) formed during the interaction between the high and low speed streams (Rawat et al., 2009). Occurrence frequency and intensity of transient solar emissions vary with different phases of the solar cycle characterized by the number

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of sunspots on the photosphere. Solar maximum is dominated by powerful solar eruptions, like solar flares and CMEs.

Most dominant mechanism for transfer of solar wind energy into the magnetosphere to produce the geomagnetic storms is magnetic reconnection between southwardly oriented IMF Bz component and the antiparallel geomagnetic field lines (see e.g. Rawat et al., 2009 and references therein).

So, a southward IMF condition is generally accepted as the most fundamental precondition for a storm or substorm to occur. However, some storms have been considered "anomalous" because the main phase storm occurred during the northward excursion of the Bz component of IMF. Such is the case of the storm occurred on 22 January 2005 in which minimum Dst reached −105 nT at 07UT (Sahai et al., 2011).

During the main phase of a geomagnetic storm at daytime the ionosphere above the geomagnetic equator presents generally an increase in the critical frequency foF2 with respect to median or quiet time values (the so-called positive ionospheric storms). Decreases in foF2 (the so-called negative ionospheric storms) are also observed during intense storms. Decreases of the peak electron density at low latitude stations occur in association with the increases observed at stations located below the trough of EA.

Electric field disturbances have been suggested as the most important contributor mechanism to explain the initial F2-region response to geomagnetic storms during daytime (see, for example, Abdu, 1997; Abdu et al., 2003, 2007, 2008; Batista et al., 2012 and references therein). This is possibly because the structure and dynamics of the quiet time equatorial ionosphere is determined by an eastward electric field in conjunction with the geomagnetic field.

Besides of perturbations of electrodynamic origin several other physical mechanisms (e.g., neutral wind effects, composition changes) seem to be operative at equatorial and low latitudes during storm periods (e.g., Prölss, 1995; Buonsanto, 1999; Danilov, 2001, and references therein).

One should expect a hemispheric asymmetry in the low latitude ionospheric response to a geomagnetic storm due possibly to the presence of different mechanisms along the various latitudinal regions during the disturbed period. As an example of that, analyzing Total electron Content (TEC) variations during the storm occurred on 7 September 2002, de Abreu et al. (2010) found that TEC variations at midlatitude stations in both hemispheres showed an *F* region positive storm phase. However, during the recovery phase, a strong hemispheric asymmetry was observed in the ionospheric response. While a TID was observed to propagate in the Southern American sector, no TID activity was seen in the Northern American sector. Also, in the Southern Hemisphere, the TEC variations were less affected by the geomagnetic storm. A perusal of TEC phase fluctuations and equatorial spread-F (ESF) ionospheric sounding data indicates that, on the disturbed night of 7–8 September, some stations showed the occurrence of ESF starting at about 0000UT (2000LT) on 8 September, whereas other stations showed that the ESF occurrence started much later, at about 0800UT (0500LT).

This paper analyses the ionospheric response during the periods of three severe magnetic storms events of 2002 and 2003 covering the magnetic equator and southern crest of the equatorial anomaly around 7.2 W-82 E magnetic longitudes. For that, the critical frequency foF2 and the peak height of F layer hmF2 of Jicamarca (equatorial station), Ascension Is and Tucuman (close to the southern crest of the EA) are used. Furthermore, possible physical mechanisms to explain the ionospheric effects of the storms are considered. The coordinates of the stations used are given in Table 1.

The goal of this paper is to present unusual observational results and try to analyze them with the current theories, showing some associations between foF2 and hmF2, which have not been frequently reported.

2. Results

The ground-based hourly foF2 and hmF2 data were provide by the Center for Atmospheric Research (University of Massachusetts-Lowell) website.

The strength of magnetic storms is determined by the variation in Dst geomagnetic index, thus the different phases of storms namely main phase and recovery phase were identified according to the distribution of Dst. Hourly values of Dst and AE indexes were obtained from the World Data Center at the University of Kyoto database: http://swdc.kugi.kyoto-u.ac.jp/dstdir.

