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Some ionospheric storm effects at an antarctic station

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Abstract

In this paper, the ionospheric response of a high latitude station to some intense geomagnetic storms occurred in 2000 and 2001 is analyzed. For that, data of the critical frequency of the F2-layer foF2 and the virtual height h′F measured at Base Gral. San Martín (68°08′S; 67°06′W) during the storms of April 6, 2000; May 23, 2000; March 31, 2001 and April 11, 2001 (high solar activity) are considered. In order to obtain the features of the disturbances, a comparison of the foF2 data with the outputs of the IRI-2001 model during quiet conditions is made. The results show in general negative storm effects (decreases of foF2 with respect to quiet conditions) following the storm commencement irrespective of the local time. Also, increases in foF2 prior to intense storms are sometimes observed. The h′F data show increases in association with the negative storm effects. The role of some physical mechanisms acting during the phases of the storms is analyzed.

Keywords: Geomagnetic storms; Ionospheric storms; High latitudes

1. Introduction

Perturbations of the terrestrial ionosphere in association with geomagnetic storms (called ionospheric storms) have been studied since more 80 years ago (Prölss et al., 1991). Numerous studies have pointed out the dynamic character of the ionosphere during geomagnetic storms. As a consequence of the variability of the ionospheric perturbations no definite morphology has emerged. Neither there is consensus about the physical mechanisms, which control the phenomenology of the ionosphere during geomagnetic storms.

The morphology patterns of ionospheric storms at middle and low latitudes are rather well known, and the dominant mechanisms responsible for them have been identified and modeled (Mendillo and Narvaez, 2009). Basically, during disturbed conditions the electron density can either increase or decrease relative to a background level, which are termed as positive or negative storm effects or positive or negative phases of the storm, respectively. Electric fields, thermospheric meridional winds, a "composition bulge", among others, have been suggested as possible physical mechanisms to explain the ionospheric behavior during geomagnetic storms (see for example Fuller-Rowell et al., 1994; Prölss, 1995; Bounsanto, 1999; Danilov, 2001, 2013 and references therein).

The systematic study of ionospheric storms has been conducted primarily with ground-based data from the Northern Hemisphere. The ionospheric effects of geomagnetic storms at high latitudes have been less analyzed. Some studies have found that at high and subauroral

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latitudes negative phases almost always are produced (Kane, 2005). For example, analyzing the ionospheric storm effects during storm period December 7–8, 1982, Prölss et al. (1991) report negative storm effects at high latitudes of the Northern Hemisphere and the Southern Hemisphere (Antarctic station Argentine Is.) during the main and recovery phases of the storm, which were attributed to changes in the neutral gas composition. Analyzing the high-latitude ionosphere structure of the Northern hemisphere during March 22, 1979 geomagnetic storm for the different local time sectors, Karpachev et al. (2007) find decreases in NmF2 during the main phase and the recovery phase of the storm. Patowary et al. (2013) study the effect of geomagnetic storms on the F2 layer by calculating the deviation, DfoF2, of foF2 during 40 magnetic storms. They observe very pronounced negative effects at daytime in summer and in winter at high latitudes of the Northern Hemisphere.

Some storm time ionospheric models have also been developed. An example is the STORM model, which is included in the International Reference Ionosphere (IRI). Some evaluations at high latitudes show that the STORM model captures the direction of the changes in foF2 during magnetic storm events but in general it underestimates the observations during intense storms (Mansilla et al., 2009). The STORM model has problems even at middle latitudes (e.g., Buresova et al., 2010).

The use of the Global Positioning System (GPS) data to record irregularities at high latitudes has been the subject of other papers. Thus, several studies have used GPS observations from a single site or network to monitor TEC fluctuations and related irregularities in the high latitude ionosphere.

Intensive phase fluctuations (termed scintillation) are observed along GPS satellite passes at high latitudes during storms, which cause dramatic changes in the total electron content (TEC). For example, Aarons et al. (2000) observe increases in TEC when analyze storms occurred on January 10, April 10–11, and May 15, 1997 using measurements of phase fluctuations and total electron content taken for GPS satellites at high latitudes of the Northern hemisphere. Kinrade et al. (2012) report significant phase scintillation on Global Positioning System signals in Antarctica during the storm period 5–6 April 2010. By analyzing GPS measurements of the northern and southern high-latitude ionosphere during severe geomagnetic storms, Shagimuratov et al. (2012) report that maximum activity of the TEC fluctuations take place when the *D*st index sharply decrease observed. Case study comparing the GPS phase scintillations in Arctic and Antarctic was done by Prikryl et al. (2011). Tiwari et al. (2013) also observe strong phase scintillation during storms occurred in 2012 with a GPS receiver installed at high latitudes of the Northern Hemisphere. By using TEC measurements from GPS data to investigate the global ionospheric response to the March 31, 2001 magnetic storm, Fedrizzi et al. (2005) observe decreases in TEC between 60° and 70° (Southern Hemisphere) and from 25° to 70° (Northern Hemisphere), along the geographic longitude of 315° E.

