

Ionospheric Precursors of Geomagnetic Storms.

1. A Review of the Problem

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Abstract—The problem of the occurrence of disturbances of the ionospheric $F2$ -layer parameters prior to the beginning of a geomagnetic storm is discussed. It is shown that disturbances (substantial deviations from quiet conditions) of both the critical frequency $foF2$ and the total electron content (TEC) in an ionospheric column are found in many studies a few hours and sometimes even two days before the SC (sudden storm commencement) moment. The amplitudes of the aforementioned disturbances are on average of 30–60%, however, they can exceed 100% in some cases. Deviations from the quiet conditions of both signs are possible; however, positive prestorm disturbances of $foF2$ and TEC are more common.

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1. INTRODUCTION

The problem of ionospheric disturbances (storms) accompanying geomagnetic disturbances is widely known, and there are dozens of papers on this problem. We note only the most known reviews (Prolls, 1995; Rees, 1995; Buonsanto, 1999; Danilov, 2001; Danilov and Laštovička, 2001). Information on later studies can be found in a review of one of the authors (Danilov, 2013a, b).

The research on ionospheric storms mainly focuses on the analysis of the behavior of the ionospheric $F2$ -layer parameters ($foF2$ and/or $hmF2$) immediately after the storm onset (in the majority of cases, it is the sudden commencement (SC)) during the phase of storm expansion (a sharp decrease in the Dst index) and the recovery phase (a slow increase in the index). Only in some publications on particular geomagnetic storms is attention paid to the presence (or absence) of substantial disturbances in ionospheric parameters in the period preceding the SC.

In this paper we focus on the behavior of the ionospheric $F2$ layer during the two days preceding the sudden commencement of a magnetic storm without discussing the complicated picture of positive and negative anomalies in the behavior of this layer (so called positive and negative phases of ionospheric storm) during the magnetic storm itself. That picture is very complicated, and only some of its details are currently known (for details, we refer readers to the aforementioned reviews), because several complicated processes of both meteorological and electrodynamic

character participate in the formation of positive and negative phases.

In the review by Danilov (2013a, b), which mainly concerns the behavior of the $F2$ region during geomagnetic storms, there is a small section on prestorm effects in the ionosphere. For a complete presentation, we will briefly repeat here part of the material of that section.

2. PREHISTORY OF THE PROBLEM

Kane (1973a, b; 1975) was the first to point out that there is sometimes a positive phase of an ionospheric storm before the SC of a magnetic storm. Danilov and Belik (1991, 1992) emphasized the existence of this effect and were the first to present by the superposed epoch method examples of several storms with the prestorm effect in one figure (see also Danilov (2001)).

In some papers on ionospheric storms, attention was later paid to the occurrence of a positive or negative disturbance of $foF2$ or $hmF2$ several hours or even a day before the SC of the geomagnetic storm; however, these papers focus on the behavior of these ionospheric parameters directly during the geomagnetic storm.

Kane (2005) and Buresova and Laštovička (2007) performed detailed studies of the problem of positive ionospheric disturbances preceding magnetic storms. Some of their results will be presented in the next section.

Blagoveshchensky and Kalishin (2009) performed a detailed study of positive phases of ionospheric storms preceding the SC. They presented many exam-

ples of positive ionospheric disturbances beginning 6–8 h prior to the phase of geomagnetic storm expansion.

Mikhailov and Perrone (2009) critically analyzed the results of previous publications by Danilov (2001), Buresova and Laštovička (2007, 2008), and Kane (2005), which concern the problem of prestorm f_oF2 enhancements. They classified the effect as a “delusion” and explained the observed prestorm enhancements by several “normal” factors, such as an increase in auro-ral activity or a durable (several days) increase in the critical frequency that is unrelated to the considered storm (so-called Q disturbances).

We will present and discuss in Section 3 the most visual examples of the presence of phases (both positive and negative) of ionospheric storms prior to the geomagnetic disturbance published by various authors. We plan to present in two later publications in this series the results of our own studies of the occurrence of ionospheric disturbances prior to the SC of geomagnetic storms and their dependence on both the characteristics of the following magnetic storm and various “external” conditions (local time, season, latitude).

It should be noted that, considering the results of the vertical sounding (VS) of the ionosphere, both in publications of other authors and in our own studies, we will discuss only the behavior of the critical frequency f_oF2 . Although the changes in the $F2$ -layer height $hmF2$ are also presented in some studies, we will not consider them, because the determination of $hmF2$ (which cannot be obtained directly from VS ionograms but should be recalculated from the M3000 parameter) is much less reliable than the determination of f_oF2 (especially during disturbances in which the underlying E -layer state could vary strongly).

Many publications on the ionospheric effects of magnetic storms based on the values of the total electron content (TEC) in the ionospheric column obtained by various positioning systems (GPS, GLONASS, etc.) appeared in the recent decade.

As in the majority of other publications, we will discuss changes in the critical frequency in terms of the Δf_oF2 value, which presents the relative deviation of f_oF2 from quiet conditions (various papers take either the quiet day nearest to the storm or the monthly median) as a percent:

$$\Delta f_oF2 = (f_oF2_{\text{obs}} - f_oF2_{\text{qui}}) / f_oF2_{\text{qui}},$$

where f_oF2_{obs} and f_oF2_{qui} are the critical frequencies observed in the analyzed period and in quiet conditions.

A similar expression is usually also used for the changes in TEC:

$$\Delta \text{TEC} = (\text{TEC}_{\text{obs}} - \text{TEC}_{\text{qui}}) / \text{TEC}_{\text{qui}}.$$

It should be noted that the conclusions on TEC behavior seem to be less reliable than the conclusions on the critical-frequency behavior, because measurements of the latter are conducted in one place, directly

in the ionosphere above the VS station, whereas satellite measurements are carried out under different zenith angles of the satellite. Therefore, the slant values of TEC are recalculated into vertical ones, which introduces additional uncertainties into the results (e.g., Shimeis et al. (2015)). Moreover, it is not clear whether the effects registered in TEC manifest changes only in the F region, because the TEC measurements are able to cover the outer ionosphere and even the lower part of the plasmasphere. Nevertheless, since many studies of the ionospheric behavior during magnetic storms have been carried out in the last decade based on TEC measurements, we will consider the prestorm effects registered in some of these measurements in the second part of the next section.

Various authors use different terminology in describing the storm intensity. We will follow the terminology accepted in the review of one of the authors (Danilov, 2013a, b): weak ($-50 \leq Dst_{\text{min}} \leq -30$ nT), moderate ($-100 \leq Dst_{\text{min}} \leq -50$ nT), and intense ($Dst_{\text{min}} < -100$ nT). Intense storms, in turn, are subdivided into strong ($-200 \leq Dst_{\text{min}} \leq -100$ nT), very strong ($-350 \leq Dst_{\text{min}} \leq -200$ nT), and prominent ($Dst_{\text{min}} < -350$ nT).

