

F-Region Variations Prior to Magnetic Storms (a Review)

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Abstract—The paper presents a review of variations in ionospheric parameters in the prestorm period obtained from an analysis of particular magnetic storms (case studies). It is demonstrated that, as a result of such analysis, deviations of these parameters (primarily, $foF2$ and TEC) are often observed on the days preceding the storm commencement (SC). Many authors pay attention to these facts and discuss their relation to space weather parameters, season, local time, and spatial distribution, and even offer suggestions on possible mechanisms of their formation. It is demonstrated that the number of such publications increased substantially in the preceding 4–5 years. It is emphasized that changes in the ionospheric state on prestorm days are detected not only in the “classical” parameters ($foF2$ and TEC), but also in other ionospheric characteristics. Publications dedicated directly to the problem of ionospheric precursors, their relation to space weather, and their possible role in forecasting coming magnetic storm are considered in detail.

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1. INTRODUCTION

The problem of changes in ionospheric parameters in the period preceding a magnetic storm is of interest for studying the physics of the processes in the near-Earth environment during changes in space weather, as well as in the applied aspect if these changes could be precursors of a coming magnetic storm. We refer the reader to the review papers by Blagoveshensky (2012), Blagoveshensky et al. (2017), Danilov (2013), and Danilov and Konstantinova (2019) for a detailed description of this problem.

We note here only the pioneer papers by Kane (1973, 1975) and the first attempts to discuss possible causes of the prestorm effects in the ionosphere (Danilov et al., 1985; Danilov and Belik, 1992). Later, observations of these effects in various parameters of the ionospheric $F2$ layer ($foF2$, $hmF2$, $h'F2$, TEC) were considered in many papers, which are described in the aforementioned reviews.

Many new studies on the ionospheric response to magnetic storms have appeared since our review (Danilov, 2013). In the vast majority of cases, these were so-called case studies, i.e., descriptions of changes in the space weather parameters and corresponding variations in the ionospheric $F2$ layer characteristics. Insofar as the main goal of such works was to study the behavior of these characteristics at different storm stages (the main and recovery phases), their entire focus was the behavior after storm commencement (SC). However, some papers briefly or in detail discussed changes in the ionospheric characteristics

1–3 days prior to SC. These changes were shown in the corresponding figures in almost all publications. Thus, even if some article did not mention the prestorm days at all, it was possible to estimate deviations of the analyzed parameters from quiet conditions at various times prior to SC. Our present review is based on all information on the behavior of the ionospheric parameters on prestorm days that we were able to find in every work.

It should be noted that several such studies after 2019 have already been mentioned in the discussion in (Danilov, 2022). For the sake of consistency, we briefly consider these publications here as well.

Let us note some important points. In the majority of cases, we had to read the values of the ionospheric parameters ($foF2$, $hmF2$, TEC) from the figures in the mentioned papers. With some small-scale figures, this was rather difficult, so the values presented in this review are not absolutely precise. However, in our opinion, this is of no principal importance, because these values are not used for any further calculations; they only have to show the presence of particular disturbances.

Taking into account papers where deviations of the observed values from quiet conditions are considered, we present them ($\Delta foF2$, $\Delta hmF2$, ΔTEC) with indication, if mentioned in the papers in question, what had been taken as the quiet values. Some authors recalculated the critical frequencies $foF2$ to the electron concentration values in the layer maximum and presented the $NmF2$ values.

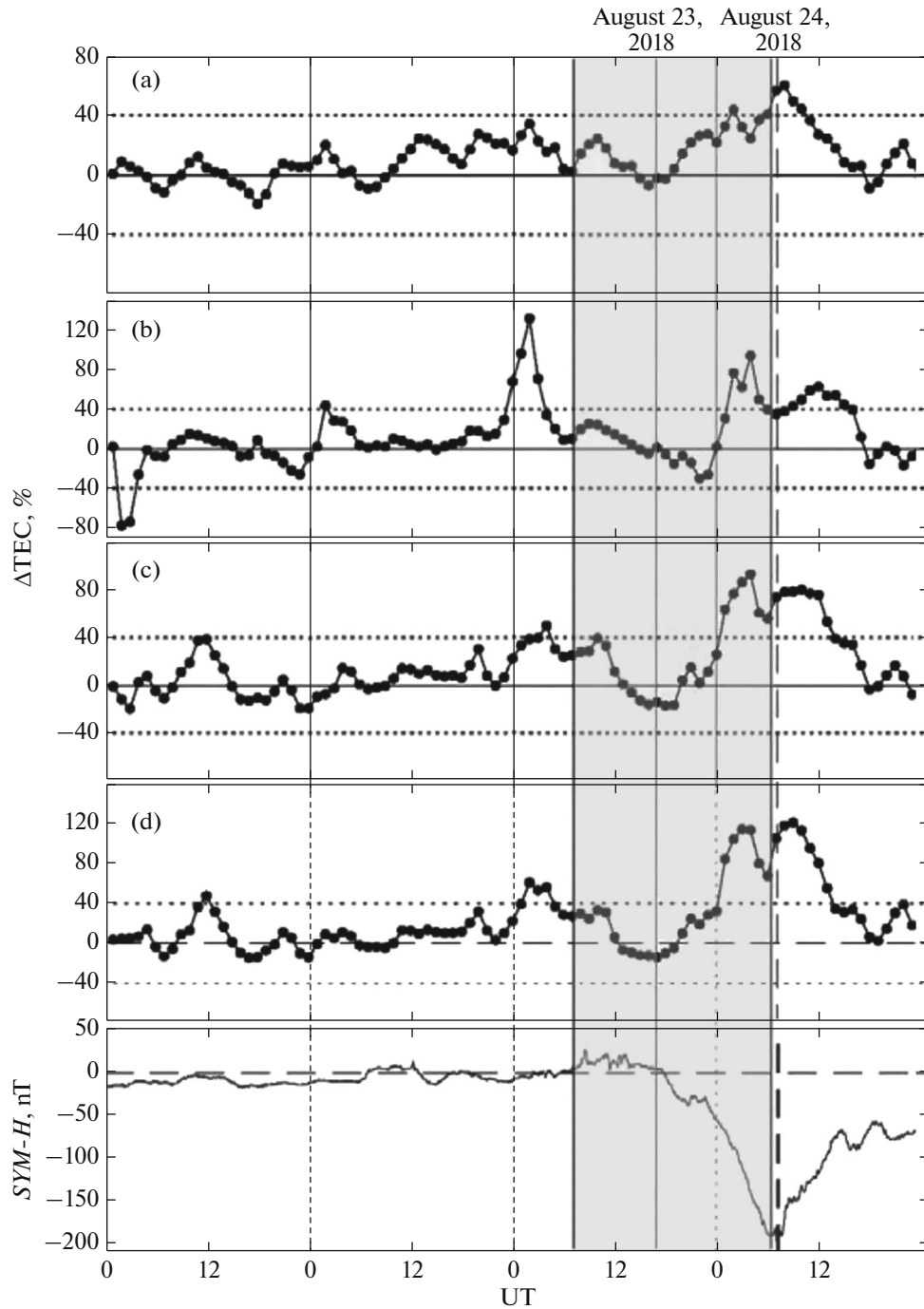


Fig. 1. Variations in ΔTEC according to measurements at points $30^\circ\text{ N } 35^\circ\text{ E}$ (a), $10^\circ\text{ N } 35^\circ\text{ E}$ (b), $0^\circ\text{ N } 35^\circ\text{ E}$ (c), and $5^\circ\text{ S } 35^\circ\text{ E}$ (d), as well as of SYM-H index (adapted from (Dugassa et al., 2023)).