Even though there are currently a large number of GPS receivers in continuous operation, they are unevenly distributed for ionosphere study purposes, being situated mostly in the Northern Hemisphere. There is relatively small number of GPS receivers located at the high latitudes of the Southern Hemisphere and, consequently, there is a reduced number of available TEC measurements and therefore limited studies. A comprehensive summary of the TEC storm phenomenon at different latitudes can be found in the paper by Mendillo (2006).

During geomagnetic storms, the majority of energy from the magnetosphere to the thermosphere is transferred in the high-latitude region. As consequence of that, there is a heating of the lower part of the thermosphere (100–140 km) in the auroral region. The main source of this heating is the Joule dissipation of the currents, but some input may be provided also by absorption of precipitating particles (Prölss, 1995).

The heating should lead to an immediate depletion of the atoms-to-molecules ratio throughout the entire thermosphere in the high-latitude region. Because the electron concentration in the peak of the F2 layer is, roughly speaking, directly proportional to the $[O]/[N_2]$ ratio (Rishbeth and Barron, 1960; Mikhailov et al.,1989, 1995), we should have a depletion of electron density (a negative phase) in all the regions where $[O]/[N_2]$ has been decreased at F-region heights. Satellite observations have shown the close relation between the $[O]/[N_2]$ ratio depletions and electron density decreases at several ionospheric sectors (e.g., Prölss and von Zahn, 1974; Prölss, 1980; Mansilla, 2008).

The aim of this paper is to provide a contribution to the understanding of the processes acting in the high latitude ionosphere during intense geomagnetic storms by using data of an Antarctic station not previously considered in ionospheric research. Although the study of individual storm effect in details is more basic in nature, reveals the inherent physical processes working in the Magnetospheri c–Ionospheric coupling.

For that, we use data of the critical frequency of the F2-layer foF2 and the virtual height h′F measured at the Antarctic station Base Gral. San Martín (68°08′S; 67°06′W) to present the temporal evolution of these ionospheric characteristics during the storms occurred on April 6, 2000; May 23, 2000; March 31, 2001 and April 11, 2001 (high solar activity). The data were provided by the Argentine Antarctic Institute (Instituto Antártico Argentino).

To obtain the features of the disturbances, a comparison of the foF2 measurements with the outputs of the IRI-2001 model without the STORM model is made (that is, with the average variation during quiet conditions). There are lacks of foF2 measurements for magnetically quiet days during the months of the considered storms, which prevent to obtain appropriate average values or monthly medians to compare with the storm data.

International Reference Ionosphere (IRI) is one of the most widely empirical model used to describe the ionosphere during magnetically quiet conditions (Bilitza, 1986, 1990, 2001, 2015). IRI provides monthly median values of electron density, electron temperature, and ion composition as a function of height for a given location, time and sunspot number. This model is being continuously revised and updated through an international cooperative effort sponsored by the Committee on Space Research and the International Union of Radio Science.

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 collected from the World Data Center (WDC) Kyoto, Japan website (http://swdc.kugi.kyoto-u.ac.jp/dstdir)

2. Results

The ionospheric responses to four intense geomagnetic storms occurred in 2000 and 2001 are presented in Figs. 1–4. The top plot of the figures shows the time evolution of Dst and AE for the storm periods. The storm sudden commencement (SC) is represented by an arrow. The lower panels of the Figures show the time variations of foF2 (perturbed and quiet values) and $h'F$ (perturbed values) during the same periods that the geomagnetic indexes. The onset of the storms (SC) is indicated with a dashed vertical line in each panel of the Figures.

Fig. 1 shows the storm time variation for the period April 4–7, 2000. The storm sudden commencement (SC) occurred on April 6 at 1639 UT. The Dst index started a downward excursion at 17UT on April 6, attaining a minimum of -288 nT at about 01 UT on April 7, after which started a regular recovery. Nearly simultaneous with SC, AE index sharply increased from 200 to 2000 nT, decreasing during the recovery phase of the storm. It can be noticed a decrease in foF2 from before the SC, which remained during the main phase and recovery phase. The depletion in foF2 observed prior to SC could be related with the relatively increased AE values observed during April 6. Although there is a lack of $h'F$ data during the main phase and early stage of the recovery, it can be seen that the virtual height is increased on April 6 and during the recovery phase, compared with days preceding the storm onset.

Fig. 2 presents the variations of Dst, AE, foF2 and $h'F$ for the storm period May 23–25, 2000. The sudden commencement of the storm occurred on May 23 at 1425 UT. An irregular main phase remained till about 09 UT on May 24 when Dst reached its minimum excursion of -147 nT. The AE index started to increase since SC, reaching the maximum values ($\sim$1440 nT) during the main phase of the storm, after which is initiated an irregular decrease with peaks of lower intensity than before. No foF2 data were available from 00 UT to 12 UT on May 24 (during the last stage of the main phase) and 22 UT on May 24 to 08 UT on May 25; however, it is evident a negative phase during the first part of the recovery, followed by a positive phase. A pronounced height increase can be observed during the end of the main phase, which was produced before started the negative phase.