3. ANALYSIS OF PARTICULAR STORMS

3.1. Behavior of Δf_oF2

Kane (2005) presented an excellent example of the occurrence of positive disturbances on October 28, 2003, the day preceding the commencement of a prominent magnetic storm.

The fact that more or less similar (in shape and amplitude) positive phases were observed at a majority of VS stations excludes the possibility that the effect was an occasional one.

A prestorm increase in f_oF2 is seen in the figures in Araujo-Pradere and Fuller-Rowell (2002) papers (Fig. 1 taken from Kane, 2005); however, the authors do not discuss this effect. Kane (2005) attempted to compare the f_oF2 behavior observed during and before the strong storm of April 6–7, 2000 ($Dst_{\text{min}} = -200$ nT), with prediction by the empirical STORM model (Araujo-Pradere and Fuller-Rowell, 2002). The results of the comparison are shown in Fig. 1 (taken from Kane (2005)) and show that the model poorly describes the f_oF2 behavior after the SC and says nothing of the strong positive phases before the SC detected at both stations.

Blagoveshchensky et al. (2003) analyzed 41 geomagnetic disturbances observed at Sodankylä (67° N, 26° E) ionospheric station. The majority of the considered disturbances were geomagnetic substorms; however, there were also storms with sudden commencement. As one of the main conclusions, the authors of that paper formulate a statement that “the increase in f_oF2 values in comparison with their quiet

median begins 6–8 h prior to the T_0 moment of the beginning of the active (expansion) phase of the magnetic storm.” According to these authors, the $foF2$ value reaches its maximum 3–4 h prior to the T_0 moment and decreases below the quiet level to the T_0 moment.

The paper by Blagoveshchensky et al. (2017) concerns the ionospheric reaction to space-weather disturbances before, during, and after the disturbance. A broad set of problems (various manifestations of the space weather, behavior not only of $foF2$ but of $foEs$ as well, etc.) is considered in that paper. Two points are important for our consideration. First, the results of Blagoveshchensky et al. (2003) were actually confirmed based on a broader set of material (72 geomagnetic disturbances, ionosondes within a latitudinal interval of 40° – 70° N in Europe, Siberia, and North America). Second, the results of the analysis of the data for all stations and all storms were summarized in the form of a very visual Fig. 2 taken from Blagoveshchensky et al. (2017).

Figure 2 graphically illustrates the statement presented above about a positive disturbance in $foF2$ with a maximum 3–4 h prior to the T_0 moment and a decrease of $foF2$ directly before this moment. Another figure in Blagoveshchensky et al. (2017) shows the $foF2$ behavior prior to and during five quite strong magnetic storms. The figure demonstrates that a positive ionospheric disturbance is observed in all five cases, although the amplitude of this disturbance is different for different storms and does not correlate directly to the storm intensity, which is characterized in that case by the ΣKp value.

Having analyzed the magnetic storms of 2008–2012 according to the Sodankylä VS data, Blagoveshchensky (2014) concluded that there was a so-called main effect (ME) for all of the considered storms. Its essence is that the first maximum in the $foF2$ occurs a few days prior to the beginning of the active phase of a magnetic storm; then, during the active phase, the $foF2$ minimum takes place, and a second maximum then forms after the active phase. According to Blagoveshchensky (2014), the ionosphere has a “memory” (inertia) from 8–9 h to two days. The occurrence of the first ME maximum could be considered a precursor of magnetic storms, and such a precursor could potentially be used to forecast the development of the subsequent magnetic storm.

In the aforementioned paper, Blagoveshchensky and Kalishin (2009) suggested that the channel of solar-wind energy penetration during prestorm enhancements of $foF2$ differs from the channel that acts during the storm itself. The former channel transports energy through the entrance layer into the magnetosphere and through the dayside cusp into ionosphere (as assumed by Danilov and Belik (1992)). According to Blagoveshchensky and Kalishin (2009),

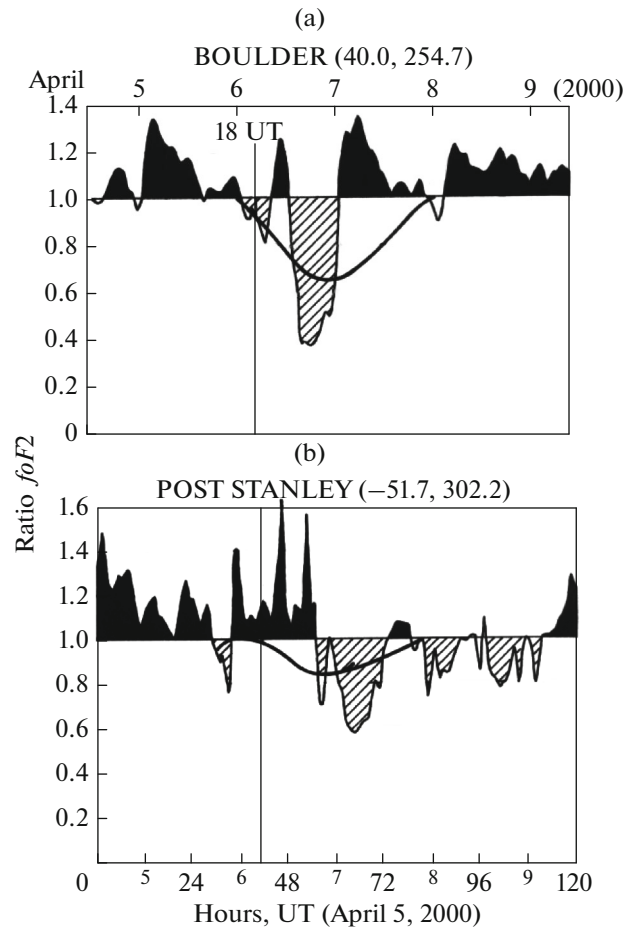


Fig. 1. $foF2_{\text{obs}}/foF2_{\text{qui}}$ ratio for April 5–9, 2000 (the storm occurred on April 6–7) for Boulder and Port Stanley stations (taken from Araujo-Pradere and Fuller-Rowell, 2002). The thick curve shows the prediction by the STORM empirical model, and the full curves are the observed values. Positive deviations are painted black, and negative deviations are shown with hatchmarks (from Kane, 2005).

the prestorm enhancement of $foF2$ could be used to predict the coming magnetic storm.

