Global Ionospheric Response to the Magnetic Storm of 21 October 1999

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Abstract: The present work aims to investigate the 21 October 1999 magnetic storm and its global ionosphere-magnetosphere response. The study uses a combination of ionosonde and magnetometers data; in addition, the data from satellite in-situ measurements, such as the Defense Meteoro logical Satellite Program (DMSP), TOPographic EXplorer (TOPEX) and WIND. A new analytical method has been used to analyze the \( \delta F_2 \) ionospheric data from eleven ionosonde stations. According to that analytical method, the \( \delta F_2 \) data has been normalized to a central location, and local time correction (LTC) values have been calculated for each station. The integrated LTC data from all stations from both eastern and western hemispheres showed a global response to the magnetic storm, which is synchronized with the storm main phase manifested by the sudden decrease in \( D_s \). During the main phase of the storm, the \( D_s \) index showed a large fall with a minimum value of \(-240 \) nT. The interplanetary Bz reversed polarity in a 19 nT southward excursion that led to detection of a prompt penetration electric field. The auroral electrojet index AE was used as indicator of high latitude convection effects on the ionospheric electric fields through prompt penetration. The global relative deviation \( \delta F_2 \) showed a damping of about \(-55\%\) during the main negative phase of that ionospheric storm; moreover, the positive phase occurred before the negative one, in harmony with the results of previous studies. We observed a similarity in the behavior of both \( \delta F_2 \) and the vertical \( E \times B \) drift during the storm. On the other hand, the DMSP results showed a disturbance in the plasma drift velocity, while TOPEX showed asymmetrical equatorial anomaly of the global TEC.

Key words:

INTRODUCTION

Electric fields, thermospheric meridional winds, a composition bulge and high latitude particle precipitation have been suggested as probable physical mechanisms to explain the ionospheric reaction to geomagnetic storms observed at different latitudes (Fuller-Rowell et al., 1994; Prölss, 1995; Danilov, 2001; Mansilla, 2004, and references therein). During the geomagnetic disturbance there is an input of energy into the polar ionosphere, which changes several thermospheric parameters, such as composition, temperature and circulation. Composition changes directly influence the electron concentration in the F2 region, while circulation spreads the heated gas to lower latitudes. The conflict between the storm-induced circulation and regular one determines the spatial distribution of the negative and positive phases. There are still unsolved problems (Danilov, 2001), the most acute ones are: the appearance of positive phases before the beginning of the geomagnetic disturbance, the occurrence of strong negative phases at the equator, the role of vibrationally excited nitrogen in forming negative phase, and the relation of positive phases to the dayside cusp.

A possible cause for the negative storm effect at low latitudes would be the arrival of the neutral winds carrying the composition changes. This is supported by satellite measurements obtained during the first part of the recovery phase of the intense geomagnetic storm at the crest region (Mansilla, 2003).

During geomagnetic storms, the disturbed solar wind compresses the Earth’s magnetosphere, and intense electric fields occur that are mapped along geomagnetic field lines to the high-latitude ionosphere (Jakowski et al., 1999; Yizengaw et al., 2004). Energetic particles precipitate to the lower thermosphere and below, expanding the auroral zone and increasing significantly the ionospheric ionization at higher latitudes (Yizengaw et al., 2005).

Intense electric currents couple the high latitude ionosphere to the magnetosphere, and the enhanced energy input causes considerable heating of the ionized and neutral gases. This leads to uneven expansion of the thermosphere producing pressure gradients, which drive strong neutral winds (Baonsanto, 1999). The disturbed neutral winds produce polarization electric fields by a dynamo effect (Aarons and Rodger, 1991) as they collide...
with the plasma in the presence of the Earth’s magnetic field (Blagoveshchensky et al., 2003). These electric fields in turn further affect the neutrals and the plasma, illustrating that the ionized and neutral species in the upper atmosphere are closely coupled.

The horizontal component of the geomagnetic field at the magnetic dip equator reflects the change in the equatorial plasma fountain, and the difference between $H$ at the equator and at a non-equatorial location is a good indicator of the vertical $E \cdot B$ drift (Horvath and Essex, 2003). Moreover, the enhanced downward $E \cdot B$ drift is the cause of such nighttime enhancement due to plasmasphere compression (Foster et al., 2002).

In our study, we aim to provide a contribution to the understanding of such effects during the occurrence of a high-intensity and long duration magnetic storm on 21 October 1999.