2. CASE STUDIES OF PARTICULAR STORMS

The majority of papers considered below presented the mentioned case studies; i.e., one or several storms were analyzed based on observations at several vertical sounding (VS) stations or reception stations of various navigation systems.

Dugassa et al. (2023) considered the behavior of the total electron content (TEC) during the storm of

August 25, 2018 (SC at 0845 UT) based on measurements at 14 GNSS receivers in four latitudinal zones. Figure 1 shows part of Fig. 4 in the cited paper. A burst of ΔTEC approximately 6 h prior to SC is seen in three (of four) latitudinal zones. It is especially well pronounced for the 10° N zone, where ΔTEC exceeds +100%. The figure also shows a peak of ΔTEC with an amplitude of approximately +40% at noon on August 23 in the 0° N and 5° S zones.

According to Fig. 6 in the same paper, the ΔTEC values based on measurements at Penk (47.8° N), Tubi (40.8° N), and Ramo (30.6° N) stations at noon on August 24 exceeded +40%.

Sharan (2022) considered the $F2$ layer response to two moderate, two strong, and two very strong magnetic storms based on observations at three VS stations in the South Atlantic region.

The moderate storm began at 0600 UT on November 22, 1975. A spike in the virtual height of the $F2$ layer by approximately 40% was observed at Raratonga (21.2° S) station at 1400 UT on November 21. The authors note that according to the measurements at the same station, “before the geomagnetic storm, $foF2$ increased during 0700–1100 UT by about 30% of the mean value (the average over 10 quiet days).”

An increase in $h'F2$ was observed at Port Moresby (9.4° S) station at 1200 UT on March 3, 1995, whereas SC occurred at 1300 UT on March 4. The author writes that from approximately 0600 UT on March 4, the critical frequency $foF2$ began to decrease and at 0900 UT reached a minimum value of 5.7 MHz, which is 30% lower than the quiet value, and that before SC, from 1100 UT, the $h'F2$ value was 26% higher than in quiet conditions. The author also notes that the prestorm disturbances were observed only for the moderate storms.

Idosa et al. (2023) analyzed the changes in TEC based on the measurements at eight high-latitude stations (four in the Northern and four in the Southern Hemispheres) during the storm of November 4, 2021 (SC at 0800 UT). Besides variations in the TEC values, their spatial gradients in both hemispheres were also analyzed. It was found that the diurnal behavior of TEC on the prestorm day of November 3 differed sharply in the Northern and Southern hemispheres. Figure 2 (adapted from Fig. 5 in the aforementioned paper) shows that on that day, a strong decrease in the TEC gradient occurred at about 1200 UT in the Northern Hemisphere and an even stronger increase occurred at about 2200 UT in both hemispheres. The authors also note the presence of these effects on the prestorm day in the Conclusion of their paper, suggesting that they could have had a meteorological origin (see Discussion).

Sawadogo et al. (2023) analyzed TEC variations based on GPS measurements at Koudougou station (geomagnetic latitude 12.2° N) during four moderate geomagnetic storms. During the storms of May 13, 2015, and May 6, 2016, on both prestorm days, a substantial (up to 40%) excess TEC value over the mean for quiet days was observed.

Naidu et al. (2023) considered $foF2$ variations based on VS measurements at four stations in the Western Hemisphere during the storms of July 16, 2017 (moderate) and May 28, 2017 (strong).

The $\Delta foF2$ value at Hermanus station (34.4° S) on July 15 was –30% at 2200 UT, +30% at 1900 UT, and

+25% at 1700 UT. Peaks in $\Delta foF2$ with an amplitude of +30% were recorded at Millstone Hills station (42.6° N) on July 15 at 0700 and 0900 UT. On the same day, strong spikes in $\Delta foF2$ were seen at Port Stanley station up to +60% at 2100 UT and up to +80% at 1800 and 2200 UT.

During the second storm, the $\Delta foF2$ values at San Vito station intensified up to +40% at 0900 and 1000 UT on May 27, whereas SC was on the same day at 2200 UT. A decrease in $\Delta foF2$ to –30% at 0500 UT was detected at Hermanus station.

Imtiaz et al. (2021) analyzed the VTEC behavior at nine GPS stations during the storm of August 25, 2018 (SC at 0009 UT). Although the authors only consider changes in ΔVTEC during the storm, the presented figures also cover three prestorm days. It follows from these figures that the ΔVTEC value at station NKLK (0.4° N) decreased to –40% at 1200 UT on August 22 and at 1400 UT on August 24. That value at station DAKR (14.7° N) was –30% at 1600 UT on August 24.

Singh et al. (2021) analyzed TEC variations during four magnetic storms based on measurements at two Indian stations. An increase in ΔVTEC up to +50% was recorded at 0600 UT on September 26, 2011, at Bangalore station (13.0° N). The beginning of the decrease in the Dst index occurs on that day at 1700 UT.

On the prestorm day, several negative deviations in VTEC from its values in quiet conditions were recorded at Varanasi station (25.2° N): on February 18, 2014, $\Delta\text{VTEC} = -25\%$ at 1200 UT during SC at 1400 UT; on July 15, 2012, $\Delta\text{VTEC} = -30\%$ at 1000 UT under SC at 1200 UT; and on December 19, 2015, $\Delta\text{VTEC} = -30\%$ at 1300 UT under SC at 1700 UT.

Adebessin and Bakare (2023) present the results of an analysis of changes in the F -region parameters during the magnetic storm of October 12, 2016 (SC at 2200 UT) based on observations at six European VS stations.

This study differs from many similar case-study papers in that not only “classical” parameters of the $F2$ layer ($foF2$ and $hmF2$) are studied, but the scale height (H), layer thickness ($B0$), and layer shape ($B1$) as well.

Positive disturbances in the electron concentration were observed during two previous days according to the Rome (42.8° N) station data. The $\Delta NmF2$ value reached +80% and +40% at 1500 and 0500 UT, respectively, on October 12 and +80% at 1500–1600 UT on October 11. Very strong spikes in $\Delta NmF2$ up to 400% at 0900 UT on October 12 and >100% at 0800–1000 UT on October 11 were recorded at the San Vito (40.6° N) and Athens (38.0° N) stations (see cutout of the corresponding picture in Fig. 3). Negative deviations from quiet values (down to –25%) were observed in the $F2$ layer height on October 11 and 12.

Mishra et al. (2020) analyzed the TEC measurements at 12 GPS stations in four regions (Australia, Brasilia, India, and South Africa) during three storms