Buresova and Laštovička (2007) analyzed 65 strong geomagnetic storms observed in 1995–2005 and looked for cases of prestorm enhancement using the data of eight ionospheric stations located in the European region. They found that quite strong prestorm increases of $foF2$ ($NmF2$) preceded geomagnetic storms in approximately in 20–25% cases. Buresova and Laštovička (2007) found also that the prestorm increase of $foF2$ occurs both in the daytime and at night and revealed seasonal variations in the frequency of the prestorm $NmF2$ enhancements. These enhancements tend to occur more often in the summer half of the year. However, the number of events is rather small, so Buresova and Laštovička (2007) suggested that the obtained seasonal distribution of prestorm events be considered only a tendency. However, this seasonal variation (if it does exist) is very important in

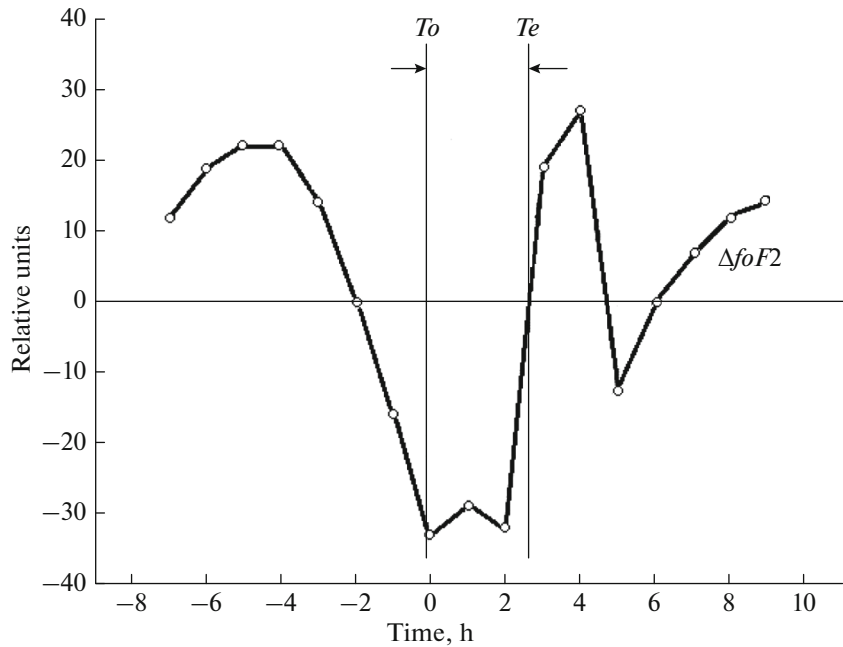


Fig. 2. Variations in the $\Delta foF2$ value averaged over 72 storms (from Blagoveshchensky et al. (2017)).

the search for sources of prestorm events, because it shows that these events are not related to seasonal variations of occurrence of strong geomagnetic storms: the majority of geomagnetic storms occur in the equinox periods. Buresova and Laštovička (2007) failed to detect any systematic latitudinal dependence of the prestorm $foF2$ increases. No corresponding changes in $hmF2$ were detected.

Figure 3 (taken from Buresova and Laštovička (2007)) presents a typical example of a strong $NmF2$ enhancement prior to the prominent storm of October 29,

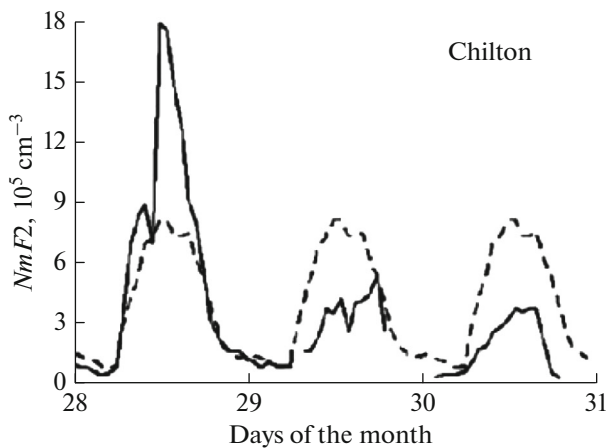


Fig. 3. Effects of the prominent magnetic storm of October 29, 2003, in $NmF2$ at Chilton station. The $NmF2$ reaction is shown (hourly values): the solid and dashed curves correspond to the measured values and the monthly median, respectively (from Buresova and Laštovička (2007)).

2003 ($Dst_{min} = -388$ nT), according to the vertical sounding data at Chilton station. It is seen that an $NmF2$ increase by approximately a factor of 2.5 occurs approximately 18 h prior to the SC (at 0611 UT on October 29).

Using data from 12 ionospheric stations of the Northern Hemisphere covering the entire interval of longitudes, Buresova and Laštovička (2008) analyzed 15 prominent storms occurring in 1995–2005. They found that all of the considered storms over European area were accompanied by a significant ($>20\%$) $foF2$ increase before the storm onset.

The attempt to determine the height profile of the prestorm enhancements, particularly the presence of the effect in the ionospheric $F1$ and E layers, was a new element in studies of the prestorm effects. Buresova and Laštovička (2008) found no systematic effects of prestorm Ne enhancements in the $F1$ layer. Neither were there any prestorm enhancements in the E region. Actually, Buresova and Laštovička (2008) found that the prestorm increase is restricted by the $F2$ layer. Figure 4 shows an example of the Ne vertical distribution during the prestorm period according to Chilton station (Buresova and Laštovička, 2008). The solid and dashed curves show the observations on July 22, 2004, prior to the SC of the geomagnetic storm (1500 UT) and the monthly median, respectively. A substantial Ne increase is distinctly seen in the F region prior to the storm as compared to quiet conditions.

The latitudinal extent of prestorm enhancements was found to be 120° – 240° based on a comparison of simultaneous $foF2$ measurements in Europe, North

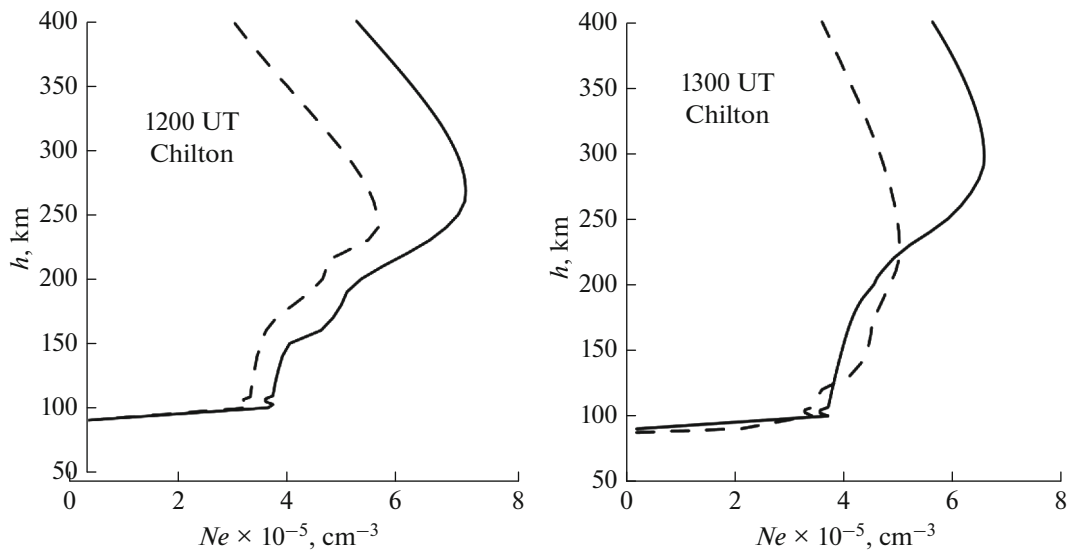


Fig. 4. Vertical distribution of the electron concentration on July 22, 2004, according to the Chilton station data from Buresova and Laštovička (2008) (see text).