As an index of ionospheric disturbance, the relative deviation of critical frequencies from the quiet level at each station was calculated as follows:

$$\mathrm{DfoF2} = [(\mathrm{foF2} - \mathrm{foF2(q)})/\mathrm{foF2(q)}] \times 100$$

where foF2 is the hourly perturbed critical frequency and foF2(q) represents the reference level (average value of five quiet days of the month of the storm). We use the average of five quiet days, instead of only one day taken as reference, because improves the representativity of the ionospheric behavior (Sobral et al., 2001). A similar expression in used for hmF2.

Positive and negative DfoF2 values correspond to positive and negative ionospheric storm effects.

The ionospheric response of three intense magnetic storms are presented in Figs. 1–3. The top plot of the figures shows the time evolution of Dst and AE for the storm

Table 1
Coordinates of the stations.

	Latitude	Longitude	Dip latitude
Jicamarca	11.9°S	283.2°E	0.64°
Ascension Is	7.9°S	345.6°E	−37.8°
Tucuman	26.5°S	294.8°E	−26.2°

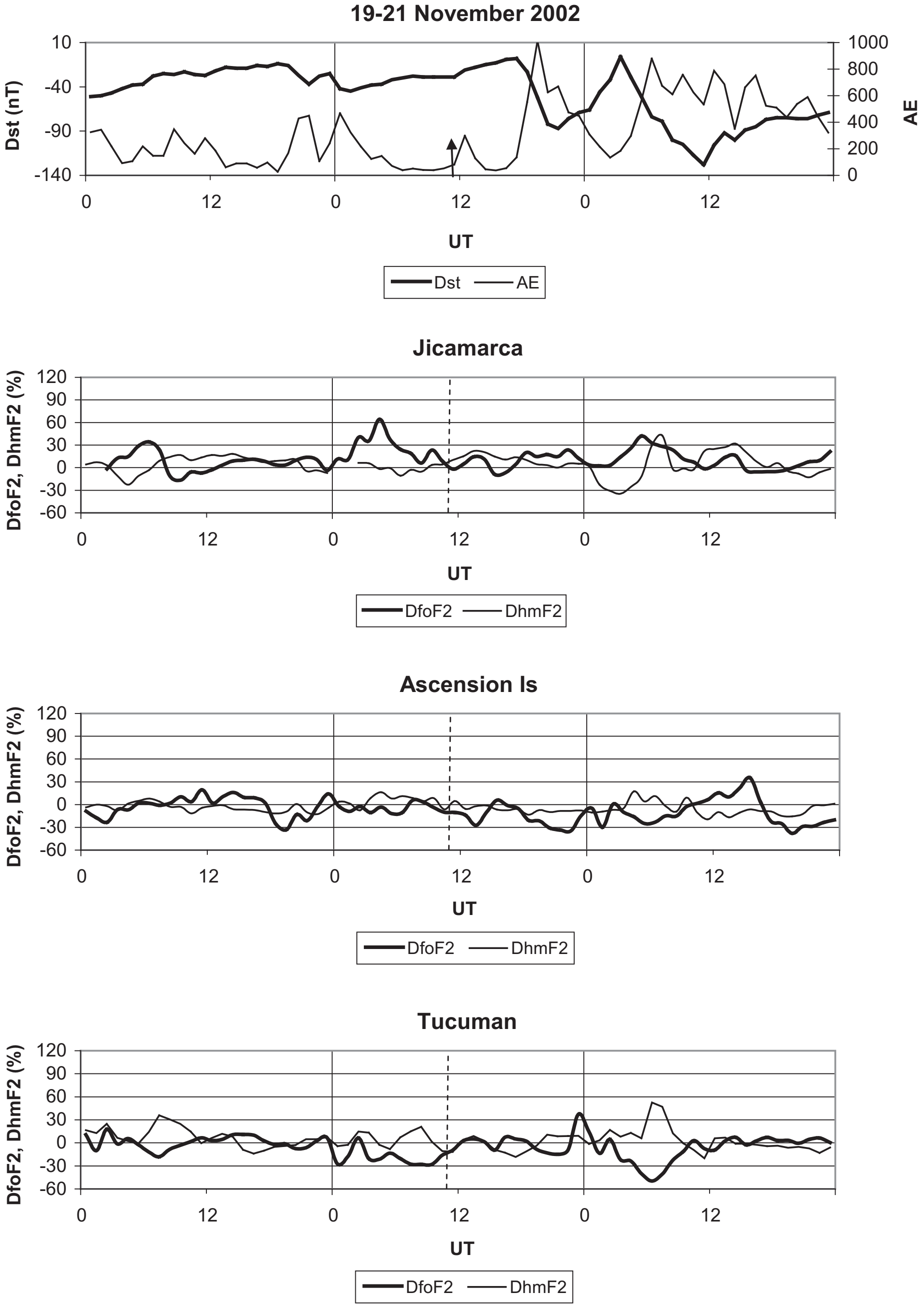

Fig. 1. Temporal evolution of Dst and AE indexes (upper panel) during the storm time period November 19–21, 2002. Variation of DfoF2 and DhmF2 during the same period for Jicamarca, Ascension Is and Tucuman respectively (lower panels). The arrow and the dashed line represent the storm sudden commencement (SC).

periods. The storm sudden commencement (SC) is represented by an arrow. The lower panels of the figures show the variation of DfoF2 and DhmF2 during the same periods for Jicamarca, Ascension Is and Tucuman respectively. The onset of the storms (SC) is indicated with a dashed vertical line in each panel of the figures.

3. Magnetic storm of November 19–21, 2002 (Fig. 1)

The first storm discussed was an intense one with a sudden commencement at 1108UT on November 20. The Dst index started a downward excursion at 15UT on November 20, attaining a first minimum of −87 nT at about 21UT and a second minimum of −128 nT at 11UT on November 21, after which started a regular recovery (not showed here). It can be noticed an enhancement in foF2 at Jicamarca prior to the SC, between about 20LT on November 19 and 02LT on November 20. In response to the storm, an irregular long-duration positive storm effect is seen over Jicamarca (between about 06UT on November 20 to 11UT on November 21, from past mid-night to pre-dawn hours) whose amplitude increases with storm development