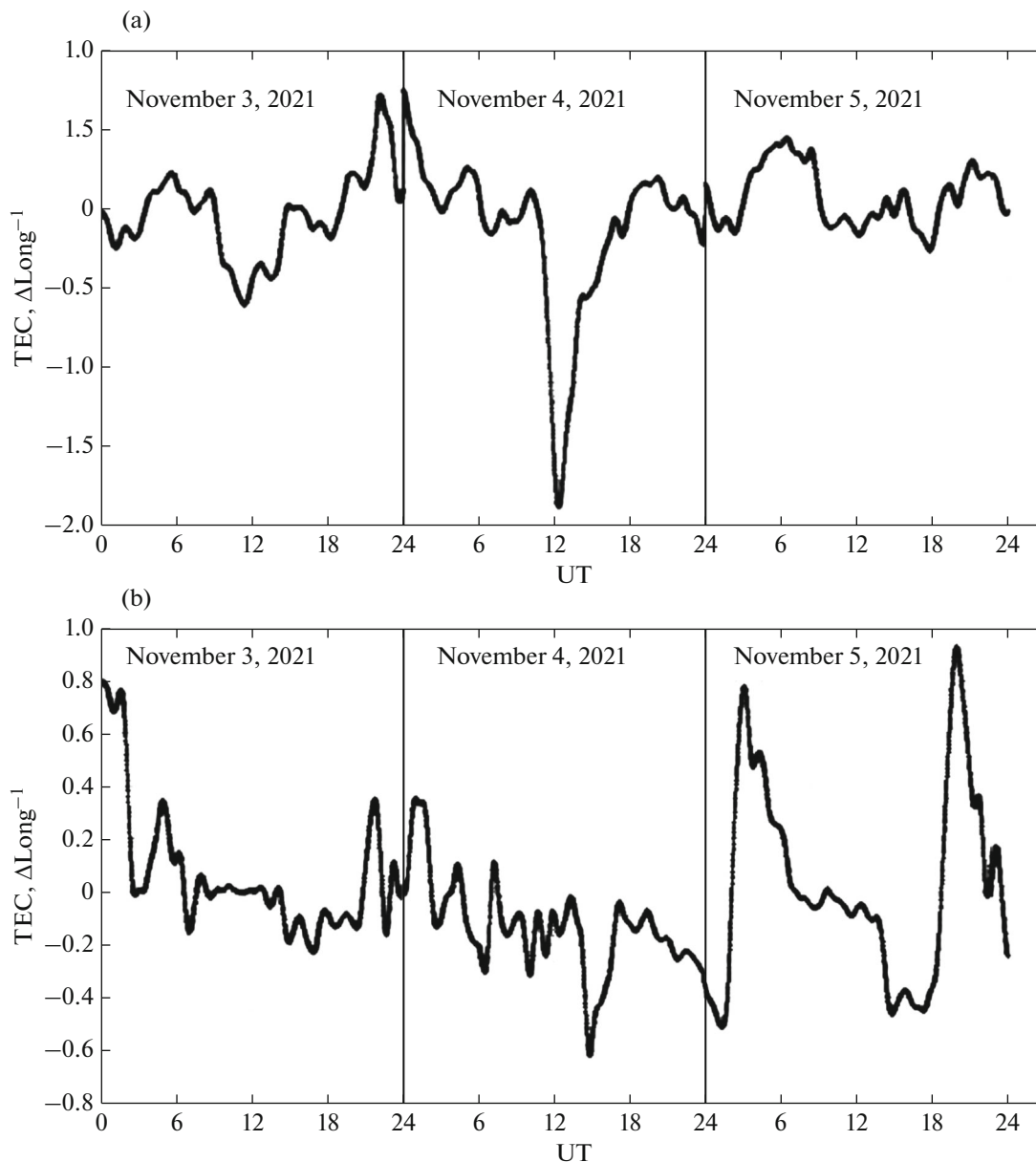


Fig. 2. Variations in longitudinal gradient of TEC on November 3–5, 2021, in Northern (a) and Southern (b) hemispheres (adapted from (Idosa et al., 2023)).

of 2015: March 17 (SC at 0500 UT), June 22 (SC at 1900 UT), and December 19 (SC at 2300 UT).

According to the data of all three stations, a decrease by a factor of approximately 2 is seen in VTEC in the Brasilia region at 1500 UT on March 16. In the Indian region, an increase in VTEC by 45% is observed at Lucknow station (26.9° N) at 1300 UT on March 16. These high values are noted by the authors in the text of the paper. No substantial deviations in VTEC from quiet conditions are recorded at two other stations of the region. No substantial deviations in VTEC on the prestorm days were recorded in the South-African or Australian regions.

According to the Lucknow station data, in the Indian sector, a negative deviation in VTEC by approximately 40% was observed from 1200 to 1800 UT on June 22. A durable deviation in VTEC by approximately a factor of 2 was seen at all three stations of the Brasilia region at 1000–1600 UT on June 21 with a maximum at about 1400 UT.

From 1200 to 2000 UT on December 19, the VTEC value at the same station in the Indian sector was 50% lower than the quiet values. In the Brazilian sector, the VTEC deviations from quiet conditions were +60% at 1800 UT at Brasilia station (16.0° S) and +50% at 1600 UT at Salvador station (12.9° S).

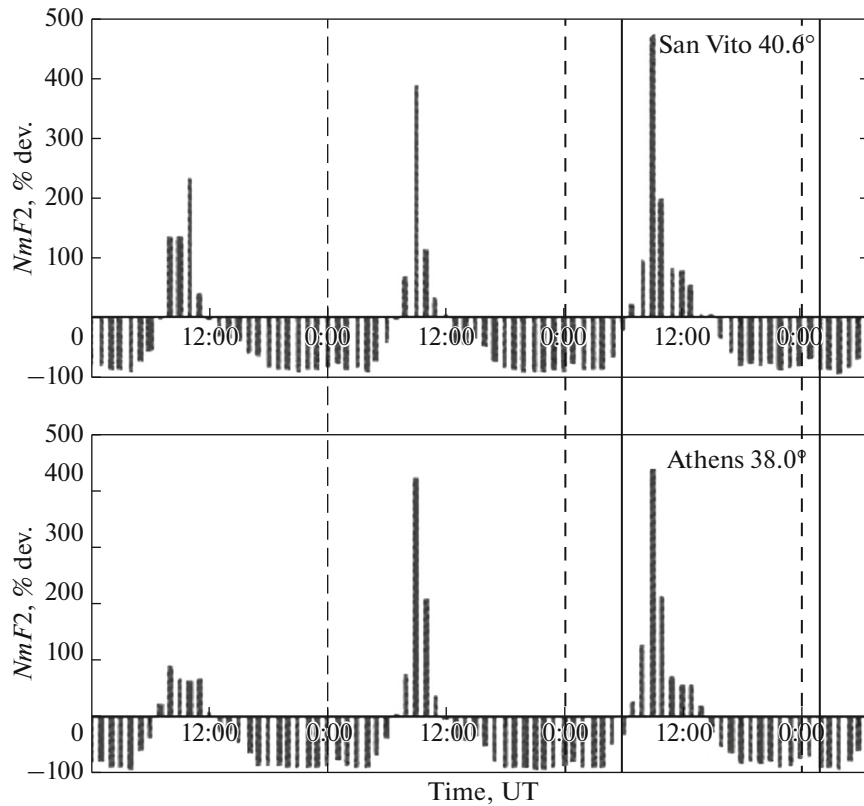


Fig. 3. Variations in $\Delta NmF2$ based on measurements at two VS stations on October 10–12, 2016 (adapted from (Adebesin and Bakare, 2023)).

De Abreu et al. (2023) analyzed 70 storms of 1999–2018 based on the TEC measurements in the Antarctic and Argentinian–Chilian sectors. The figures presented in the paper as examples show deviations in TEC on prestorm days from quiet values, which are shown with a possible scatter ($q + \sigma$).

For example, 3 h prior to the storm of September 22, 1999 (SC at 1900 UT) at 1600 UT, the VTEC value at Punta Arenas station (53.1° S) was approximately 65% higher than the mean quiet value ($q + \sigma$). The same is true for 0500 UT on the same day. At 1600 UT on September 21, the above-mentioned excess was 60%.

Two hours prior to SC on December 14, 2006 (SC at 2100 UT) at Palmer station (64.8° S), VTEC = 23 TECU, whereas the mean value ($q + \sigma$) = 8 TECU, with the increase in VTEC beginning at 1600 UT. The cut-out from the corresponding figures is shown in Fig. 4.

Prior to the October 7, 2015 storm (SC at 0200 UT), the $\Delta VTEC$ value at Palmer station at 0600–1000 UT on October 6 was approximately -40% . At 2100–2200 UT on the same day, the observed values of VTEC > 17 TECU, whereas the mean value ($q + \sigma$) < 10 TECU.