America, and Eastern Asia. It should be noted that Buresova and Laštovička (2008) found only weak prestorm effects before that storm in the American and Eastern-Asian longitudinal sectors.

Prior to the very strong storm of July 15, 2000 ($Dst_{\min} = -300$ nT), positive phases with an amplitude up to 30% were observed at the midlatitude stations Hobart and Canberra (Southern Hemisphere) and Leningrad and Wallops Island (Northern Hemisphere) (Mansilla, 2007).

During the very strong storm of November 24, 2001 ($Dst_{\min} = -224$ nT), Nogueira et al. (2011) found an increase in the $\Delta foF2$ parameter at ~ 2000 LT on November 23, whereas the storm commenced at 0400 LT on November 24. Figure 2 in Nogueira et al. (2011) shows that at least until the midnight of November 23–24, all of the magnetic parameters (Dst , AE , Bz , Ey) were at absolutely quiet level.

Analyzing the global ionospheric response to the moderate geomagnetic storm of August 3, 2010 ($Dst_{\min} = -90$ nT), in three longitudinal sectors (Asia/Pacific, Europe/Africa and America), Mansilla and Zossi (2012) found that one of the main ionospheric effects of the considered storm was the fact that Japanese, Australian, and American stations showed a well-pronounced $foF2$ increases 4–5 h prior to the storm, irrespective of the local time.

In their later papers, Mansilla (2014) and Mansilla and Zossi (2016) considered observations by the VS method at stations in the American sector during some other storms. Both positive and negative ionospheric disturbances were observed prior to the SC. An especially strong positive phase was observed prior to the SC of a prominent magnetic storm of October 29, 2003 (which was also analyzed by Buresova and Laštovička

(2008), see above). The maximal $\Delta foF2$ value reached 120% at Jicamarca and Tucuman stations and 90% at Ascencion station (Mansilla, 2014). The positive ionospheric disturbance lasted from 6 to 15 h.

Patowary et al. (2013) analyzed 40 magnetic storms of the 1970–1980s, including eight VS stations of the Far-east and Australian regions. The main goal of the paper was to study seasonal and latitudinal differences in the ionospheric reaction to magnetic storms during the storms. However, the figures presented in the paper show that positive ionospheric disturbances were observed before the SC at many stations. Unfortunately, Patowary et al. (2013) present the absolute values of $\Delta foF2$ in MHz but not the relative values in percent as the majority of authors do, so it is difficult to understand from the figures whether these positive disturbances were substantial. However, Fig. 3 in Patowary et al. (2013) shows (and the authors pay attention to this fact) that substantial $\Delta foF2$ enhancements were observed 3–4 h prior to the SC of the March 26, 1976, storm at all six stations shown in the figure.

Liu et al. (2014) analyzed the $foF2$ behavior at the stations of the Far-eastern and Australian regions during the magnetic storm with an SC at 0000 UT on July 15, 2012. They found that positive values of $\Delta foF2$ of the order of 20–30% were observed 10–14 h prior to the SC at Beijing, Wuhan, and Sanya stations. $\Delta foF2$ values that were the same in amplitude but negative were observed over the entire day (in UT) of July 14 at Darwin, Townsville, and Brisbane stations.

Adekoya et al. (2012a) considered some peculiarities of the ionospheric reaction observed in the equatorial and midlatitude regions to two very strong geomagnetic storms of October 19–23, 2001, and May 13–17, 2005

($SYM-H_{min} = -300$ nT). The relation of the prestorm phenomena to the ionospheric behavior during the geomagnetic storm itself was of particular interest. Adekoya et al. (2012a) found that moderate disturbances of the ionospheric $F2$ layer in the prestorm period could foretell a strong ionospheric disturbance during the main phase of the geomagnetic storm. The reaction of the ionospheric $F2$ layer at low and middle latitudes does not differ strongly in the period of the storm main phase or the prestorm period. The ionospheric reaction during the prestorm period looks astonishing. Adekoya et al. (2012a) found that weak and moderate negative phases were observed in the prestorm period at all stations located at low and middle latitudes.

Adekoya et al. (2012b) studied a moderate geomagnetic storm of April 2–6, 2004 ($Dst_{min} = -101$ nT), using data from the ground-based ionosondes at mid-latitudes. The latter were split to high–mid and low–midlatitudes. Adekoya et al. (2012b) found that the $foF2$ behavior during the main phase of a magnetic storm depends on the $foF2$ behavior in the prestorm period (in a different way from different latitudinal zones). At low–midlatitude stations, the positive–negative phase in Ne behavior (a PN storm) that forms in the prestorm period predicts an intense negative storm during the main phase of the magnetic storm. At high–midlatitudes and low–midlatitudes, the PN and NP ionospheric storms in the prestorm period predict strong negative and intense positive phases, respectively, during the main phase of the magnetic storm.

Adekoya et al. (2013) conducted a detailed analysis of the prestorm $foF2$ effects in six magnetic storms in 2000–2005 based on eight VS stations located within the latitudinal range from 33° S to 36° N. They found that, prior to the storm of April 6, 2000 (SC at 1200 UT), the maximal $\Delta foF2$ value at Darwin station (13° S) was 55% at 0600 UT. This value exceeded 20% for 5 h in the first half of April 6. Two hours prior to the SC of the July 15, 2000, storm, the $\Delta foF2$ value at Point Arguello station (36° N) was -40% .

According to Adekoya et al. (2013), the $\Delta foF2$ values at Darwin station reached 130% at 0600 UT on September 16 and 17, 2000, during the September 17, 2000, storm (SC at 1330 UT). Overall, on September 16 and 17 (before SC), the $\Delta foF2$ value exceeded 60% for 22 h. During the same storm, the $\Delta foF2$ value at Louivale station (29° N) was negative (-50%) at 1900 UT on September 16, 2000.