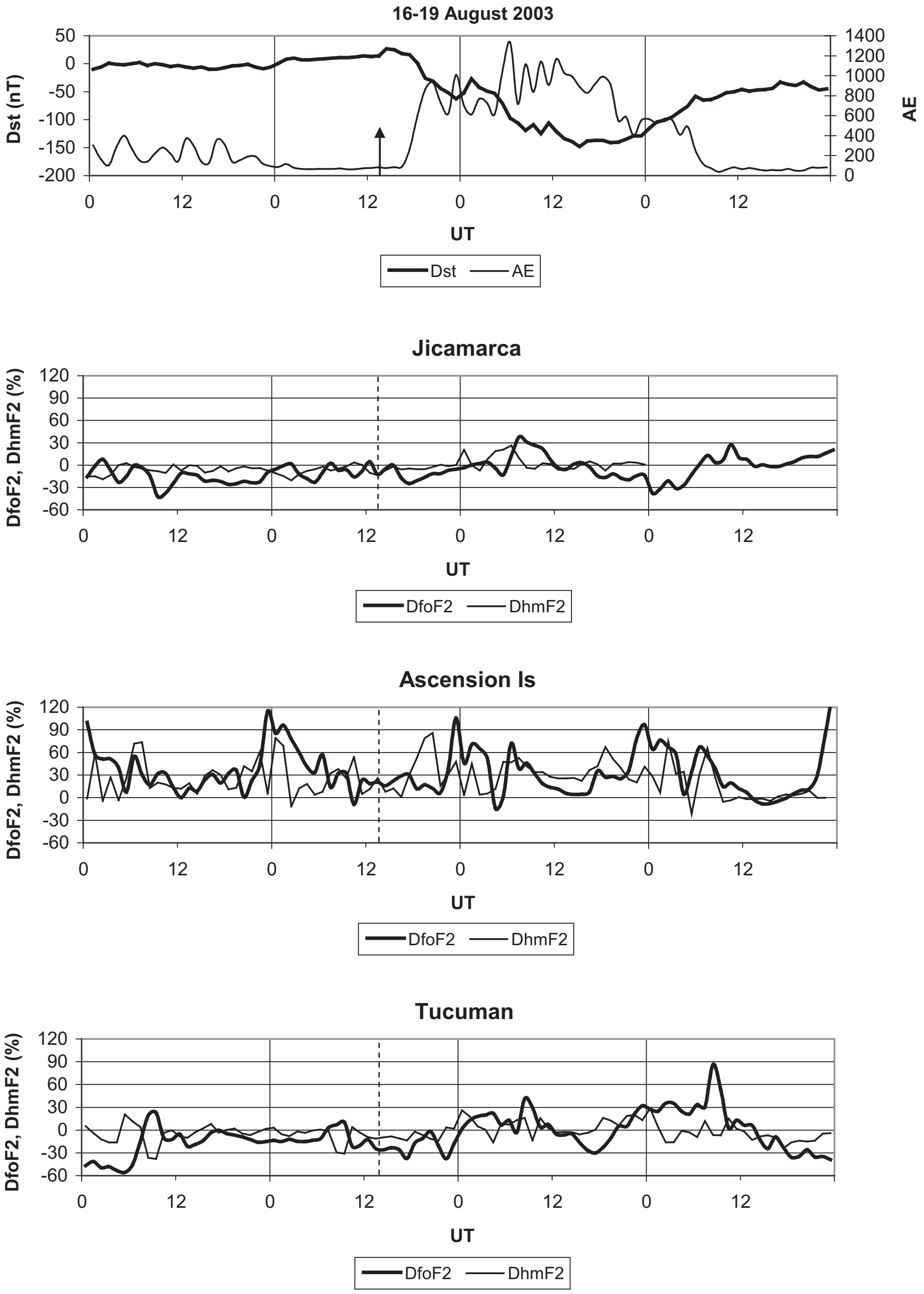

Fig. 2. The same as Fig. 1, but for the storm period August 16–19, 2003.

(~40% change close Dst value reaches its minimum value, in the nighttime hours) and a negative one over Ascension Is, between about 06UT on November 20 and 10UT on November 21. At Tucuman a short duration positive effect occurring during pre-evening hours on November 20 is followed by a negative effect (~50% change) from about 02UT to 10UT on November 21 (in the nighttime hours), which is produced simultaneously with the enhancement at Jicamarca. A delayed positive effect is seen at Ascension Is (~40% change) in the daytime hours on November 21. The outstanding feature in DhmF2 are the decreases produced in association with the positive storm effects observed at Jicamarca and Ascension Is and the increase one in association with the negative effect observed at Tucuman on November 21. In general, the changes in the height of F layer hmF2 start before the changes in foF2.

4. Magnetic storm of August 16–19, 2003 (Fig. 2)

The second storm discussed is also intense one with sudden commencement at 1421UT on August 17. This storm had a minimum Dst excursion of −148 nT at 15UT on August 18. It is noticed an enhancement in foF2 at Ascension Is prior to the storm onset, of 20UT on August 16 up to 10UT on August 17 (from 19LT to 09LT). In response to the storm at Jicamarca is observed a minor negative