The behavior of $foF2$ and TEC at two Brazilian stations, Sao Paulo (2.6° S) and Cachoeira Paulista (22.7° S), during two storms of June 22, 2015 (SC at

1800 UT) and March 17, 2015 (SC at 0500 UT) is discussed in (Picanco et al., 2021).

According to the measurements at Sao Paulo station on June 21, the $\Delta foF2$ values were -50% and -40% at 1500 and 1900 UT, respectively. At the same station, the $\Delta foF2$ value was -50% at 2000–2400 UT on March 6.

All these effects in $foF2$ are seen also in measurements of both VTEC and the Disturbance Ionospheric Index (DIX) calculated from the aggregate observed data. The authors note that the prestorm disturbances led to the facts that that index reached 2.

Mansilla and Zossi (2022) performed a detailed study of the August 26, 2018 storm (SC at 1900 UT) based on observations at five VS stations. Observations on the calmest day in August (August 6) were used as the quiet background.

A spike in $\Delta foF2$ up to $+40\%$ was recorded 2 h prior to SC at Jacamarca station (2.3° S).

At Sao Luis station (2.6° S), decreases in $hmF2$ were observed on August 26 from 380 to 260 km at 1300 UT, from 330 to 270 km at 1500 UT, and from 350 to 270 km at 1600 UT. Peaks with $\Delta hmF2 = +40\text{--}50\%$ were observed at Jacamarca station (12.0° S) from 1100 to 1600 UT.

Based on the VS data, the authors also calculated the TEC values and obtained the following: 12–15 TECU

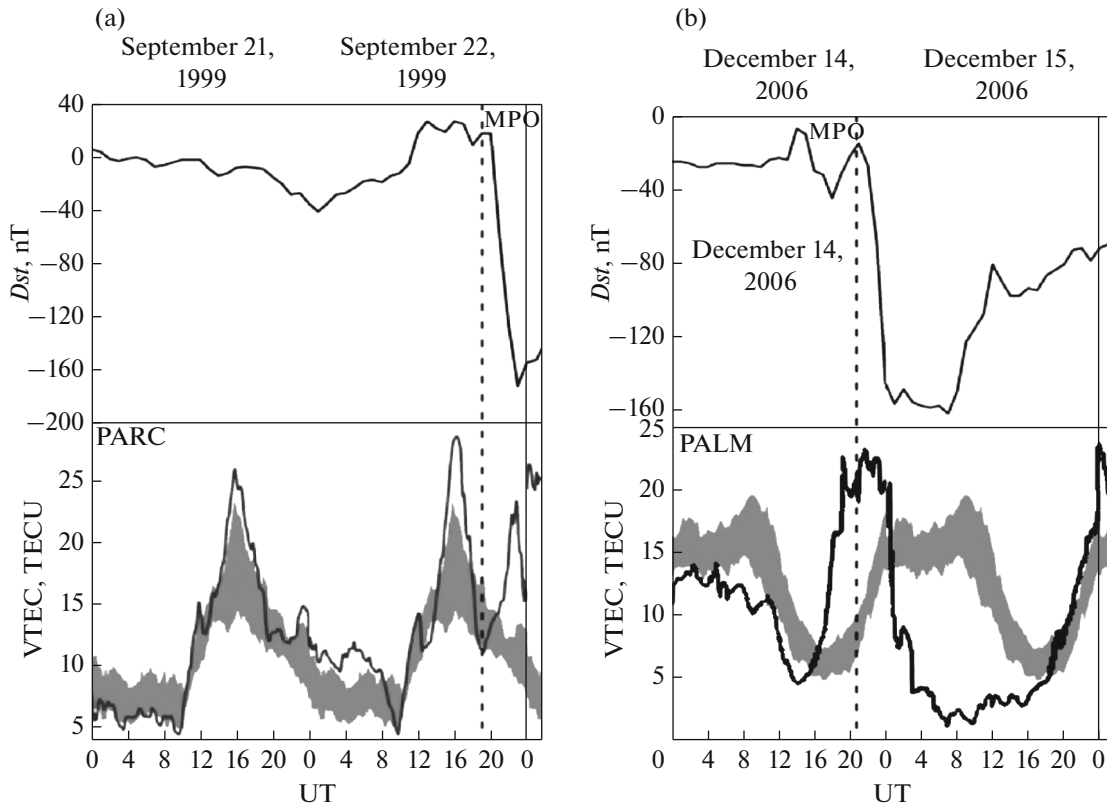


Fig. 4. Variations in Dst and VTEC according to Punta Arenas station data on September 21 and 22, 1999 (a) and Palmer station data on December 14 and 15, 2006 (b) (adapted from (Abreu et al, 2023)). Vertical dashed lines show time of SC. Shading shows quiet values of VTEC \pm standard deviation.

from 1100 UT to the time of SC for a quiet background of 3–8 TECU at Sao Luis station and 22 TECU at 1400 UT for a quiet background of 8 TECU at Port Stanley station (51.7° S).

Mansilla and Zossi (2023) also analyzed observations at five South American VS stations and calculated the TEC values based on VS ionograms during the storm of June 21, 2015. Figures in that paper show that a drop in $foF2$ by 50% at Fortaleza station (3.9° S) 16 h prior to SC. At Cachoeira station (13.9° S), an increase in $foF2$ by 70% was observed 2 h prior to SC, and an increase in $foF2$ by 30% 2 h prior to SC at Boa Vista station (12.3° N). According to the observations at Fortaleza station, a decrease in TEC by 50% was recorded 2 h prior to SC.

Swarnalingam et al. (2022) analyzed four magnetic storms in June and July, 2012 and in March and December, 2015 based on TEC observations. A vast material of satellite and ground-based measurements of TEC and N_e was analyzed.

The paper does not contain ionospheric parameter variations according to measurements in particular points, but contains maps of TEC. Neither are there presented the TEC values on a quiet day. However, since the results of TEC and N_e measurements during the prestorm days and several days after the SC are

presented in detail, the material of the paper makes it possible to draw some conclusions related to the problem discussed in this paper.

Figure 4 in the aforementioned paper shows that the TEC values (according to both the COSMIC-1 data and ground-based measurements) two days prior to the storm of July 14, 2012 were much higher than on July 21. The top panel of that figure shows the measured absolute values of TEC during three prestorm days and six days after SC. It is clearly seen that during the prestorm days within a wide latitudinal belt of $\pm(30-40)^\circ$, there are three time intervals when the TEC value was 10 TECU and more. At the same time, on July 21 when according to the data of magnetic measurements, the recovery phase has long ended, the TEC value did not exceed 6–7 TECU.

Even stronger effects are seen in the COSMIC-1 data in Fig. 8 of (Swarnalingam et al., 2022) for the June 17 storm. Here, many times during the three prestorm days (absolutely quiet according to many magnetic indices) the TEC values rise much higher than 10 TECU, whereas the TEC value does not exceed 4–6 TECU beginning from the third day after SC. The increase in the TEC value on June 15 and 16 (as compared to June 21, which could be considered a quiet day) was even stronger than during the main

phase of the June 17 storm, the region of TEC positive disturbances on the prestorm days also covering the middle latitudes.

Absolutely the same is true also for December 18 and prestorm hours of December 19, 2015. Approximately 2 h prior to SC, a strong increase in TEC not seen in any later days is observed in a wide latitudinal interval from 20° N to 20° S.

According to Fig. 13 in the aforementioned paper, during three days prior to SC of the March 17, 2015 storm, spikes in TEC are seen around noon; however, no such spikes are seen on March 21 when according the *Dst* index behavior, the recovery phase of the storm has already ended.

The effect of electron concentration intensification prior to the July 14, 2015 storm could also be seen in the altitudinal profiles of *Ne* at a latitude of 60° N (the top part of Fig. 6 in the aforementioned paper). At heights of the *F2* layer in the 18 h prior to SC, the *Ne* values are $(4-5) \times 10^{11} \text{ m}^{-3}$, whereas beginning from the second day after SC, the *Ne* at these heights is $(2-3) \times 10^{11} \text{ m}^{-3}$. Note that both considered storms are summer ones.