Prior to the March 30, 2000, storm (SC at 2300 UT), the $\Delta foF2$ value was $\sim 30\%$ from 0700 UT to 1200 UT at Dyess station (32° N) and 20–30% from 0200 UT to 1300 UT at Eglin station (30° N), whereas a peak in $\Delta foF2$ ($\sim 75\%$) was observed at Darwin station approximately 6 h prior to the SC. Prior to the April 11, 2001, storm (SC at 1200 UT), peaks in $\Delta foF2$, which reached 60% at 0700 UT on April 10 and 45% at 0500 UT on April 11, were registered at Eglin station. Before the

SC of the August 24, 2005, storm (0030 UT), the $\Delta foF2$ value at Puerto Rico station (19° N) was -60% at 2200–2300 UT on August 23.

Mahrous (2007) considered the $foF2$ reaction to the very strong storm of October 21, 1999 (SC at 2200 UT, $Dst_{min} = -240$ nT), averaging the observations at 11 VS stations within the latitudinal range from 60° N to 52° S. He found that, according to the averaged data, the first $\Delta foF2$ increase began at 2000 UT on October 20 and reached a maximum of 30% at 0000 UT on October 21; $\Delta foF2$ then decreased for 3 h.

Bakare and Chukwuma (2010) analyzed the data from two geomagnetic storms (on April 14, 2006 and August 24, 2005) at the VS stations of the American region. They found a positive ionospheric storm phase ($\Delta foF2$ from 20 to 30%) with a maximum approximately 3 h prior to the SC of the April 14 magnetic storm at all stations (Boulder, Dyess, Eglin, and Puerto Rico). During the August 24 storm, a negative phase with a maximum of $\sim 50\%$ was observed at all stations ~ 8 h prior to the SC. However, it should be noted that estimates of the presence or absence of ionospheric effects prior to the considered magnetic storm depend on the moment (UT) at which the SC is taken. The Dst index demonstrated a small increase (up to 32 nT) from 0000 UT to 0800 UT, when a sharp decrease began. If, as is often done, one takes as the SC the moment of the sharp decrease in Dst , the changes in the critical frequency presented above refer to the prestorm period and are of interest for our consideration. If one takes the 0000 UT moment as the SC, the values indicated above fall in the period of the storm itself and are irrelevant to our consideration.

The $foF2$ behavior during the same storm of August 24, 2005, was analyzed by Adebessin and Adekoya (2013). They also found a negative phase ~ 3 h prior to the SC with an amplitude of 30–40% at Darwin and Puerto Rico stations but found no substantial $foF2$ deviations from the quiet values at stations Learmonth and Dyess. Positive $\Delta foF2$ values of 20–40% were observed at Eglin station. These $\Delta foF2$ values correspond to the period before 0000 UT, which surely precedes the storm beginning.

Adekoya and Adebessin (2015) analyzed six very strong storms of 2000–2005 according to VS data at low-latitude and midlatitude stations. The storm of April 6, 2000 ($Dst_{min} = -288$ nT), began at 1200 UT. Already on the morning of April 5, negative $\Delta foF2$ values (-34% at 0300 UT) were observed for several hours at Darwin (13° S) station. A positive $foF2$ disturbance (with a maximum of $\Delta foF2 = 54\%$ at 0600 UT) was registered in the morning on April 6. During the very strong storm of July 15, 2000 ($Dst_{min} = -301$ nT), the $\Delta foF2$ value at Learmonth (22° S) station increased to 42% 12 h prior to the SC. At Grahamstown station, this value decreased to approximately -30% 9 h prior to the SC, whereas it stayed at a level of -30% at Juliusruh station (55° N) 5–9 h prior to the SC.

A magnetic storm with $Dst_{\min} = -201$ nT began at 1300 UT on September 17, 2000. A very strong positive disturbance with $\Delta foF2 \sim 170\%$ was observed at Darwin station on September 16 and 17 from 0000 UT to 1200 UT. Between these positive disturbances, the $\Delta foF2$ value decreased to -40% at 1800 UT on September 16. A negative disturbance ($\Delta foF2 = -60\%$ 7 h prior to the SC) was observed at Juliusruh station.

Prior to the March 31, 2001, storm ($Dst_{\min} = -387$ nT; SC at 0000 UT), strong positive disturbances (90% on March 29 and 80% on March 30) were observed at 1700 UT at Darwin station. At Grahamstown station (33° S), the $\Delta foF2$ value decreased to -40% at 2300 UT on March 29. For two days prior to the storm of April 11, 2001 ($Dst_{\min} = -271$ nT; SC at 1200 UT), negative disturbances with a minimal $\Delta foF2 = -55\%$ at approximately 2200 UT were observed at Learmonth station on both April 9 and 10. A positive disturbance with a maximum of 0.55% at 0500 UT on April 11 was observed at Juliusruh station.

Prior to the August 24, 2005, storm ($Dst_{\min} = -216$ nT; SC at 0300 UT) the prestorm effects were observed only at Darwin station. The $\Delta foF2$ value reached 45% at 1200 UT on August 22.

Buresova et al. (2014) considered weak geomagnetic storms during the solar activity minimum. During the disturbance of January 4–9, 2008, they found at Pruhonice station a positive disturbance, with $\Delta foF2$ reaching 40% a few hours before the beginning of a substantial increase in Dst , which was then changed by a slow decrease. No substantial $foF2$ deviations from the median were observed at Grahamstown station. Positive $\Delta foF2$ values with an amplitude of 20–40% were registered during approximately the same period as at stations of the American region (Millstone Hill and Port Stanley).

Mandrikova et al. (2018) analyzed the $foF2$ behavior at three stations (Paratunka, Wakkanai, and Norfolk) during three storms of 2015. They determined $foF2$ deviation from quiet conditions with a method slightly different from that usually used. A description of the method can be found in Mandrikova et al. (2015). Mandrikova et al. (2018) obtained strong and long positive $foF2$ disturbances before the SC of the corresponding magnetic storm for all three storms at all three stations. The duration of these disturbances was ~ 40 h for the storm of March 17, 2015, about 8 h for the storm of December 19, 2015, and 22–24 h for the storm of February 17, 2015.