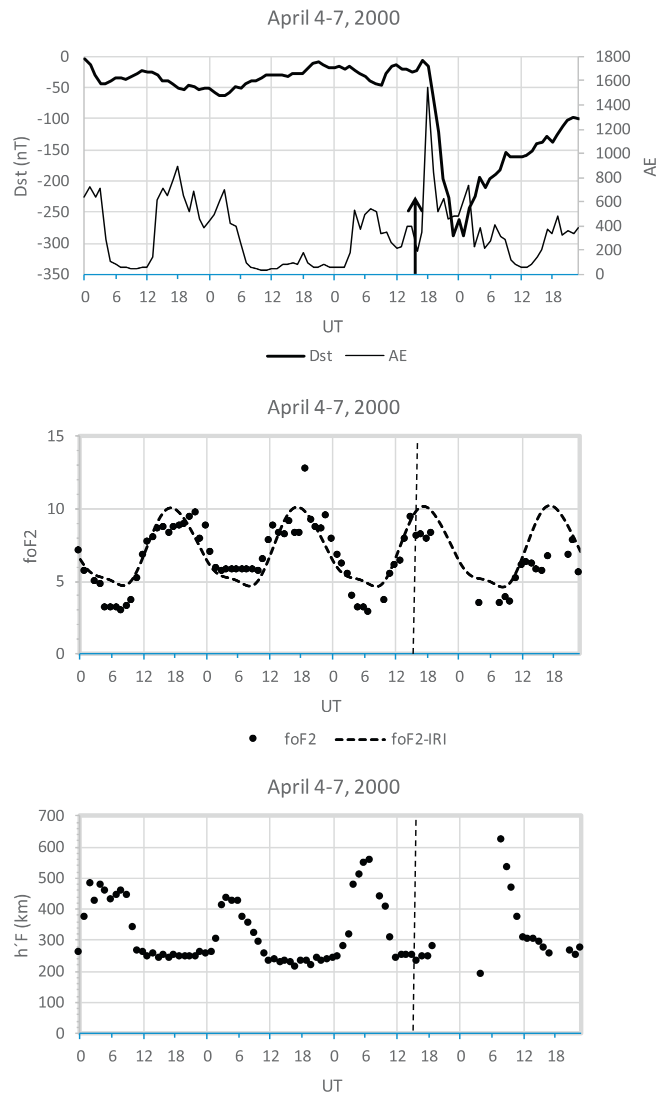

Fig. 1. Temporal variation of Dst and AE geomagnetic indexes (upper panel), measured foF2 data (solid circles) and outputs of the IRI-2001 model (middle panel), and measured $h'F$ values (lower panel) at Base Gral. San Martín for the April 4 – 7, 2000 storm period. The sudden commencement of the storms (SC) is indicated with a dashed vertical line in each panel of the Figures.

Fig. 3 shows the behavior of the Dst and AE indexes and the ionospheric characteristics foF2 and $h'F$ from March 31 to April 3, 2001 storm period. The storm onset was on March 31 at 0052 UT. The maximum deviation of Dst was of -387 nT at 09 UT on March 31 (end of the main phase). After that, a relatively steady recovery phase takes place. The AE index increased in response to

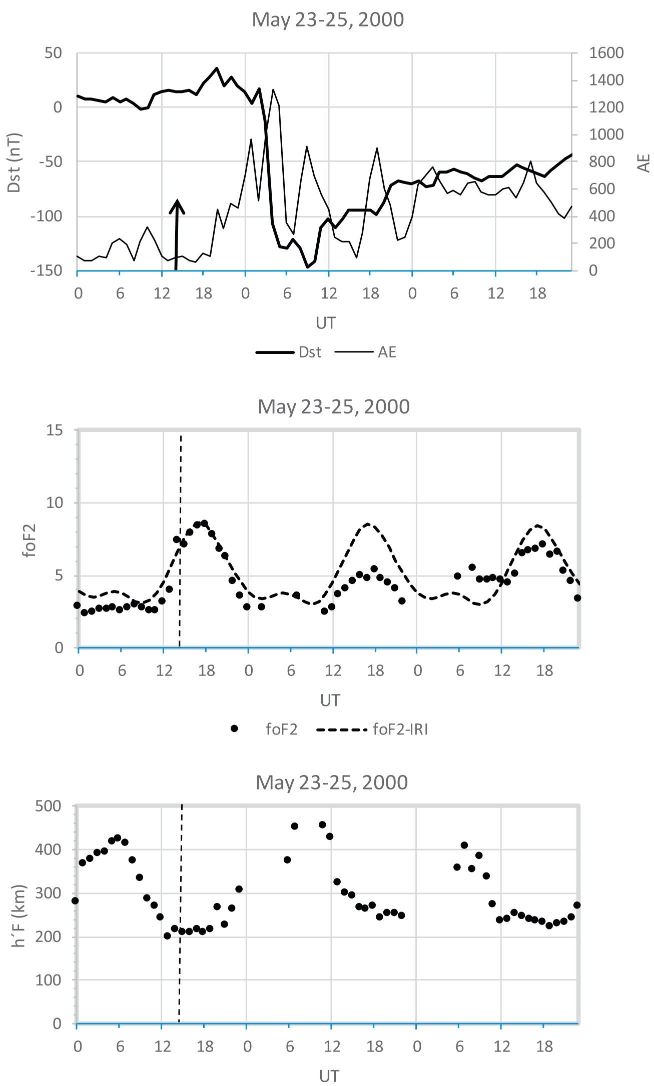

Fig. 2. The same as in Fig. 1, but for the May 23 – 25, 2000 storm period.