Akinyemi et al. (2021) considered the ionospheric response to the storm of October 24, 2011, based on the TEC values measured at three GPS stations in Nigeria. The figures presented in the paper show that at two of three points, an increase in TEC by 30% is observed approximately 6 h prior to SC.

Astafyeva et al. (2021) analyzed the storm of August 25, 2018 based on the satellite (GLONASS) and ground-based (GPS) measurements of TEC. The TEC-slips parameter, i.e., the number of sudden jumps in TEC relative to the total number of observations, was an analyzed parameter. A very strong jump in TEC-slips was observed at high latitudes 2 h prior to SC. It was strong at low latitudes but absent at middle latitudes.

The results of satellite measurements of *Ne* in the *F* region during the storm of August 25, 2018 (SC at 1200 UT) were considered in detail by Spogli et al. (2021). The maps of the *Ne* spatial distribution in the equatorial region show that this distribution on August 24 was different from the distribution on a quiet day of August 10: the equatorial anomaly peak was shifted northward by 10°. The authors note that “the deviation in the prestorm conditions from quiet behavior is an astonishing feature of the storm.”

The VS data show that 6–8 h prior to SC, there was a strong decrease in *hmF2* at Sao Luis station (2.5° S). There were also decreases in *hmF2* at that station at 0400 and 1200 UT on August 24.

Yonas et al. (2022) analyzed the variations in the $[O]/[N_2]$ ratio at a height of 625 km based on the measurements by the GUVI device onboard the TIMED satellite during four storms: April 23, 2012, March 17, 2013, March 17, 2015, and August 25, 2018, in four lat-

itudinal regions. The variations in this ratio both in the periods of the storms and during two prestorm days are presented. In only one case was a substantial deviation from the quiet conditions obtained: $\Delta([O]/[N_2]) = -35\%$ 8 h prior to SC of the 2013 storm.

Zhai et al. (2023a) considered the ionospheric response to the storm of November 4, 2021 (SC at 0000 UT) based on VS observations at stations AS00Q (around 10° S) and CAJ2M (around 22° S). The results of observations on three days, November 3–5, are presented in the paper. At the same time, November 3 is considered a quiet day, and the two disturbed days are compared with it. No possibility of occurrence of prestorm disturbances on November 3 was taken into account.

However, a peak of $NmF2 = 24 \times 10^{11} \text{ m}^{-3}$ is seen in Fig. 6 in the aforementioned paper at 1700–1800 UT (1600–1700 LT) at station AS00Q, whereas $NmF2 = 15 \times 10^{11} \text{ m}^{-3}$ at the local noon (1300 UT). A similar increase from $15 \times 10^{11} \text{ m}^{-3}$ at the local noon to $(19-23) \times 10^{11} \text{ m}^{-3}$ at 1700–1800 UT is also seen in the CAJ2M station data. However, the latter is 2 h westwards of the former, so this increase in *Ne* corresponds at two stations to the same UT time, but different LT times. This could be important for analysis of the processes which cause the prestorm disturbances.

The paper by Joshua et al. (2021a) was dedicated to a detailed analysis of the *F*-region behavior according to VS measurements at four Northern Hemisphere stations during three storms of 2010: March 28 (SC at 1800 UT), May 28 (SC at 2000 UT), and August 3 (SC at 1700 UT).

The corresponding figures in this paper show the deviations of the observed *NmF2* values from the background values, which are based on observations on ten quietest days of each month. These figures show that many positive and negative $\Delta NmF2$ values with an amplitude higher than 40% are observed both on the prestorm day and during the hours of the storm day prior to SC. We limit ourselves only by the most illustrative examples.

At Pruhonice (50° N) station, $\Delta NmF2 = -80\%$ at 0800 UT on March 27 and 28, and $\Delta NmF2 = +80\%$ at 0800 UT on May 28.

At San Vito (40° N) station, $\Delta NmF2 = +104\%$ and $+80\%$ on August 2 at 0600 UT and 0700 UT, respectively.

At Hermanus (34° N) station, $\Delta NmF2 = +80\%$ at 0400 UT on August 3.

At Ilorin (8.5° N) station, $\Delta NmF2 = 70-80\%$ at 0200 and 0600 UT on August 3.

The authors discuss the $\Delta NmF2$ behavior prior to each storm. In particular, they emphasize that the *NmF2* disturbances on May 27 occurred in the absolutely quiet period in the geomagnetic aspect (*Dst* = 0 nT and *Kp* = 13). They also note the negative disturbances in *NmF2* at Ilorin and Hermanus stations on

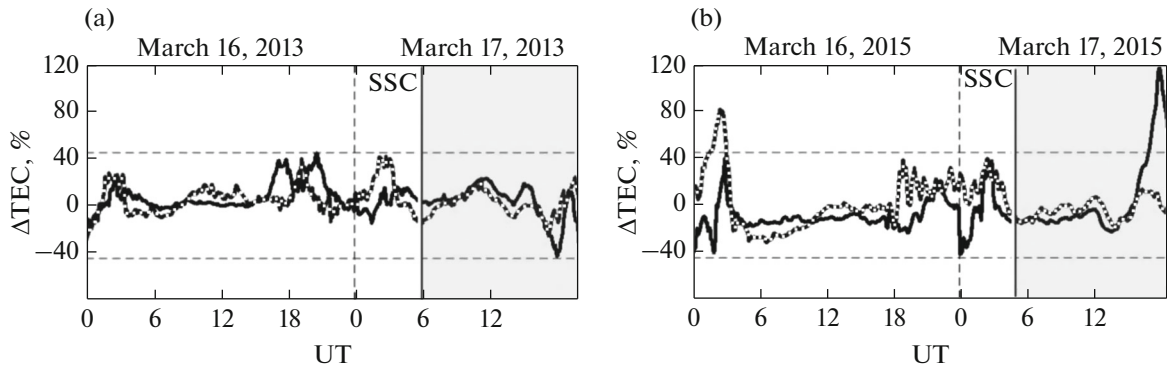


Fig. 5. Changes in ΔTEC prior to storm of March 17, 2013 (a) and March 17, 2015 (b). Solid and dashed curves correspond to Addis Ababa and Mbarara stations, respectively (adapted from (Habyarimana et al., 2023)).

August 3 and a strong spike in $NmF2$ at San Vito station on August 2.

Joshua et al. (2021b) study just the prestorm effects (premagnetic storm signatures, PMS). The authors analyzed the critical frequencies $foF2$ measured at 12 ionospheric stations located within a wide range of latitudes and longitudes. Seventeen magnetic storms of 2010–2012 were considered. The common method of recalculating $foF2$ to $NmF2$ and calculating the disturbed $\Delta NmF2$ values by comparing the observed values on prestorm days to those on magnetically quiet days was used. At the same time, only events with $\Delta NmF2$ exceeding 44% by the absolute value were considered as PMS. To avoid the influence of the preceding magnetic disturbances, the behavior of several magnetic indices during six previous days was considered.

The main conclusions of Joshua et al. (2021a) are the following:

1. PMS are observed with a quiet ring current ($Dst > -25$ nT).
2. PMS are observed with moderate auroral activity ($AE > 100$ nT).
3. PMS are observed with weak geomagnetic activity ($Ap < 7$; $Kp < 3$).
4. On average, the $NmF2$ deviations from quiet conditions are stronger at equatorial and low-latitude stations than at midlatitude stations.