**Magnetospheric Response:**

A strong magnetic storm was recorded on 21 October 1999 due to the passage of a coronal mass ejection detected by SOHO/LASCO on 18 October (Dal Lago et al., 2006). Its impact on the Earth’s magnetosphere appeared about two days later. Fig. 1 shows the $D_s$ index (top panel), IMF $B_z$ component measured by WIND (middle panel) and the auroral electrojet index AE (bottom panel).

![Fig. 1: Ds index (top panel), IMF Bz component measured by WIND (middle panel) and the auroral electrojet index AE (bottom panel). The vertical dashed line represents the triggering time of the SSC main phase.](image)

This storm occurred in only one step decrease after the Sudden Storm Commencement (SSC) at 22UT on October 21, defined by a vertical dashed line in the figure, with a minimum value of the $D_s$ index of $-240$ nT when the $B_z$ reversed polarity in a 19 nT southward excursion.

The AE index intensity remained quite high during the storm period. The sudden northward $B_z$ intensity variation (that is, a decrease in southward $B_z$) occurred on 21 at 22UT and a simultaneous sudden decrease in the AE index are consistent with the hypothesis of the penetration of an eastward disturbance electric field (Fejer, 1991; Sobral et al., 1997).
Ionosonde Data:

Ground-based hourly $\nu$F2 data, which is proportional to the square root of NmF2, provided by the Space Physics Interactive Data Resource (SPIDR) of the NGDC-NOAA have been collected during the time period 20–25 October 1999. The station codes, names and their geographical longitudes and latitudes are listed in Table 1. The locations of the eleven-ionosonde stations used in this study are shown in Fig. 2. The circles represent the stations location, and the lines represent the grid to the central station.

Table 1: A list of ionospheric stations from which data were used in this study with their geographical longitude and latitude,*

<table>
<thead>
<tr>
<th>Code</th>
<th>Station</th>
<th>Long.</th>
<th>Latit.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Leningrad</td>
<td>30.7</td>
<td>60</td>
</tr>
<tr>
<td>S2</td>
<td>Juliusruh*</td>
<td>13.4</td>
<td>54.6</td>
</tr>
<tr>
<td>S3</td>
<td>Chilton</td>
<td>-1.3</td>
<td>51.6</td>
</tr>
<tr>
<td>S4</td>
<td>Moscow</td>
<td>37.3</td>
<td>55.5</td>
</tr>
<tr>
<td>S5</td>
<td>Uppsala</td>
<td>17.6</td>
<td>59.8</td>
</tr>
<tr>
<td>S6</td>
<td>Millstone</td>
<td>-71.5</td>
<td>42.6</td>
</tr>
<tr>
<td>S7</td>
<td>Boulder</td>
<td>105.3</td>
<td>40</td>
</tr>
<tr>
<td>S8</td>
<td>Novosibirsk</td>
<td>83.2</td>
<td>54.6</td>
</tr>
<tr>
<td>S9</td>
<td>Hobart</td>
<td>147.3</td>
<td>-42.9</td>
</tr>
<tr>
<td>S10</td>
<td>Grahamstown</td>
<td>26.5</td>
<td>-33.3</td>
</tr>
<tr>
<td>S11</td>
<td>Port-Stanley</td>
<td>-57.9</td>
<td>-51.7</td>
</tr>
</tbody>
</table>

Fig. 2: Geographic map of the eleven ionosonde stations (circles) that provided data for this study, with normalization to the central station as the intersection of the (lines).

A new more general method has been used to analyze the data from the above stations (Mahrous & Radicella, 2006). Calculating the average value of the geographical longitude of the 11 stations, it was equal 10.9 degree. We define the central station among all the triggered stations; this should be the nearest one to the average. Upon this simple calculation, Juliusruh station was the central station. Calculating the local time difference between each station and the central one, that local time correction (LTC) should be added (or subtracted) to the original data. It should be noted also that the same results should be obtained in case of choosing any other station and calculating the LTC corresponding to it.