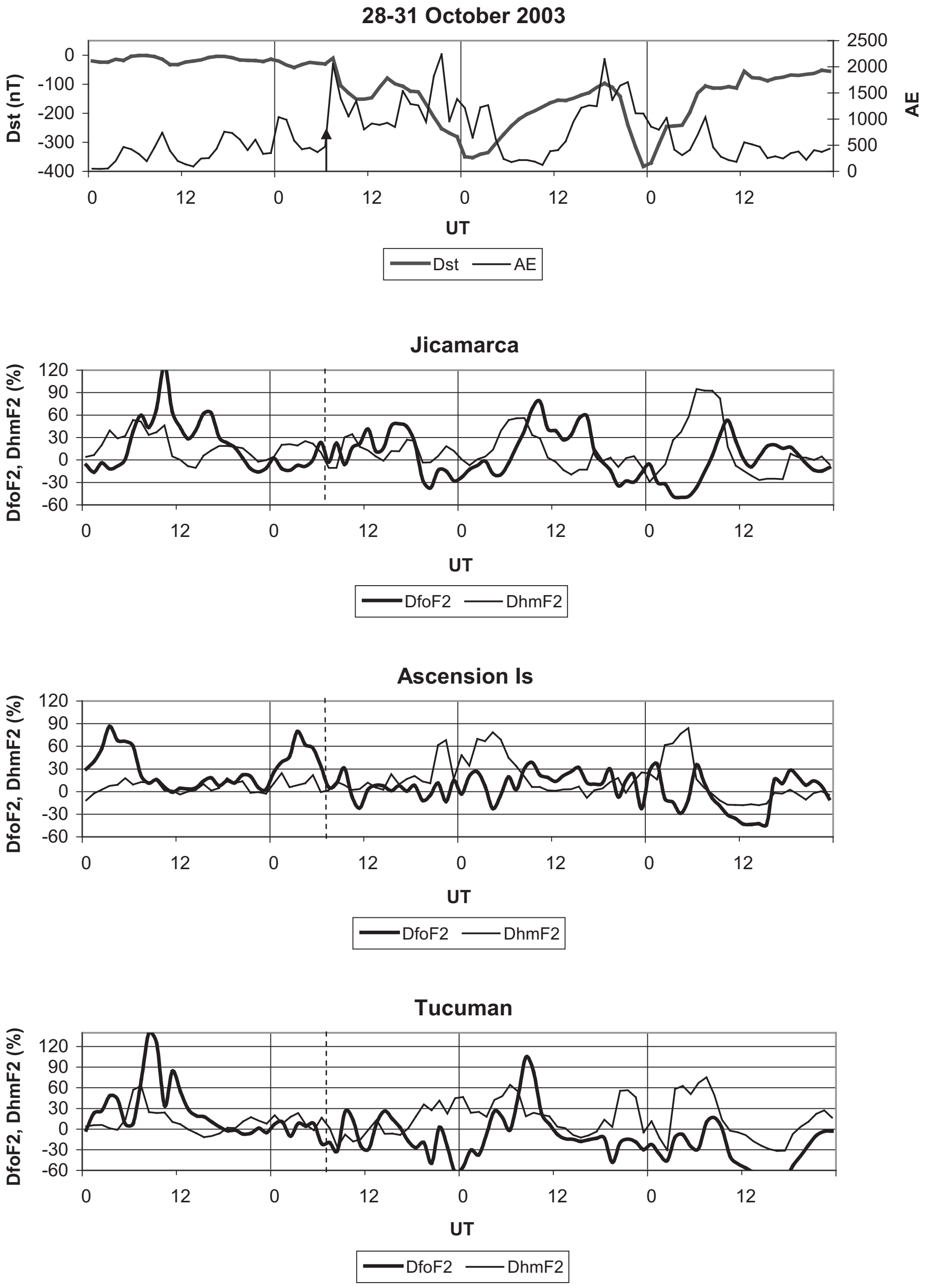

Fig. 3. The same as Fig. 1, but for the storm period October 28–31, 2003.

effect (during daytime hours), which is followed by a positive one between 05UT and 12UT on August 18 (from local midnight to dawn hours) and by a negative one during the recovery phase. At Ascension Is a small negative effect is initially observed and is followed by an irregular positive storm effect since 22UT on August 17 until about 08UT on August 19, showing two crests (~90% change) centered around local midnight. Tucuman also shows a small negative storm effect after SC followed by fluctuations with positive and negative effects. A delayed positive effect can be seen at Tucuman (~90% change) during the recovery stage, between 20UT (16LT) on November 18 and 10UT (06LT) of the next day. The behavior of DhmF2 show short duration increases (varying from 30% to 90%), which started before of the positive storm effects observed at Jicamarca, Ascension Is and Tucuman.