The main result of Joshua et al. (2021a) for the problem discussed in this paper is that the PMS events in the ionosphere are not a result of earlier geomagnetic storms but are independent events which “pave way” to the coming magnetic storm. We will return to the conclusions of (Joshua et al., 2021b) in the Discussion section.

Balodis et al. (2023) considered the ionospheric response to the storm of March 17, 2015, analyzing the influence of that storm on the accuracy in determining position by the GNSS. The observations at the European stations of GNSS were analyzed. The accuracy in determining position, expressed as “positioning dis-

crepancy clouds” was an analyzed parameter. The authors noted (which is included in the abstract of the paper) that during the prestorm day of March 16, changes in the observed parameters were seen, manifesting the occurrence of substantial ionospheric scintillations.

Habyarimana et al. (2023) considered the TEC behavior during the storms of March 17, 2013 (SC at 0600 UT) and March 17, 2015 (SC at 0500 UT) based on measurements at two points. The deviation ΔTEC of the observed TEC values from the corresponding values in quiet conditions was analyzed. Figures in that paper show that the ΔTEC value at Mbarara (0.6° S) station was +40% at 1700 and 2000 UT on the prestorm day of March 16, 2013. The same deviation in TEC was observed at Addis Ababa (9.0° N) station at 1900 UT. The authors emphasize that the prestorm increases in ΔTEC had approximately similar amplitude at both stations.

Prior to the storm of 2015, ΔTEC values of -40% and $+40\%$ were observed at Addis Ababa station at 0000 UT on March 17 and at 0300 UT on March 16, respectively. A very strong spike in $\Delta\text{TEC} \sim +80\%$ was recorded at Mbarara station at 0200 UT on March 16, and ΔTEC was $+35\%$ at 1900 UT on March 16 and at 0200 UT on March 17. The authors note that strong spike and consider it a prestorm effect in the low-latitude ionosphere (see Fig. 5 adapted from two figures in Habyarimana et al. (2023)).

Berenyi et al. (2023) considered the behavior of the F -region parameters during two strong storms of November 12, 2012 (SC at 2300 UT) and March 17, 2015 (SC at 0500 UT) based on observations at five European VS stations.

The authors note that positive deviations in $foF2$ and TEC from quiet values were observed in the prestorm period of November 11–12 ($Kp = 1+$). Figures in that paper show that according to the measurements at Athens station, the $\Delta foF2$ value was $+25\%$ at 1000 UT on November 11 and at 1100 UT on November 12. An increase in ΔTEC by 20–30% on both days

with a maximum around noon is seen at all five stations. The authors found no substantial effects either in $foF2$ or in TEC on the prestorm day of March 16, 2015.

Zhai et al. (2023b) studied the TEC response in the North American and South American regions to the storm of August 25, 2018. The authors concentrated attention at the TEC behavior during various phases of the storm. However, the map in Fig. 2 in that paper for 1600 UT shows that the ΔTEC value at latitudes of $46^\circ\text{--}48^\circ\text{ N}$ was 3–4 TECU or approximately +40%. The authors note that increase in TEC in the text. The beginning of the Dst index decrease occurs at 1800 UT. The substantial increase in the Kp and AE indices began at the same time, so that time could be considered the time of SC.

Kumar and Parkinson (2017) paid great attention to the problem of ionospheric precursors. The general opinions of the authors on that problem will be presented below in the Discussion section. Here, we give only some particular results. The $NmF2$ changes according to the measurements at 132 VS ionosondes prior to, during, and after 967 geomagnetic storms in the period from 1965 to 2015 were analyzed.

The storm of March 1, 1981 (SC at 1300 UT) is presented based on the Canberra station measurements as an example. According to Fig. 3 in that paper, $\Delta NmF2 = +22\%$ at 1700 UT on February 28. It should be emphasized that the quiet background for comparison was constructed with particular care: all quiet days within an interval of ± 45 days of the storm were averaged. Figure 4 shows that there is a mean increase in $\Delta NmF2$ (averaged over 967 magnetic storms) by 6–10% above approximately 40° N .

Kumar and Parkinson (2017) formulated several general features in the prestorm disturbances behavior. They noted that the increase in the electron concentration in the prestorm period begins at high latitudes and then moves to middle and low latitudes. According to their results, the prestorm disturbances begin most often during the equinoctial storms and most seldom in winter, and more often in the daytime than at night.

Katsko and Emelyanov (2023) studied the behavior of the ionosphere during the storm of December 18, 2019 (SC at 1100 UT) based on VS and incoherent scatter observations in Kharkiv. The storm was very weak: the minimum Dst index was only -28 nT . December 16 was considered a quiet day, and the measurements on the following days were compared to it. On the prestorm day of December 17, three deviations in $foF2$ with an amplitude of approximately 20% were observed: positive at 0900 and 1500 UT and negative at 1200 UT. The authors note the presence of these deviations in the text of the paper.

Unfortunately, the paper does not contain the incoherent scatter data for the benchmark quiet day. However, the changes in Ne at a height of 300 km on December 17 have a distinctly unusual character: two

well-pronounced peaks are seen at 0800 and 1300 UT, which differs from the well-known typical diurnal behavior of $NmF2$.

Timocin (2019) applied an unusual method of analyzing the $foF2$ response to geomagnetic disturbances. He considered a disturbance the time when the Kp index was 4+. In the majority of cases, this corresponds to a weak magnetic storm. Observations by the VS method at Manila station (14.7° N) during one year (1991) were analyzed. The deviation $\delta foF2$ of the critical frequency at the given hour from its average value over the year was considered. The superposed epoch method was used to construct the $\delta foF2$ variation 50 h prior to and after the aforementioned moment. The daytime (0600–1800 LT) and nighttime (1900–0500 LT) hours of the day were discussed. The results of applying that method show that a substantial deviation in $\delta foF2$ from its zero values begins approximately 20 h prior to the aforementioned time, with the deviation having positive and negative signs during the daytime and nighttime hours, respectively.

Bojilova and Mukhtarov (2023) studied the response of the ionosphere to the storm of February 3, 2022 (SC at 0000 UT). The TEC values from the CODE databank were considered, and the spatial distribution of the deviation ΔTEC of the observed values from those in quiet conditions was analyzed. According to Fig. 3 in that paper, $\Delta\text{TEC} = -25\%$ at 2000 UT on February 2 at point ($70^\circ\text{ N}; 00^\circ\text{ E}$). At 1700 UT at point ($70^\circ\text{ N}; 180^\circ\text{ E}$), $\Delta\text{TEC} = +20\%$.

The behavior of the ionosphere during the storm of August 25, 2018 (a decrease in Dst from 1800 UT) was studied by Lissa et al. (2020). The TEC variations according to the measurements at several reception points were analyzed. At the Lucknow point (26.9° N), $\Delta\text{TEC} = -60\%$ at 0900 UT on August 25. At the Waltair point (17.7° N), $\Delta\text{TEC} = +60\%$ at 1300 UT on the same day, and $\Delta\text{TEC} = +40\%$ at 1200 UT on August 24.

To study the $foF2$ behavior in magnetically disturbed conditions, Giri et al. (2023) applied wavelet analysis. The observations by the VS method at Boulder station (40° N) during a very strong storm of March 17, 2015 and a weak storm of January 27, 2022 served as the initial data. The authors concluded (and this is even included in the abstract of the paper) that $foF2$ was increasing during two days prior to the strong storm, whereas there was no such increase prior to the weak storm, and that increases or decreases in $foF2$ could be used as magnetic storm precursors.

Younas et al. (2022) discussed variations in the $[O]/[N_2]$ ratio based on satellite measurements at heights of the F region during four storms. It is known that under a constant ionizing radiation flux, this ratio governs the equilibrium electron concentration in the $F2$ layer maximum. The authors found that during three of the four storms according to measurements at middle latitudes of the Northern Hemisphere, a decrease in $[O]/[N_2]$ by 20–25% is observed 4–6 h prior to SC.