Fig.3 shows the diurnal variation of $\nu$F2 critical frequency in MHz normalized to the central station during 20–25 October 1999. Station names are written on the y-axis, the vertical dashed line represents the triggering time of the SSC. The last three stations of Fig.3, which are S9, S10, S11, belong to the southern hemisphere while the rest belong to northern hemisphere. It is interesting to notice that all the 11 stations having the same behavior, that is, a regular daily variation within the frequency range (3.5–11 MHz) on undisturbed day of 20th, and a damping by the end of 21st at 22UT which is synchronized with the storm main phase. The decrease in the $\nu$F2 continued for the whole disturbed day of 22nd, reaching a maximum value of 2 MHz for stations (S1, S2, S3, S5, S8, S9). The recovery phase started on the 23rd by the return of $\nu$F2 to the regular values.

Global Ionospheric Response:

According to the used analytical method, the $\nu$F2 data has been normalized to a central location, therefore, it is possible to draw all the data from the 11 stations in one figure like the dot-points in Fig.4.
Fig. 3: Diurnal variation of $\alpha$F2 parameter with LTC during 20–25 October, 1999. Station names are written on the y-axis, the vertical dashed line represents triggering time of the SSC.

The average value of the whole data is represented by the curve in the same figure. The figure also shows a regular diurnal variation of $\alpha$F2 value during 20th and 21st, a damping during 22nd and recovery by 23rd. The signature of the geomagnetic storm on the global ionospheric response manifested by the $\alpha$F2 parameter is clearly shown in that figure.
Fig. 4: The mean value of $\delta F_2$ measured by the 11 stations, the vertical dashed line represents triggering time of the storm main phase.

Fig. 5: The relative deviation of $\delta F_2$ measured by the 11 stations, the vertical dashed line represents triggering time of the storm main phase.

As an index of the ionospheric disturbance, we calculated the relative deviation of critical frequencies from the quiet level $D \delta F_2$. This technique has been used by many authors like Blagoveshchensky et al. (2003) and Danilov A.D. (2001), according to the following equation

$$D \delta F_2 = \left( \frac{\delta F_{\text{dist}} - \delta F_{\text{qui}}}{\delta F_{\text{qui}}} \right) \times 100\% \quad (1)$$

Where $\delta F_{\text{dist}}, \delta F_{\text{qui}}$ are the critical frequency of $F_2$ layer during disturbed and quite periods respectively. Fig.5 shows the relative deviation of $\delta F_2$ measured by the 11 stations, the vertical dashed line as represented in the previous figures.

显著的低幅值的$D \delta F_2$偏差观察到与SSC有关，达到最大值$-55\%$在22 UT。正的增强$D \delta F_2$出现了两次。第一个峰值发生在20 UT，最大值为30%在21 UT。第二次发生在20 UT，与SSC开始的巧合。
Vertical $E \times B$ drift:

The equatorial electrojet current produces the strong enhancement of the H-component magnetic field, which is observed by magnetometers located near the magnetic equator. The D$_a$ ring current and global dynamo contribution to the H-component can be removed by subtracting the H-component recorded at a non-equator magnetometer ($H_{\text{non-equator}}$) from the H-component value measured by a magnetometer at the magnetic equator ($H_{\text{equator}}$). The difference is the only part of the H-component field that is related to the equatorial electrojet current contribution which, in turn, is directly related to the east-west electric field that triggered the system to create the electrojet current. Therefore, the $E \times B$ drift can be estimated using the resulting DH ($H_{\text{equator}} - H_{\text{non-equator}}$) value of the H-component field (Yizengaw et al., 2005).

Figure 6 displays the parameter DH for the two stations Ascension Island (Asc) at (-7.9° N, 345.62° E geomagnetic) and M’Bour (Mbr) at (14.39° N, 343.04 E geomagnetic), which have been used to determine $H_{\text{equator}}$ and $H_{\text{non-equator}}$, respectively. The figure also shows a damping of DH of about -1.8 nT occurred on October 21 at 23 UT.

![Figure 6](image_url)

**Fig. 6:** The DH (difference between the horizontal component of the geomagnetic field (H) at the equator and at non-equator regions) obtained from the magnetometer data at Ascension Island (Asc) at (-7.9° N, 345.62° E geomagnetic) and M’Bour (Mbr) at (14.39° N, 343.04 E geomagnetic) to estimate vertical $E \times B$ drift.