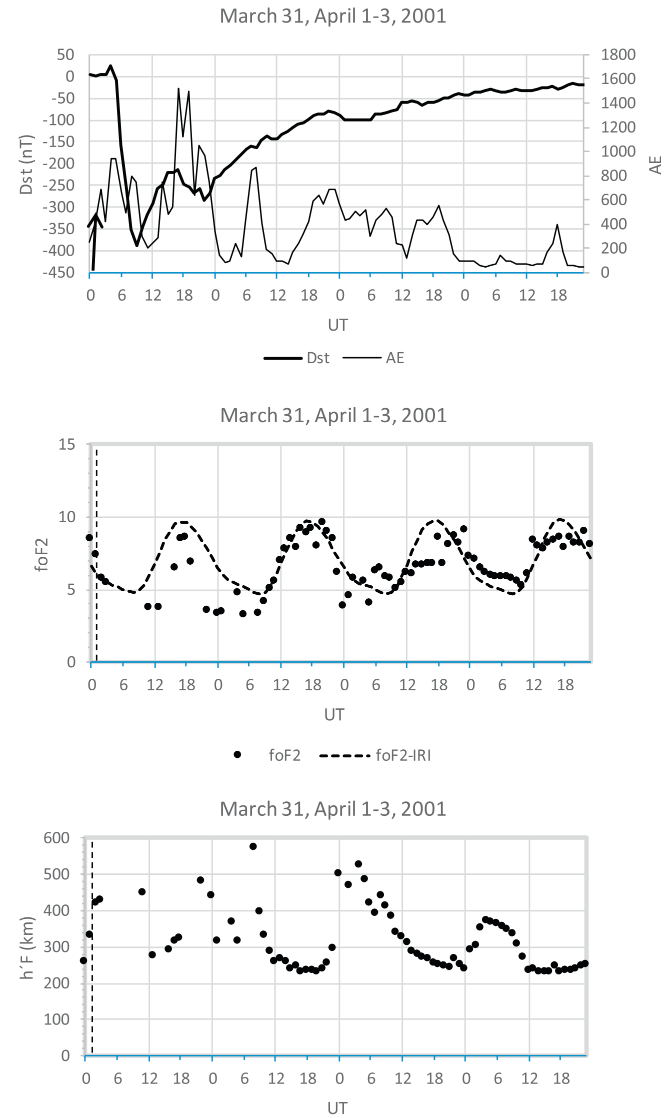

Fig. 3. The same as in Fig. 1, but for the March 31 – April 3, 2001 storm period.

the storm onset and it reached higher values that during the main phase after the end of this one (~1500 nT), which was followed by a disturbed behavior. The available data of foF2 suggest a negative phase during the main phase and first stage of the recovery (March 31 and early hours on April 1). After that, an irregular behavior is seen, which may be due to the disturbed AE index as discussed below. Unfortunately, some gaps of h′F data prevent to determine precisely their behavior in response to the storm. However, the h′F data obtained during the recovery phase (April 1–2) are greater than on April 3.

Fig. 4 shows the variations of the Dst and AE indexes and also of the ionospheric characteristics foF2 and h′F for the storm period April 10–13, 2001. The SC was April 11 at 1519 UT. The main phase remained till 00 UT on April 12, when Dst reached its minimum value of −271 nT. A steady recovery occurred after the end of main phase, on April 12 and half day the following day. Meanwhile AE, which was disturbed prior to the storm, sharply increased (up to 1700 nT) from about 01 UT on the storm day to the first part of the recovery. Subsequently is produced an important decrease, increasing again during April 13. A short duration increase in foF2 is observed before the beginning of the storm, which is in association with the enhanced auroral electrojet activity. In response to the storm, a long duration depletion in foF2 is initiated, which remained during the main and recovery phases of the storm. Unfortunately also in this storm, the gaps of h′F data prevent to precisely determine their behavior in response to the storm. Some h′F data measured during the main phase seem to be greater than in following days.

The upper panel of Fig. 5 shows the first and the third geomagnetic storms, the storm day and the following day. By means of Dst, it can be seen that these storms are similar both in the local time of the sudden commencement as well as in intensity and variations of the main phase and recovery phase. The lower panel, which presents