Mandrikova et al. (2021) developed a new method of analyzing and modeling ionospheric parameters. They applied that method, in particular, to analyze $foF2$ measurements during the magnetic storms of August 25, 2018, and May 10, 2019, at two VS stations.

The authors found that “positive ionospheric anomalies ... with a maximum intensity of approximately at 1000 UT at Paratunka station and approximately at 1600 UT at Moscow station are observed on August 24.” That intensity exceeded the threshold value (which is determined as a complex parameter related to the confidence probability) at 0900 UT at Paratunka station and 7 h later at Moscow station.

Mandrikova et al. (2021) also noted that a few hours prior to SC on May 10, 2019, a positive anomaly of average intensity was observed according to the Paratunka station data. The maximum of the anomaly fell on 1100 UT on May 10, and the $foF2$ value exceeded the threshold value 7 h prior to SC.

Chernigovskaya et al. (2021) analyzed the F -region response to the storms of March 17, 2015 (SC at 0600 UT) and June 22, 2015, based on the observations at eight VS stations at approximately the same latitudes but at different longitudes of the Northern Hemisphere and at 28 points of the GLONASS system at midlatitudes of the Northern Hemisphere.

The paper was aimed at revealing longitudinal effects in the $F2$ layer behavior during the main and recovery phases of magnetic storms, so the prestorm days were not considered. However, the figures in the paper show the data both for two prestorm days (March 15 and 16) and eight days after the SC (to March 25). That makes it possible to estimate the deviations in $foF2$ on the prestorm days by comparing them to March 25, when the recovery phase of the storm had already ended with a high probability, and that day could be considered as geomagnetically quiet. For example, it is distinctly seen in Fig. 5 in the considered paper that within a longitudinal interval of 120° – 160° both on March 15 and 16, there are time periods when $foF2$ exceeds 10 MHz, whereas in the same periods of March 25, the $foF2$ values are 7–8 MHz. The same pattern is seen for TEC within a longitudinal interval of 140° – 160° : in the first half of March 15 and 16, the TEC values are 24–26 TECU, whereas in the first half of March 25, they are 18–20 TECU. It follows from Fig. 3 in the considered paper that the days of March 15 and 16 were absolutely magnetically quiet: the Dst and Ap indices were close to zero and the Kp index did not exceed 3+.

An even more convincing pattern is seen in Fig. 6 in (Chernigovskaya et al., 2021). Within the considered longitudinal interval of 0° – 160° ~ 35 h prior to SC of the magnetic storm at 1800 UT on June 22, the TEC values are much higher than on June 30–July 2 (these days could be conventionally accepted as quiet). Figure 3 shows that the prestorm days of June 20 and 21 were magnetically quiet.

According to Fig. 7, decreases in $hmF2$ are observed during the prestorm day of March 16. Similar decreases are seen also on June 22.

Ye et al. (2023) discuss the response of the ionosphere to the storm of July 16, 2003 (SC at 0300 UT). Although mainly ionospheric irregularities are analyzed in the paper, Fig. 3 shows $foF2$ changes during July 16–18 according to measurements at four VS stations.

At Wakkanai (45.0° N) station at 1300 UT on July 15, intensification in the $foF2$ value by 20% is observed compared to quiet value obtained by the running mean method over 27 days.

At Kokobunji station (35.7° N) at the same time (1300 UT), intensification in $foF2$ by 20% is also observed. A similar increase was recorded on the same day at 0800 UT.

In the Yamagawa station (31.2° N) data, intensification in $foF2$ by 25% at 1300 UT and a decrease by 25% at 1800 UT are seen.

At Okinawa station (26.6° N), intensification in $foF2$ by 30% at 1300 UT and a decrease by 30% at 1800 UT are observed.

Fetisova and Mandrikova (2022) presented a new method for modeling and analyzing the $F2$ layer parameters in magnetic storm periods. Observations by the VS method at Paratunka station are presented. A decrease in $foF2$ compared to the quiet conditions (the 27-day median) is observed prior to the April 16, 2021 storm (SC at 0000 UT) in the first hour of April 14 and 15.

The authors write that “prior to the event on the background of a weakly disturbed magnetic field, oscillation processes were observed in the ionosphere. At the beginning of April 15, a gradual increase in the electron concentration began, which led to formation of a positive ionospheric disturbance with a weak intensity. That positive anomaly formed 18 h prior to commencement of the magnetic storm.”

Fetisova and Mandrikova (2022) noted the appearance of oscillation processes also prior to the May 12, 2021 storm. They write that on May 11 “...6 h prior to SC, a positive ionospheric anomaly of a moderate intensity ...with a duration of approximately 20 h formed.” At the same time, the authors emphasize in particular that the presence of that anomaly is confirmed by their modeling results.

A similar effect of a positive anomaly in $foF2$ that began prior to SC was also recorded before the magnetic storm of May 27, 2017. Resuming the results of their study, the authors state that “...a few hours prior to commencement of moderate and strong storms, an effect of increasing the electron concentration in the ionosphere begins.”

A large group of authors (Mosna et al., 2020) studied in detail the behavior of the ionosphere during the strong magnetic storm of September 8, 2017, based on

observations by the VS method (Pruhonice station) and oblique sounding (OS) (a network of circuits). Although the main accent in the paper is made when analyzing the dynamic processes directly on the days of the storm, the authors also mention the state of the ionosphere prior to SC (on September 6 and 7). The authors note that in the second half of September 6 and in the daytime of September 7, intensification in $foF2$ compared to the quiet median was observed at Pruhonice station. Figure 4 in the aforementioned paper distinctly shows that on September 6, the $foF2$ values for several hours rose above 6 MHz, reaching 6.5 MHz, whereas the quiet median was 5.5 MHz. The excess of the observed $foF2$ values (7 MHz and higher) above the medians (5.5 MHz) was even stronger and lasted longer on September 7.

Mosna et al. (2020) emphasize that the character of the change in $foF2$ was very similar to the character of the TEC changes according to observations at the network of circuits in northern Russia during the same storm. Since the Pruhonice station latitude is 50° N, and these TEC measurements were conducted within the latitudinal interval of 57° – 67° N, it is evident that the detected changes in $foF2$ and TEC on the prestorm days covered a large territory.

Adekoya et al. (2023) considered in detail ionospheric effects of the magnetic storms of October 13, 2016 and September 8, 2017 based on observations at 32 ionospheric stations in two geographic sectors. Numerous figures in the paper distinctly show deviations (both positive and negative) of the observed values of $NmF2$ on the two prestorm days of both storms from the quiet values (averages over six quiet days). The authors emphasize that the prestorm effects were better pronounced in the American sector than in the Asian–Australian one.

3. DISCUSSION

The aim of the previous section was to demonstrate that in the majority of publications that study the response of the ionospheric F -region to geomagnetic storms, on prestorm days there is indication of (a few or even tens of hours prior to SC) deviations in the main parameters ($foF2$, $hmF2$, TEC) from their values in quiet conditions. In many papers, the authors themselves note cases of such unusual deviations on prestorm days and offer hypotheses on their physical nature. It is noteworthy that the number of such papers has substantially increased precisely in recent years, demonstrating that the problem of prestorm variations has become relevant.

It is worth noting a few points in the papers considered in the previous section, which could be related to discussion of the nature of prestorm effects. First, it is important that the prestorm effects in the ionosphere are detected not only in the changes in “classical” parameters ($foF2$, TEC), but in the height of the $F2$

layer ($h'F2$, $hmF2$), in navigation system errors (Katsko and Emelyanov, 2013), and in ionospheric scintillations (Balodis et al., 2023).