5. Magnetic storm of October 28–31, 2003 (Fig. 3)

This storm was also intense, with a sudden commencement at 0611UT on October 29. The storm had a maximum negative Dst excursion of −383 nT at 23UT on October 30. As the first one, this storm showed a two steps development. The Dst amplitude started decreasing since SC and reached its first minimum amplitude of −353 nT at 01UT on October 30; afterwards there was a step rice and a decrease again to reach −383 nT. Significant positive deviations in foF2 can be seen at equatorial and low latitudes before the SC: between 05UT (00TL) and 21UT (16TL) on October 28 at Jicamarca (∼120% maximum change), between 01UT (00LT) and 09UT (08LT) at Ascension Is (there is other enhancement a few before SC), and between 00UT (20LT) and 16UT (12LT) at Tucuman (∼140% maximum change). In response to the storm onset, a positive deviation is produced at Jicamarca during daytime hours, followed by a negative deviation (∼30% change) between 19UT (14LT) on October 29 and 06UT (01LT) of the next day, and a positive deviation again of ∼90% from past midnight to noon on October 30. Ascension Is presents a small positive effect in response to SC, which is followed by no significant changes until about 01UT on October 30 when start an irregular positive for about 22 h (∼30% change). Tucuman shows initially a fluctuating positive effect in response to the storm, which change to negative (∼60% change) from about 18UT on October to 04UT on the next day (from past noon to around midnight) and to positive again (90% change) between around midnight to dawn hours. In general, it can be seen that DhmF2 start to increase prior to the positive effects observed at Jicamarca, Ascension Is and Tucuman. Also there is an increase in hmF2 nearly simultaneous with the significant negative storm effect observed at Tucuman.

6. Discussion

Both negative (decreases in foF2) and positive (increases in foF2) storm effects are observed at low and equatorial latitudes during disturbed conditions, which modify the typical latitudinal structure of the EA.

As an example, Fig. 4 shows the structure of the EA for the storm occurred on October 29, 2003. To a better view how the structure of EA is modified during disturbed conditions, a middle latitude station (Port Stanley) has been added. This station is located in the same longitudinal sector that equatorial and low latitude stations. Data prior to the storm are used as reference. The figure shows the changes in EA during the development of the storm: at 18UT on October 29 (afternoon hours), 01UT (pre midnight hours), 12UT (early morning hours) and 18UT on October 30 (afternoon hours). It can be seen a “smoothing” several hours after the storm onset, in the afternoon hours, and negative effects at the crests and positive ones at the trough, on the next day. At middle latitudes initially can be observed a positive storm effect followed by a long-duration negative storm effect.

Enhancements in ionospheric electron density prior to intense geomagnetic storms but at high latitudes have been already observed (e.g., Kane, 2005; Mansilla, 2011). Although there is no simple explanation for the ionospheric positive disturbances occurring before storm onset a probable mechanism is a soft particle precipitation (emanating from solar flares but reaching the Earth a few hours later) in the region of the dayside cusp, as already was considered by Kane (2005).

Our observations show increases in ionization during night-time hours and also during pre-dawn and daytime hours before the storm onset. The more significant disturbances observed during night-time and daytime hours have associated increases in the height hmF2. Prior to the storm occurred during October 2003, nearly simultaneous increases can be seen over equatorial and low latitudes stations. This may be due to a large scale phenomenon, which produces upward movements of F layer, that is, the intensification in electron density seems to be dynamically controlled. In general, the AE index increases from 200 to 400–500 nT prior to increases in foF2, which indicates auroral activity for several hours. The penetration electric field of eastward polarity associated with the AE intensification is superposed on the normal electric field also of eastward polarity, which produces the increases in DfoF2 (Danilov, 2013).