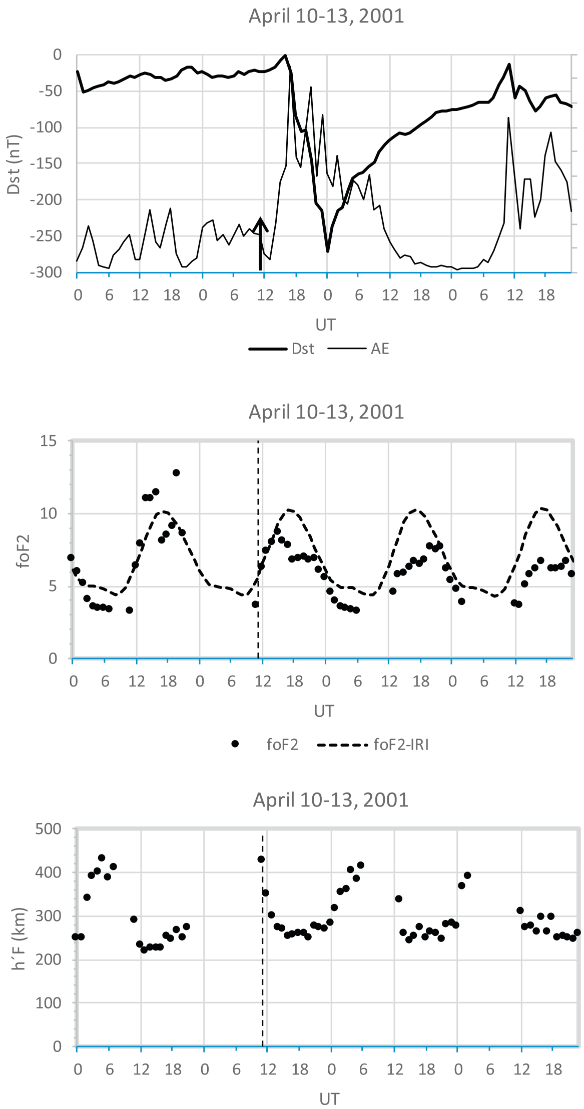

Fig. 4. The same as in Fig. 1, but for the April 10 – 13, 2001 storm period.

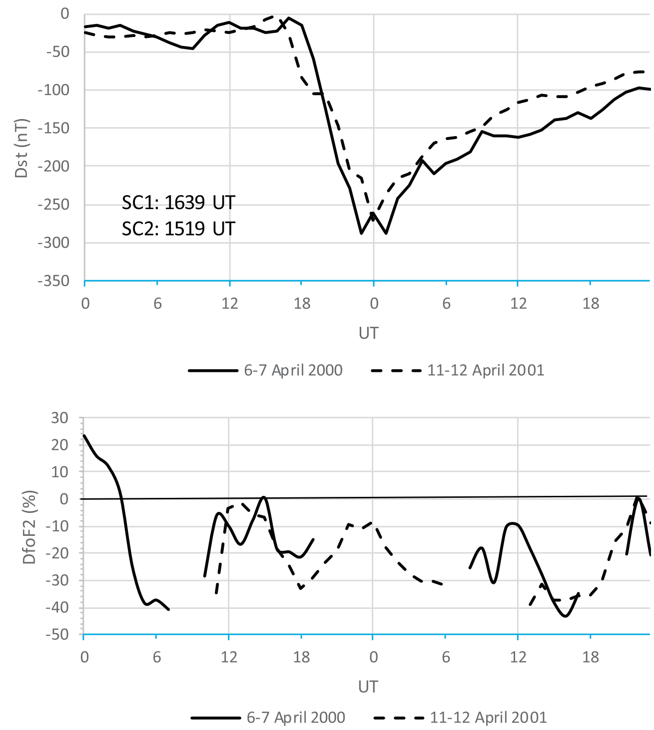

Fig. 5. Temporal variation of Dst geomagnetic index for the storm periods April 6–7, 2000 and April 11–12, 2001 (upper panel) and relative deviation between measured foF2 values and IRI outputs, in percentage (lower panel) at Base Gral. San Martín.

the relative variations of foF2 with respect to the quiet time values (IRI model), shows that negative storms effects seem to have similar variation and duration. Obviously, much more verifications are need to obtain a pattern of behavior or see any regularity in the ionospheric response, at least in this region, during intense geomagnetic storms. For that, it is necessary try to find geomagnetic storms with similar magnitude and variation during the different stages.

In addition, foF2 and h′F values at Port Stanley (51.6°S; 302.1°E), which is close to Antartic, were also used. Storm time and quiet time values from Port Stanley were obtained from the Digital Ionogram DataBase (DIDBase) by the site http://ulcar.uml.edu/DIDBase/. Figs. 6–8 present the April 4–7, 2000, May 23–25, 2000 and April 10–13, 2001 storm periods respectively. The upper panel of the figures shows the evolution of Dst and AE indexes. The middle panel presents the behavior of foF2 storm time data (solid circles) and superposed both the average of the quietest foF2 values of the month of the storm (thin line) and the IRI predictions under quiet conditions, that is, with the STORM model turned off (dashed line). The lower panel presents the storm time values of h′F (solid circles) and the average of the quietest time values (thin line). Fig. 6 shows, at difference of the Antarctic station, an increase in foF2 during the main phase, followed by a negative storm effect during the recovery phase of the storm. During the storm period, the virtual height h′F remains increased with respect to the quiet time values. The initial foF2 response to the storm at Port Stanley suggests different feature of one complex mechanism. Storm-time equatorward wind particularly in winter (when positive effects lasts longer due to opposite direction of background wind) transports to subauroral and middle latitudes first air with more atomic oxygen moved out of auroral zone due to its strong thermal expansion, and only later air with more molecular ions. Fig. 7 shows no significant changes in foF2 during the storm period: a small negative effect can be seen during the main phase followed by small positive and negative effects during the recovery phase. Comparing with the Antarctic station, the magnitude of the negatives effects decreases with latitude, which indicates a mechanism equatorward as discussed below. Similar to the first storm (April 4–7, 2000), in Fig. 8 is seen a positive storm effect during the main phase and first stage of the recovery followed by an irregular behavior while the virtual height presents increases (with respect to the quiet time conditions) in association with the negative effects. The analysis shows that although the stations are close to