Having detected substantial increases in Δ TEC on the prestorm days of September 9 and 10, 2015, Sawadogo et al. (2023) suggested that they are explained by variations in the Dst index. However, this index was both positive and negative on prestorm days, and the curves for these days did not differ from the curves for quiet days.

Picanco et al. (2021) noted that the detected deviations in the parameters of the low-latitude ionosphere on the prestorm days could be precursors of geomagnetic storms.

Noting the presence of negative deviations in the ionospheric parameters on the prestorm days from their regular behavior, Astafyeva et al. (2021) assumed that these deviations could have been caused by fluctuations in the interplanetary electric or magnetic fields (IEF/ Bz), which induce prompt penetration electric fields (PPEF). However, no indications of such fields on prestorm days has been found.

Analyzing their results on variations in the $[O]/[N_2]$ ratio during four storms, Younas et al. (2022) noted that only in one case was a substantial (by 35%) decrease in that ratio observed on prestorm days. In other cases, it does not differ from the background one. That makes us cautious about suggesting that the prestorm effects in $foF2$ are related precisely to changes in the thermospheric composition at heights of the $F2$ layer. Liu et al. (2008) found that increases in $foF2$ are not accompanied by substantial changes in $hmF2$ in the prestorm period.

Habyarimana et al. (2023) noted that according to the measurements at two points, Mbarara (0.6° S) and Addis Ababa (9.0° N), the prestorm increases in Δ TEC during the storm of March 17, 2013, had approximately the same amplitude at both stations. This makes it possible to see the geographic scale of the event. Mosna et al. (2020) concluded that the changes in $foF2$ and TEC on the prestorm days cover a large territory. They believe that this is an additional argument against the meteorological nature of these events.

Zhai et al. (2023a, b) detected that the intensification of $NmF2$ prior to the storm of November 21, 2021, occurred at two stations at the same UT time but different LT times (the stations have different longitudes). This may indicate that the prestorm effects are governed rather by universal time than by local time, and this could be important for analyzing the processes that cause these effects.

Kumar and Parkinson (2017) paid a great attention to the problem of ionospheric precursors. They emphasize that their studies demonstrate increases in ionospheric parameters a few hours prior to SC of a magnetic storm and in some cases almost a day prior. Kumar and Parkinson (2017) write: “Our results indi-

cate that the prestorm intensifications are definitely real and on average start some 60 h prior to actual SC ...though it is difficult to imagine how the ionosphere 'knows' that a geomagnetic storm is imminent.”

According to their data, the increase in electron concentration occurs first in the prestorm period at high latitudes, then gradually travels down the latitudes, reaching the equator during the main storm phase. They also note that the high-latitude prestorm increases in N_e are more intense in the Northern Hemisphere than in the Southern.

The figures in (Ye et al., 2022) show that negative deviations in $foF2$ appear in the prestorm period only at low latitudes.

Kumar and Parkinson (2017) repeated their analysis (see above) increasing the limitations on quiet conditions on the prestorm day. There became less storms, but the picture did not change. They conclude that the cause is not in the disturbed conditions on the prestorm days, and that the prestorm enhancements could “have roots” in the dayside cusp region as suggested by Danilov and Belik (1992). The authors also express the hope that the prestorm effects in the ionosphere are important for space weather forecasting.

As noted in the previous section, the observation results of (Chernigovskaya et al., 2021) indicate an increase in $foF2$ and a decrease in $hmF2$ on prestorm days. This provides some keys to the processes responsible for the observed effects. If the intensification in $foF2$ was related to the thermospheric composition (the $[O]/[N_2]$ ratio), then with a decrease in the $F2$ layer maximum to layers with a lower ratio, the $foF2$ value also should have decreased. Evidently, some other mechanism is at work.

Indosa et al. (2023) believe that prestorm disturbances in the ionospheric parameters may be recommended as precursors to magnetic storms. According to them, positive disturbances directly prior to SC could have a meteorological origin, whereas the meteorological cause of the disturbances tens of hours prior to SC is less probable. Since the formation mechanism behind prestorms effects is still unknown, it can be suggested that several mechanisms work in different ways during different storms.

Mikhailov and Perrone (2009, 2021) categorically refute the concept of prestorm ionospheric disturbances. Recently, Danilov (2022) criticized the position of the aforementioned authors and described results of many researchers in support of that concept. We believe that the results of recent years considered in this review provide additional arguments in favor of that concept, so here we do not return to the publications (Mikhailov and Perrone, 2009, 2021).

A series of our papers (Danilov and Konstantinova, 2020a, b; 2021a, b, c, d; Konstantinova and Danilov, 2020, 2021) was published in 2020 and 2021 with results of detailed analysis of characteristics of $foF2$ prestorm deviations based on the data from the Slough

(254 storms) and Juliusruh (272 storms) stations. The dependences of the characteristics of these deviations on various internal parameters (solar activity, storm intensity, season, etc.) were obtained. A brief description of the results obtained in those papers can also be found in (Danilov, 2022).

Based on the Slough station data, 254 storms over a period from 1976 to 2010 were considered and 1353 events ($foF2$ deviations from quiet conditions) were found: 996 and 357 deviations had a positive and negative sign, respectively. Based on the Juliusruh station data, 272 storms during the same period were analyzed and 2682 events were found: 2007 and 675 deviations had a positive and negative sign, respectively.

Joshua et al. (2021a, b) studying, namely, prestorm effects in the ionosphere (PMS, see above), found that PMS phenomena are frequently observed for the southward components of the interplanetary magnetic field and sometimes during moderate auroral activity. They believe this indicates that these phenomena (although they are observed on magnetically quiet days) could be related to solar wind pressure. At the same time, according to (Joshua et al., 2021a), the meteorological source of PMS is hardly probable but cannot be excluded altogether.

Returning to the problem of PMS as precursors, Joshua et al. (2021b) suggested that a combination of several parameters of the solar wind, IMF, and magnetosphere can lead to a situation when a magnetic storm has not yet begun, but certain changes in the ionosphere are seen that predict a magnetic storm. The authors believe that “... PMS may likely serve as a pointer to the occurrence of geomagnetic storms when properly understood.” The authors emphasize the importance of that problem, bearing in mind the importance of forecasting space weather events and, primarily, magnetic storms.

Objecting to the conclusions of (Mikhailov and Perrone, 2009, 2021), who explain prestorm effects as Q-disturbances, Joshua et al. (2021b) claim: “It is however evident that after every PMS geomagnetic storm usually follows, either immediately or within 24–48 h.” Clearly, this is not the case with Q-disturbances.

4. CONCLUSIONS

This paper is primarily aimed at demonstrating that the problem of ionospheric disturbances in the period prior to geomagnetic storms does exist and is attracting the ever increasing attention of specialists. It should be emphasized that after publication of our review in 2019 and even after the relatively recent paper (Danilov, 2022), many publications have appeared that confirm the existence of such disturbances. The majority of this review is dedicated precisely to describing the corresponding results of these studies.

In our opinion, it follows from the presented material that many researchers have drawn attention to prestorm disturbances in the *F*-region parameters (primarily, *foF2* and TEC) and even state some conclusions on their possible physical nature. The existence of such disturbances raises no doubts. Many authors believe that they are precursors to magnetic storms. If that is so, the importance of their studies is huge.

Evidently, further studies of the behavior of ionospheric parameters on days preceding magnetic storms are needed; they should be based on analysis of many storms and measurements at many points and have the objective of obtaining the most complete picture of the dependence of both positive and negative deviations in the ionospheric parameters in the prestorm period on their values in completely quiet conditions and on various external factors, primarily, space weather parameters (solar activity, geomagnetic indices, parameters of the solar wind and interplanetary magnetic field), as well as on season, local time of SC, etc.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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