![Figure 7](image_url)

**Fig. 7:** The ground orbit track of DMSP F13
DMSP Data:
The DMSP satellites circle the Earth in Sun-synchronous dawn-dusk orbits at nearly 850 km altitude. The DMSP F13 flew close to the central ionosonde station, as shown in Fig. 7, at 6:30 UT. The data of DMSP F13 during October 22 is shown in Fig. 8. The top panel shows the plasma temperature observed at the satellite height for both ions (continues line) and electrons (points). The second, third and fourth panels, from the top, represent the plasma drift velocities in x, y and z directions; and the bottom panel indicates the ion and electron fluxes. The figure shows that the maximum flux density of $2 \times 10^5$ ions cm$^{-2}$ take place within the mid-latitude (between $60^\circ$ - $1.2^\circ$ S geographic) region. The plasma temperature depict a variation between 1500 k ~ 5000 k for both ions and electrons over the same region.

![Fig. 8: The topside F-region plasma temperature (top), plasma drift velocities in x, y and z directions (2nd, 3rd and 4th panel from top), and ions and electron flux (bottom) obtained from the DMSP F13 satellite during October 22.](image)

Topex Data:
Traveling in a 66-deg inclination orbit at an altitude of 1336 km, the TOPEX satellite provides about 95% of full geographic coverage of the Earth’s oceans approximately every 10 days. TOPEX uses a dual-frequency altimeter to measure the range delay difference between the two frequencies and to compute the ionospheric range error, and thus obtains downward viewing TEC information. The TOPEX altimeter measures the vertical electron content beneath the satellite. Since the TOPEX altimeter is designed only to measure ocean heights, there are data gaps over landmasses as shown in the tracks of Fig.9. The colours of the tracks are corresponding to the density of the vertical electron content beneath the satellite during October 21st. The figure shows asymmetrical equatorial anomaly of the global TEC.

RESULTS AND DISCUSSIONS
The case study of the ionospheric response to the magnetic storm of 21 October 1999 has revealed many interesting features. The SSC occurred on October 21st at 22UT as a result of southward turning of IMF Bz, after which the $D_s$ index reached its minimum value of $-240$ nT.

The simultaneous sudden decrease in the AE index synchronized with the sudden southward Bz intensity variation occurred on 21st at 22UT was the signature of the penetration of an eastward disturbance electric field.
We used a new more general method to analyze the data from the 11 stations used in this study. According to that analytical method, the $\sigma F_2$ data has been normalized to a central location. It was interesting that all the stations distributed in both northern and southern hemispheres having the same $\sigma F_2$ trend during the storm (Fig. 3), which allowed us to study the global ionospheric response of such magnetic storm. A regular daily variation of $\sigma F_2$ within the frequency range 3.5–11 MHz occurred on the undisturbed day of 20th.

As seen in Fig. 5, the $D\sigma F_2$ showed a significant negative low amplitude deviation observed during the storm main phase, reaching its maximum value -55% on 22nd at 09UT. This is a well-known negative ionospheric storm response. One the other hand, the positive enhancement (or peak) was also observed two times in the $D\sigma F_2$ curve.

Positive effects sometimes are being observed before the beginning of the magnetic disturbances. Some papers (Danilov and Belik, 1991, 1992; Danilov, 2001) suggests for this effect mechanism associated with soft particle precipitation in the region of the dayside cusp. Another possibility is due to the north crest movement to higher latitudes because of the storm time electric fields (Prölss, 1993).

The first maximum occurred on 21st at 00UT. We don't have an explanation of that peak except that this time is almost coincident with the arrival time of the shock associated with the ejecta from the CME, which caused the magnetic storm of our study as verified from Cane H.V. and Richardson I.G. (2003). The arrival time of that shock has been detected by ACE satellite on 21st at 02UT. This could be an explanation of the enhancement in the $D\sigma F_2$ due to the injection of the energetic particles accelerated by the shock. Further analysis is required regarding this research point.

The second peak occurred just before the beginning of the negative phase of $D\sigma F_2$. It is in harmony with the results of Danilov & Belik, (1991, 1992) and Danilov (2001) who detected such behavior during some geomagnetic storms.

The difference between the horizontal component of the geomagnetic field $H$ at the equator and non-equator locations was used as indicator of the vertical $E \times B$ drift. It was interesting to notice such coincidence in the behavior of both $E \times B$ drift (Fig. 5) and $D\sigma F_2$ (Fig. 6) curves during the storm, which sustain the signature of the penetrating electric field during the SSC onset.

An enhancement of both fluxes and velocities of ions and electrons has been detected by DMSP F13, while, TOPEX results showed asymmetrical equatorial anomaly of the global TEC measured during the storm.

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REFERENCES