There are several different mechanisms, which are responsible for the positive effects. In the case of storm of October 2003, the initial positive storm effect produced during daytime mainly can be explained in terms of a prompt penetration of eastward electric field, which may be correlated with the southward turning of the interplanetary magnetic field Bz. The signature of a penetration eastward electric field is present because foF2 enhancements occurring simultaneously at all stations are observed.

Thus, depletions in electron density during daytime (e.g., Jicamarca and Tucuman, during the storm of August 2003) at F2-region heights during the main phase can be

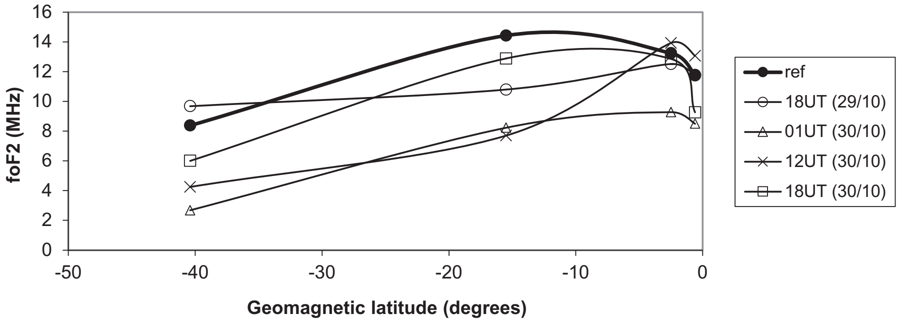

Fig. 4. Structure of the Equatorial Anomaly at different UT during the long-duration main phase of the storm of October 2003.

attributed to an increase in the electric field during storm time as a result of the enhancement of the ring current.

Corroborating this assumption, Sahai et al. (2011) found that equatorial stations show unusually rapid uplifting of the F-region peak heights (hpF2/hmF2) and a decrease in the NmF2 (proportional to foF2) coincident with the time of storm sudden commencement occurred on 21–22 January 2005. At higher low and middle latitudes the effect is not produced. They attributed the observed phenomenon to the prompt penetration electric field and enhanced equatorial fountain effects. The eastward electric field moves the equatorial F-region to higher altitudes, and the plasma particles flow downward to higher latitudes along the geomagnetic lines and result in the density decrease over the equator.

The results obtained suggest that the electric field for the October 2003 storm possibly caused a super fountain effect in the American sector because decreases of the electron density are observed over the magnetic equator and also at low latitudes.

Manucci et al. (2008) studied daytime ionospheric responses for four great geomagnetic storms (the October 2003 storm among then) using measurements of the GPS receiver onboard the CHAMP satellite at 400 km altitude. They found that three of four great storms show significant low- to middle-latitude daytime total electron content (TEC) increases above the satellite within 1–2 h of the defined start time for three of the storms (∼1400 local solar time). Manucci et al. (2008) suggest that the TEC response is associated with variability in the prompt penetration of electric fields to low latitudes, reinforcing the importance of this mechanism.

Using radar measurements from the Jicamarca Radio Observatory, magnetometer observations from the Pacific sector and ionosonde data from Brazil to study equatorial ionospheric electric fields during the November 2004 geomagnetic storm, Fejer et al. (2007) found very large eastward and westward daytime electrojet current perturbations with lifetimes of about an hour (indicative of undershielding and overshielding prompt penetration electric fields, when the southward IMF, the solar wind and reconnection electric fields, and the polar cap potential drops had very large and nearly steady values. Their result is inconsistent with the recent suggestion that solar wind electric fields penetrate without attenuation into the equatorial ionosphere for several hours during storm main phase. Moreover, they conclude that the relationships of prompt penetration and solar wind electric fields, and polar cap potentials are far more complex than implied by simple proportionality factors.