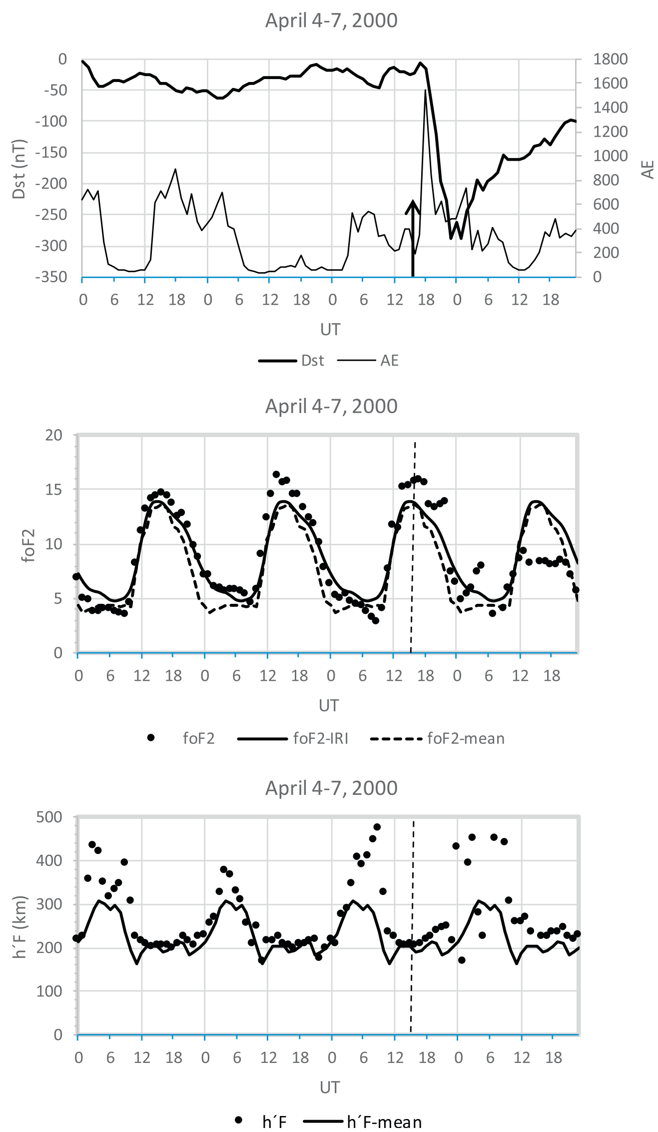

Fig. 6. Temporal variation of Dst and AE geomagnetic indexes (upper panel); disturbed foF2 data (solid circles), average of the quietest foF2 values of the month of the storm and IRI predictions under quiet conditions (middle panel), and storm time h´F (solid circles) and average of the quietest time values (lower panel) at Port Stanley, for the April 4 – 7, 2000 storm period. The sudden commencement of the storms (SC) is indicated with a dashed vertical line in each panel of the Figures.