According to Berényi et al. (2018), the $foF2$ values at Nagycenk station (Hungary) during the strong storm of November 12, 2012, substantially exceeded the background values in the daytime during the two days preceding the SC. It was impossible to determine the $\Delta foF2$ values, because the critical frequencies were above the upper limit of ionosonde sensitivity. According to measurements at the same station during the day preceding the SC of the March 17, 2013, storm, the $foF2$

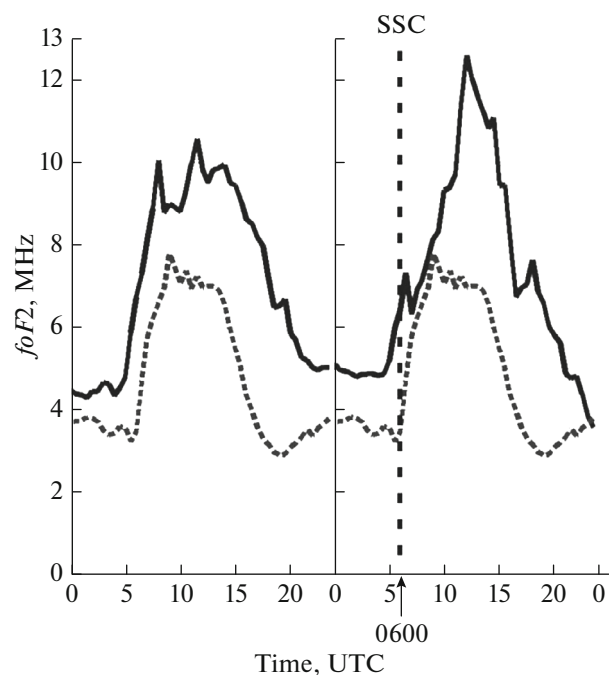


Fig. 5. Variations in $foF2$ during March 16–17, 2013, according to Berényi et al. (2018). The solid and dashed curves show the measurements on March 16 and 17 and the background values, respectively.

value in the daytime was approximately 10 MHz, whereas the background $foF2$ value was 7–7.5 MHz (Fig. 5 taken from Berényi et al., 2018).

According to Ghodpage et al. (2018), the VS measurements at the low-latitude Tirunelveli station show an $foF2$ increase at night of March 17 from 0500 to 0700 LT (a very strong magnetic storm with the minimal $Dst \sim -220$ nT began at 0945 LT on March 17) as compared to the night on March 16 (a quiet day). According to Fig. 4 in Ghodpage et al. (2018), a $foF2$ decrease was observed in the first half of the day on March 16 with a minimum of ~ 6 MHz at 1100 LT. Although the $foF2$ behavior in the other quiet day is not discussed by Ghodpage et al. (2018), the aforementioned figure shows that the undisturbed critical frequency in that time should not be lower than 10 MHz.

Grandin et al (2015) used the superposed epoch method to conduct a statistical analysis of 95 events of the arrival of high-velocity solar-wind fluxes on the Earth. They considered the ionospheric reaction with the use of measurements at Sodankylä ionospheric station. The moment of the arrival of these fluxes in the magnetopause was taken as the reference point (moment 0). It follows from Fig. 1 in Grandin et al (2015) that this moment almost coincides with the SC moment, as determined by the $SYM-H$ index. The analysis shows that, during the day preceding moment 0 (day -1), the upper and lower quartiles deviate by ~ 1 MHz above and below the median, respectively, whereas all three curves coincide or differ slightly during the previous day (day -2).

This shows that both positive and negative $foF2$ deviations from the median are observed quite often during the day preceding the SC. This effect is well pronounced for winter months, whereas it is much weaker in summer and is almost absent in equinoxes.

Lei et al. (2018) analyzed the magnetic storm with an SC at 2100 UT on September 7, 2017, and with a minimal Dst index equal to -147 nT on September 8. The analysis was based on observations at three VS stations of China and TEC measurements (see the results in the second half of this section). The VS data showed that a substantial excess of $NmF2$ over the monthly median (the maximal value of $\Delta NmF2$ reached 120%) was observed at 0300–1100 UT on September 7 at Shaouang station (27° N). No substantial deviations of $NmF2$ from the median were observed at Sanya (18° N) and Wuhan (31° N) stations.

Analyzing the strong magnetic storm of May 15, 2005, Galav et al. (2014) presented the results of VS observations at Alma-Ata station. It follows from these data (Fig. 2 in Galav et al., 2014) that the $foF2$ values for ~ 3 h were substantially lower than the $foF2$ value averaged over quiet days of the month and were far outside the limits of the $\pm 2\sigma$ band. During that period, the minimal $foF2$ value was ~ 4.2 MHz ~ 7 h prior to the magnetic storm SC.

Zolotukhina et al. (2017) analyzed in detail the magnetic storm of March 17–19, 2015. It follows from Fig. 7 of that paper that an excess of the observed $foF2$ values over the background values was detected at Dikson station 3 h prior to the SC (0500 UT on March 17). The amplitude of that excess reached a maximal value of $\sim 30\%$ 1 h prior to the SC.

Polekh et al. (2017) considered the ionospheric reaction to the same storm of March 17–19, 2015, using TEC data and observations at the VS stations of the Far-eastern region. Although that paper focused on the storm period itself, it follows from Fig. 3 in Polekh et al. (2017) that the $\Delta NmF2$ value was 50 at Zhigansk station (66° N) 5 h prior to the SC, % and gradually decreased to zero to the SC moment. The $\Delta NmF2$ value at Yakutsk station (62° N) 5 h prior to the SC was about 40% and decreased to zero approximately 1 h before SC. The $\Delta NmF2$ values at more southern stations during this period were within $\pm 20\%$.

3.2. Behavior of Δ TEC

Yizengaw et al. (2004) analyzed the TEC reaction to the strong magnetic storm of September 22, 1999, according to observations at seven reception points of the GPS system in the Southern Hemisphere. According to this paper, negative TEC deviations from quiet values were observed for 12 h before SC at four points with the southern latitude above 35° . The Δ TEC values were -30 to -85% , with the Δ TEC value at McMurdo point (78° S) staying at a level of approximately -80% for 9 h.

In order to reveal the behavior of the prestorm ionospheric disturbance at low latitudes under low magnetic activity, Liu et al. (2008a) analyzed the selected low-latitude events of TEC increases using TEC measurements by the receivers of the GPS global and regional networks. They analyzed the TEC behavior during the February 10, 2004 ($SYM-H_{\min} = -100$ nT), January 21, 2004 ($SYM-H_{\min} = -140$ nT), and March 4, 2001 ($SYM-H_{\min} = -75$ nT) storms. They found that low-latitude TEC enhancements were observed during the long period of low geomagnetic activity before the storm for all three considered storms. The TEC enhancements (Δ TEC) were on the order of 20–30 TECU prior to the February 10, 2004, storm. The TEC deviations from the median of ~ 20 –30 TECU and 30–40 TECU were observed for 1.5 days prior to the storms of January 21, 2004, and March 4, 2001, respectively.

Liu et al. (2008a) discovered a very important fact. The effect was of a regional character: the indicated Δ TEC values were observed only within a narrow longitudinal band with a center at 120° E. This fact is very important for the study of the nature of the prestorm effect. The local character of the TEC enhancements detected by Liu et al. (2008a) makes it more difficult to relate these enhancements to changes in the global parameters of the space weather and indicates its relation to regional effects, which are probably of the “coupling-from-below” type (e.g., oscillation of planetary waves).