The second positive effects observed during the storm of October 2003 are occurring between around nighttime hours to dawn/noon hours. Batista et al. (2012) observed unusual intensifications of the F region electron density at latitudes close to the southern crest of the AE at predawn-morning hours. They suggest that large scale traveling ionospheric disturbances that are launched during highly disturbed conditions and/or equatorward surges in the thermospheric meridional winds seem to be the most probable causes of these disturbances.

However, Fig. 3 shows that the foF2 disturbance effects are produced nearly simultaneously at different latitudes. Also, it is known that near equator meridional winds do not rise the F2-layer therefore they cannot be responsible for the positive effects. For that reason it is reasonable to assume other mechanism to explain the positive effects.

In addition to the disturbed electric fields at high latitude which can promptly penetrate to equatorial and low latitude with timescales of about a few hours (above mentioned), another kind of electric field perturbations associated with ionospheric disturbance dynamo effects, which appear later and last longer, can be responsible for the late positive effects. Due to enhanced energy and momentum deposition into the high latitude ionosphere, the disturbance dynamo will significantly contribute to perturbed electric fields some hours after the SC, and take effect about 12–15 h later (Fejer, 2002; Liu et al., 2004). The deviations observed in foF2 and hmF2 are consistent with the assumption that several hours after SC, the ExB plasma drifts of storm origin cause the near simultaneity of height disturbances and then the electron density disturbances.

Besides of electrodynamic effects, another way to modify the EA is through wind-induced drifts. Storm time equatorward-directed winds oppose the poleward transport of ionization along the magnetic fields (fountain effect). This hinder the formation of the EA and generate negative storm effects in the anomaly crest region and positive storm effects above the equator. Because several hours are required for the generation and propagation from high to low latitudes of the storm winds such an explanation is plausible to explain the effects observed at equatorial and low latitudes during the storm of November 2002.

The negative effects also can be caused by changes in the neutral gas composition. In fact, changes in the gaseous composition of the thermosphere (increase in the molecular nitrogen density and a concurrent depletion in atomic oxygen density) can expand from high to low latitudes during intense storms and this affect the ionization production and loss balance (e.g., Prölss, 1995; Mansilla, 2003). Such is the case of the delayed negative storm effects observed during the recovery phases of the storms of August and October 2003, which have associated no variation in the height of the F2-layer.

Delayed increases of electron density sometimes observed at daytime during the recovery phase may be attributed to increases in atomic oxygen (Mansilla, 2006). At low latitudes possibly a combined effect of O increase and upward plasma drift due to enhanced equatorward winds is the responsible mechanism for the maintenance of enhanced electron density values.

Summarizing, the intense magnetic storms afford an opportunity to study in detail the EA response features. The prompt penetration electric field on the EA can be important but their effect is of short lived. More significant ionospheric effects have seen produced by the disturbance dynamo electric field due to the storm-time circulation. So, the development of ionospheric responses reflects the importance of thermospheric storms. The role of storm-time winds is important because they modify the "fountain effect" and transport the composition changes toward low latitudes.

It is noticed that the picture of prompt penetration of electric field into the ionosphere and its role in forming positive disturbances at low latitudes is still rather controversial (Danilov, 2013). As an example of that, Sojka et al. (2012) examined the role of the thermospheric wind during storm conditions and find that it has potentially an equally large effect, with a longitudinal dependence of its own that may either enhance or counteract the effect of the expanded electric field.

The results also show that it is reasonable to assume that a greater geomagnetic storm will result in stronger and extended ionospheric effects as is observed during the storm of October 2003.

In general studies of ionospheric storm-time effects at the EA region have been performed during intense geomagnetic storms; these effects present an important degree of complexity. It is necessary additional studies during moderate storms to gain a better knowledge of the ionospheric response and to obtain possible patterns of behavior in these conditions.

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