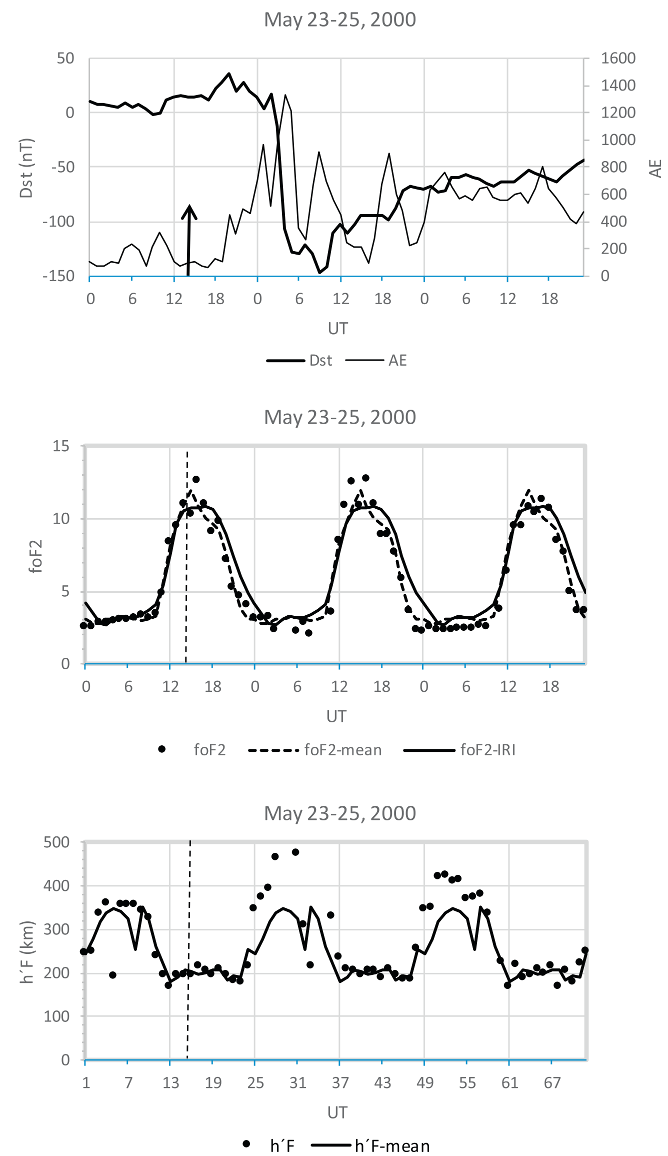

Fig. 7. The same as in Fig. 7, but for the May 23–25, 2000 storm period.

the Antarctic sector, they may present different ionospheric disturbances than stations located in the Antarctic.

3. Discussion and conclusion

All the considered storms started between daytime hours or local noon. In contrast with middle latitudes, where the morphology of F-region is rather complicated, the Antarctic ionospheric response to the storms predominantly were long duration negative phases, during the main phase and recovery phase. The results obtained here agree with previous studies, in which decreases in foF2 are observed at high latitudes during geomagnetic storms (e.g., Kane, 2005; Kurkin et al., 2008). Some researchers studied the ionospheric disturbances during the March 31, 2001 geomagnetic storm. Fedrizzi et al. (2005) describe the local time and geomagnetic latitude dependence of the TEC with an emphasis on the effects in the Southern Hemisphere. They observe TEC depletions at high latitudes of the Southern Hemisphere (between 60° and 70° geographic longitude) along the geographic longitude of 315°E, approximately at the same longitude as the ionospheric station Base Gral. San Martín.

Krankowski et al. (2005) analyze the development of TEC fluctuations in March 2001 at Antarctic stations. They report fluctuations of moderate intensity at the station O'Higgins (63.32°S; 57.90°W) during the main phase of the storm, which are attributed to small- and middle-scale irregularities.

Moreover, sometimes short duration positive effects can been observed prior to the beginning of the storm.

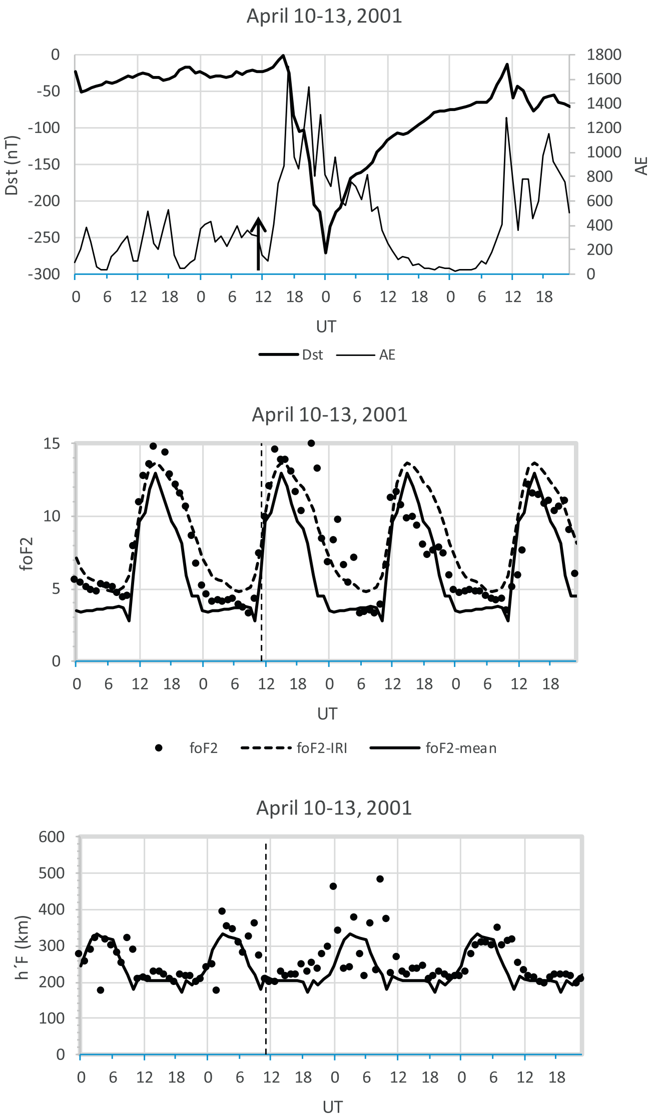

Fig. 8. The same as in Fig. 7, but for the April 10–13, 2001 storm period.