Liu et al. (2008b) studied the enhancement of the electron concentration prior to three other geomagnetic storms (on April 21, 2001 ($Dst_{\min} = -120$ nT), May 29, 2003 ($Dst_{\min} = -150$ nT), and September 22, 2001 ($Dst_{\min} = -60$ nT)), using observations by ground-based ionosondes and TEC measurements along the 120° E meridian in the Asian-Australian sector. All three events demonstrated absolutely similar features. Strong prestorm increases in $foF2$ and TEC were observed simultaneously for these storms. The increases demonstrated a latitudinal dependence and had a tendency to occur at low latitudes with maxima near the northern and southern crests of the equatorial ionization anomaly (EIA) and minima in the equatorial region. Liu et al. (2008b) stated that the latitudinal dependence that they have obtained differs from the results of Buresova and Laštovička (2007), who found no latitudinal effect in the European region. However, the difference in the latitudinal and longitudinal intervals considered in two papers could provide a natural explanation for the difference in the obtained dependencies.

Saranya et al. (2011) also confirmed the existence of a regional effect in the prestorm enhancements of $foF2$ and TEC. They studied the prestorm effects over the Trivandrum equatorial station and Waltair low-latitude station for 18 storms with $Dst_{\min} < -100$ nT in 2000–2005. It was found that a substantial enhance-

ment of $foF2$ and TEC is usually observed prior to the beginning of the storm over Waltair station, whereas no enhancement is observed over Trivandrum station. Saranya et al. (2011) concluded that the Dst -index value does not influence the effects of prestorm enhancement. Since prestorm enhancement was observed both in the daytime and at night, it is clear that solar flares could not be the main mechanism responsible for the prestorm effects.

The TEC values in the Far-eastern, Australian, and American regions during the July 15, 2012, storm (SC at 0000 UT) were analyzed by Liu et al. (2014), as mentioned in the first part of this section. It follows from Fig. 2 in Liu et al. (2014) that local TEC enhancements with $\Delta\text{TEC} \sim 20\text{--}30\%$ were observed from 1200 UT on July 14 at latitudes from 0° to 50° N. Figure 6 in Liu et al. (2014) shows that the ΔTEC increase to $50\text{--}60\%$ began in the American region at latitudes of $0^\circ\text{--}60^\circ$ N approximately 5 h prior to the SC.

De Abreu et al. (2014) analyzed in detail the variations in VTEC (TEC in a vertical ionospheric column) values measured by the network of GPS receiving points of the South American and African regions during two moderate geomagnetic storms of May 2 and 29, 2010. The most interesting result for this study is that de Abreu et al. (2014) found a positive VTEC disturbance on May 1, 2010 (a geomagnetically quiet day), with a maximum approximately 17 h prior to the magnetic storm. As the authors note themselves (it is seen also in Fig. 3 in de Abreu et al., 2014), this positive disturbance was observed in the aforementioned time at mid- and low latitudes of the African sector. The disturbance amplitude decreased with a decrease of the latitude, and the disturbance was not observed at the reception points of the equatorial zone. No substantial prestorm VTEC effects were observed according to the measurements in the South African sector. No prestorm VTEC effects were observed during the magnetic storm with a gradual commencement on May 29, 2010.

The clearest example of VTEC changes prior to the May 2, 2010, storm is shown in Fig. 6 (taken from de Abreu et al., 2014). It is clearly seen (the authors themselves present this value) that, according to the measurements at the MBAR and MAL2 points, the VTEC increase on May 1 was about 70% as compared to the quiet conditions (i. e. $\Delta\text{VTEC} \sim 70\%$).

Shimeis et al. (2015) considered TEC variations measured at the Euro-African chain of the reception stations during the geomagnetic storm of April 5, 2010. Figure 3 of this paper, in which the TEC values for several reception stations for the storm period and quiet day are presented, shows that the data of at least four stations note an excess of TEC values during the period of 24–18 h prior to the SC over the TEC values on quiet day. The amplitude of that excess can be visually estimated as 20–50%.

Adebiyi et al. (2015) presented the TEC measurements at four points (two in the Northern (Hailsham (HERS) and Penc (PENC)) and two in the Southern (Port aux Francais (KERG) and Sutherland (SUTH)) Hemispheres) during four moderate geomagnetic storms. Prior to the SC of all four storms, substantial ΔTEC values of positive or negative sign were observed. Adebiyi et al. (2015) note that the strongest prestorm effects were observed before the storm of October 11, 2010 (SC at 0600 UT). A long negative ΔTEC deviation with an amplitude of 35% was observed at the HERS point ~ 1 day before the SC. The next negative deviation with an amplitude exceeding 40% began 8 h prior to the SC and lasted until the storm onset. A similar negative ΔTEC disturbance was observed during the same hours at the PENC point. At the KERG point, the negative disturbance began 14 h prior to the SC, lasted until the storm onset, and had an amplitude reaching 70%. At the SUTH point, “splashes” of a positive disturbance with a duration of 2–3 h and amplitude up to 40–60% were observed from 0500 UT on October 10, 2010.

Similar positive “splashes” of ΔTEC with durations of 2–3 h and amplitudes of 40 to 80% were observed at the PENC point from 0000 UT on November 29, 2006 before the SC of the geomagnetic storm at 2200 UT on that day. At the HERS point, a stable positive ΔTEC disturbance with an amplitude reaching 40% was observed from 1000 UT on November 29 until the SC.

Blagoveshchensky and Sergeeva (2019) analyzed in detail the strong magnetic storm of September 7, 2017, using the data of both vertical and oblique soundings of the ionosphere and TEC measurements. The paper focused on the influence of the aforementioned storm on the conditions of radio-wave propagation, so none of the usual data on $foF2$ behavior with time were presented. Just from the figure with ΔTEC data (Fig. 9 in Blagoveshchensky and Sergeeva, 2019), one can conclude the following. According to the measurements at Sverdlovsk point, an ΔTEC increase to $\sim 30\%$ was observed on September 6, 2017 (more than one day before the SC at 2000 UT on September 7). The next increase with a maximum exceeding 50% was observed on September 7, ~ 8 h prior to the SC.