Pre-storm positive phase both in foF2 and in TEC were already observed by some researches (e.g., Araujo-Pradere and Fuller-Rowell, 2002; Kane, 2005; Mansilla, 2004). Our results suggest that the positive disturbances could be produced before intense geomagnetic storms (see storms of April 2000 and 2001). Some researchers (e.g., Danilov and Belik, 1991, 1992; Danilov, 2001) suggest that positive phases prior to the storm onset result probably from enhanced ionization due to particle precipitation in the region of the dayside cusp, as the cusp is the only formation which starts to react to the coming geomagnetic disturbances before any geomagnetic index does: the cusp begins to move equatorward a few hours before the beginning of the Dst depletion. Pre-storm enhancements at middle latitudes were in more detail described by Buresova and Lastovicka (2007, 2008).

The depth of the negative phases seems to be not linked directly to the severity of the magnetic disturbance. As examples of this, in storm of May 2000, minimum Dst index was of −147 nT and the relative decrease of foF2 was ∼44% during the recovery phase, while in April 2001 were −271 nT and ∼35% respectively. It is interesting to note that negative phases started nearly simultaneously with the drop of Dst (the main phase onset).

The primary cause for negative storm phases at high latitudes is a change in the neutral gas composition. The prominent features of these neutral gas perturbations are an increase of the molecular nitrogen and oxygen densities and a concurrent decrease of the atomic oxygen density. Magnetospheric energy deposition into the polar upper atmosphere during geomagnetic storms significantly affects the thermospheric neutral composition and ionospheric plasma density from high latitudes to the equatorial region. Joule heating of the polar upper atmosphere induces an upward expansion of heavy molecular gases (O2 and N2). If the thermospheric dynamical regime stayed unchanged during magnetic disturbances, the zone of depleted [O]/[N2] (and so of foF2) would be limited by the high-latitude ionosphere (approximately by the auroral oval). But the heating induces also its own circulation (which may conflict to the background circulation) which at F2-layer heights tends to bring the air equatorwards to lower latitudes. That leads to the drift of the negative phase equatorward (see e.g. Richmond and Lu, 2000; Danilov, 2001 for details).

In supporting this explanation, we can see an uplift of the F region (through h′F) due to the equatorward neutral wind, which is produced by the mentioned energy injection into the polar atmosphere during periods of geomagnetic disturbances. Unfortunately, lack of ionospheric data in some hours prevents to determine whether the uplifting of F region occurred before or is nearly simultaneous with the beginning of the negative storm effects. It is pointed out that the h′F values could change substantially if the conditions in the lower part of the ionosphere on the way of the sounding radio rays are changing. And they might change due to changes in precipitating particles ionizing the E region.

As was mentioned, it is considered that both the increase in the molecular nitrogen and the decrease in the atomic oxygen contribute to the decrease in the electron density (e.g., Prölss, 1995). However, satellite measurements show that the negative phases are caused mainly by an increase in molecular nitrogen concentration and practically no changes in atomic oxygen concentration (e.g., Kil et al., 2011; Mansilla and Zossi, 2012). Therefore, the disturbance in $[O]/[N_2]$ in the F region is primarily determined by the change in $[N_2]$.

The enhanced AE index during the recovery phase could be influencing for the maintenance of the prolonged negative storm effects at high latitudes, which remained also during the recovery stage of storms. Danilov (2001) observed that the negative phase in most cases demonstrates a well-pronounced dependence on the intensity of the magnetic disturbance as expressed by various geomagnetic indices, particularly the AE index. For that reason, the duration of negative storm effects may possibly reach days during continued magnetic activity.

Elements that complicate the simple picture above mentioned involve electric fields of magnetospheric origin, which may penetrate to F-region heights during geomagnetic disturbances. Due to the magnetic field geometry at polar and high latitudes, those fields do not produce strong vertical drifts as at low latitudes but they are able to influence the F2-layer behavior via the recombination coefficient. At high temperatures, the rate coefficient is approximately proportional to the square of the temperature. This temperature increases with the square of the electric field strength. Therefore, the recombination coefficient will change with the fourth power of the electric field intensity. Thus, an increase of the electric field leads to a depletion of the electron density (see Prölss, 1995 for details).

Therefore it is suggested that the negative storm effect observed a few hours after the storm sudden commencement (e.g., storm of April 2001) is initiated by these substantial electric fields. During the storm development, the neutral composition changes possibly promote and/or substitute the initial effect of an electric field.

It should be noted that the disturbed ionospheric data from Base Gral. San Martín (68°08′S; 67°06′W) have not been used previously in ionospheric researches. Hence the importance to analyze and know the ionospheric behavior during geomagnetic storms of this high latitude station, which is located in an unfrequently studied region.

In conclusion, in this paper is presented the ionospheric response of an Argentine Antarctic station to some intense geomagnetic storms occurred in 2000 and 2001. The results show in general long duration negative storm disturbances during the main phase and recovery phase of the storms started between daytime hours and local noon. These negative phases seem to be independent of the intensity of storms. Also, sometimes are observed positives phases before the beginning of intense magnetic storms, which could be the effect of particle precipitation. This study suggests that the most likely causes for the negative phases are the penetration of enhanced electric fields of magnetospheric origin into the ionosphere followed by perturbations of the neutral gas composition.

This is the first study of ionospheric parameters from the Argentine Antarctic region during storm conditions. The results of this remote region are important to be reported because they can help to describe better the morphology and modeling of the high latitude ionosphere particularly in the Southern Hemisphere.

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