The magnetic storm with SC at 2100 UT on September 7, 2017, was studied by Lei et al. (2018), as noted in the first part of this section. The TEC data were obtained at 25 and 6 reception points in the Northern and Southern Hemispheres, respectively. The excess of the observed TEC values over the median (the ΔTEC value was 20–30%) was observed at the JXNC (29° N), HSKD (31° N), and MHBG (54° N) reception points in the period from 0300 to 0900 UT on September 7. At the low-latitude DLTV (12° N) and SYBG (18° N) stations, small negative TEC deviations from the median were observed on September 6. Positive TEC deviations were observed

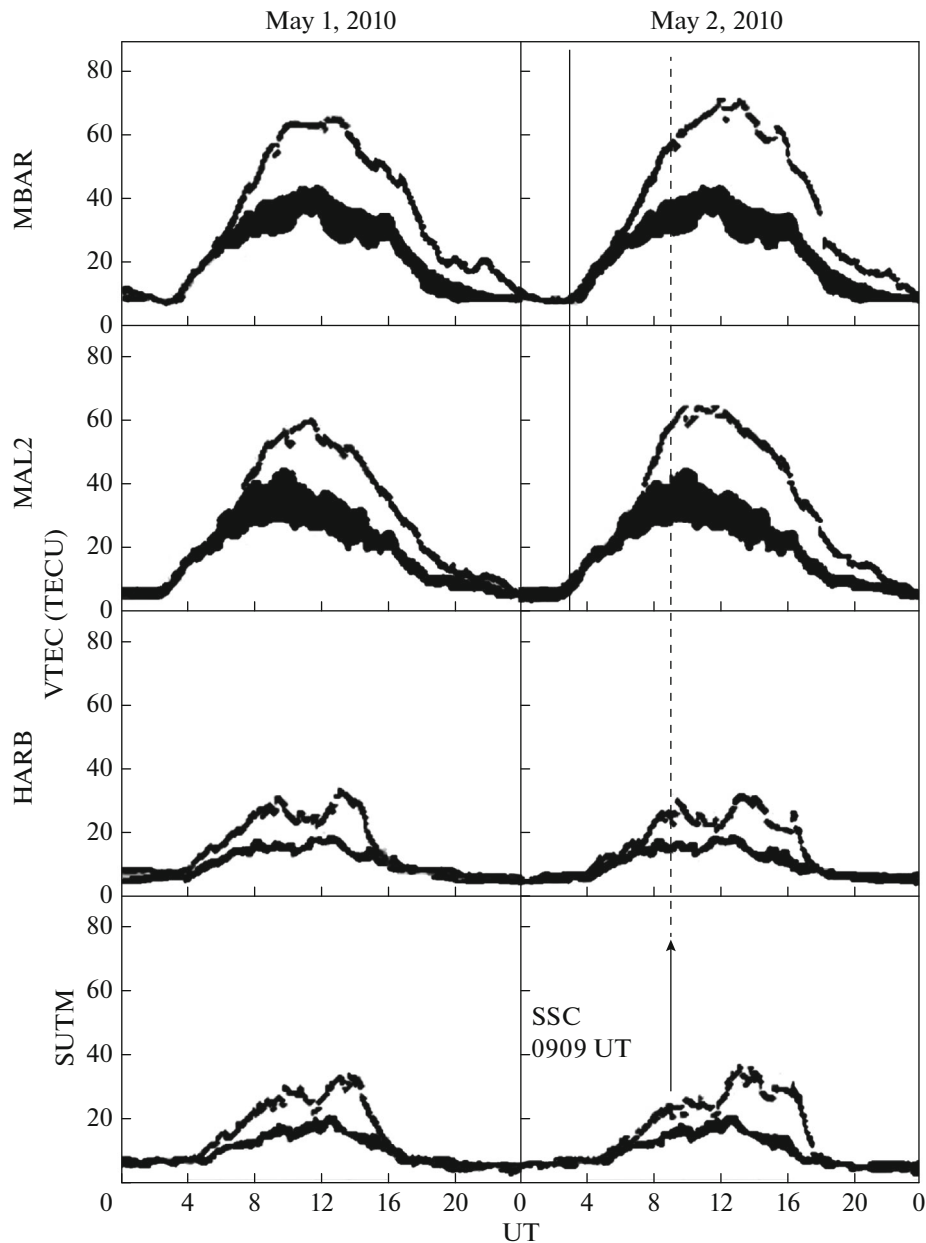


Fig. 6. VTEC variations on May 1 and 2, 2010, according to the measurements at four points (from de Abreu et al. (2014)). The curve and band show the real observations and the VTEC diurnal variation on a quiet day \pm the standard deviation. The GPS reception point codes are MBAR = Uganda, MAL2 = Kenya, HARB = Pretoria, SUTM = Sutherland.

on September 7 at all points of the Southern Hemisphere.

4. DISCUSSION AND CONCLUSIONS

It follows from the previous section that changes in the $F2$ -layer critical frequency f_oF2 and the ionospheric column TEC are registered quite often prior to the SC of the magnetic storm. These changes associated with the f_oF2 and TEC behavior in geomagnetically quiet conditions (Δf_oF2 , ΔTEC) on average are 30–60%; however, it can be much higher in some

cases, exceeding 100%. In the majority of cases, these deviations have a positive sign, but cases of negative deviations also have been registered.

The duration of the indicated changes can be from 2–3 h up to 6–8 h. The time interval between the registration of the maximal values of the deviations and the SC moment (the onset of the magnetic storm) is different in different cases. The indication of prestorm changes in f_oF2 and TEC 3–4 h prior to the SC are encountered most often. However, there are cases in which the considered changes precede the SC by many

hours and even by days. There are registered cases in which the substantial change in $foF2$ or TEC observed a few hours prior to the SC was registered also during the days preceding the day of the SC.

There is no clarity in the question on the dependence of the occurrence of $\Delta foF2$ or ΔTEC values on latitude. Although there have been attempts to find this dependence for several storms in the American, European, and Far-eastern longitudinal sectors (see the previous sections), it is still impossible to draw a clear picture of this dependence.

The problem of the physical mechanisms of the prestorm effect is absolutely obscure. It is clear that these effects should be related to some processes in the near-Earth environment, magnetosphere, and ionosphere. However, the question of the particular processes is still open. Danilov and Belik (1991) drew attention to the fact that the dayside cusp begins its equatorward motion a few hours prior to the appearance of other signs of the magnetic disturbance. It was assumed in many papers that the mechanisms of prestorm ionospheric effects are related to the electric fields. Various intermediate mechanisms of possible influence on the ionosphere of the so-called “interplanetary preshock regions” are considered in detail in a monography by Blagoveshchensky (2012).

The problem of prestorm changes in the ionospheric F region clearly requires further study. In the next part of this work, the authors plan to analyze the prestorm $foF2$ changes according to the data from two European VS stations, Slough (Chilton) and Juliusruh, for a large number of storms in order to reveal the dependence of prestorm effects on various external factors (local time, season, solar activity, etc.). For the next step, we plan to analyze prestorm effects for a limited number of specially selected magnetic storms based on data from the global network of VS stations in order to reveal the latitudinal and longitudinal dependence of these effects.

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