THE SECOND G3 (STRONG) GEOMAGNETIC STORM IN 25TH SOLAR CYCLE ON 3-4 NOVEMBER 2021

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Abstract. In this paper is analyzed the reaction of the ionosphere over Bulgaria during the G3 (Strong) geomagnetic storm on 3-4 November 2021 on the basis of data from constantly acting monitoring of the state of the ionosphere at the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences. The global geomagnetic indices (Kp and Dst), which characterize the time development of the storm and the data for the solar wind, are presented. The model values (MAK model, working on the NIGGG website) of the global index of geomagnetic activity, which is calculated in real time from solar wind data show good agreement with definitive values of this index from global data centers. The values of Total Electron Content (TEC) and the forecast values of the critical frequencies of the ionosphere (foF2 and MUF3000) for Bulgaria during the storm are presented. Due to the lack of data from the ionospheric station Sofia, the values foF2 and MUF3000 are calculated on the basis of TEC and are used to prepare daily forecasts for the propagation of radio waves on the territory of our country. A very good coincidence between the model values and the measured ones was reported. As a result, the reaction of the ionosphere was monitored, which in the considered interval 3-5 November and in the conditions of a geomagnetic storm is positive. An explanation of the observed behavior of the critical frequencies of the ionosphere is also purposed. All parameters discussed in this work are subject to monitoring activities under the Project "National Geoinformation Center" (NGIC) financed by the National Roadmap for Scientific Infrastructure 2017-2023.

Key words: geomagnetic activity, solar wind, ionosphere, critical frequencies, Total Electron Content.

Introduction

The geomagnetic storm is a complex geophysical phenomenon of cosmic origin. It has two main manifestations – a change in the values of the geomagnetic field and a change of the electron density of the ionosphere. These two phenomena are result of the particle precipitation, emitted by the Sun, into the Earth`s magnetosphere and ionosphere. The electric currents generated in them cause both variations in the geomagnetic field and a change in the temperature regime of the ionosphere and hence a change in the ionospheric plasma. The change in the electron density of the ionosphere directly affects the long-distance radio communications made with meter radio waves, as well as the accuracy of satellite navigation. For these reasons, controlling variations in ionospheric density (so-called "ionospheric storms") is essential for radio communications and satellite navigation. For this purpose, the National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences has developed empirical models that provide in real-time: nowcast and forecast of some of the main parameters in geophysics: a) the values of the global index of geomagnetic activity Kp, b) the critical frequencies of the ionosphere over Bulgaria and c) Total Electron Content (TEC).

The relationship between Interplanetary Magnetic Field (IMF) components and geomagnetic activity plays an important role in the physical understanding of the solar wind-magnetosphere interaction (Kamide et al., 1998; Tsurutani and Gonzalez, 1997). This relationship is a key element in Space Weather modeling and forecasting (NSWP, 2000). On the basis of such connections the empirical model for forecasting Kp-index was created and subsequently improved (Muhtarov and Andonov, 2000; Andonov et al., 2004), which uses some of the data on the components of the solar wind: a) vertical component of the interplanetary magnetic field Bz, b) speed and c) pressure of the solar wind.

The model allows calculating the values for every 15 minutes, which are published on website of the National Institute of Geophysics, Geodesy and Geography at the Bulgarian Academy of Sciences. Due to the absence of a station for vertical sounding of the ionosphere, an empirical model has been developed (Bojilova and Mukhtarov, 2021; Mukhtarov and Bojilova, 2021a), which allows to calculate estimated values of the critical frequencies of the ionosphere (foF2 and MUF3000) by TEC data obtained from the Center for Orbit Determination of Europe. These values can be used to determine the parameters of radio paths on the territory of Bulgaria, which are used by government organizations.

The geomagnetic storm on November 3-4, 2021 is the second storm of rank G3 (Strong) for the 25th solar cycle. This storm occurred in conditions of comparatively low solar activity (for November the average number of sunspots is 35). Usually during low solar activity geomagnetic storms are caused by plasma flows ejected by the so-called "coronal holes" of the Sun. The considered storm on November 3-4, 2021 was the result of Coronal Mass Ejection (CME), recorded by the DSCOVR satellite.

The designation G3 (Strong) is perceived in the NOAA Space Weather Scales (https://www.swpc.noaa.gov/noaa-scales-explanation) for geomagnetic storms in which the geomagnetic activity index Kp reaches 7. On average, about 200 such geomagnetic storms are registered for each solar cycle. The first geomagnetic storm for the current cycle was registered in May 2021.

Data and methods

The geomagnetic activity is described by the Dst- and planetary Kp-index that are received from: Goddard Space Flight Center (https://omniweb.gsfc.nasa.gov/), the values of solar wind (including Bz-component, Density, Speed, and Pressure) are taken from the same webpage. The TEC values for Sofia are obtained by the Center for Orbit Determination of Europe (CODE) at Astronomical and Physical Institutes of the University of Bern (ftp://ftp.unibe.ch/aiub/CODE/). TEC data have a grid spacing of 5◦ x 2.5◦ in longitude and latitude respectively. The values in point with coordinates on Sofia are obtained by interpolation. The data for the critical frequencies over Bulgaria are calculated by an empirical model from TEC (Bojilova and Mukhtarov, 2021; Mukhtarov and Bojilova, 2021a). The data for the other ionospheric station San Vito (Station Code: VT139, 40.6°N, 17.8°E), subject to this work, are taken from Global Ionosphere Radio Observatory (GIRO) https://giro.uml.edu/didbase/scaled.php.

Results

The main task of the present study is to trace the behavior of the empirically modeled geophysical parameters in NIGGG in disturbed conditions. As mentioned, geomagnetic storms are characterized by changes in the Earth‘s magnetic field due to its interaction with streams of charged particles emitted by the Sun. When considering such phenomena of interest to geophysics, indices are used that characterize the global change in the Earth‘s magnetic field.

The Kp-index is used to characterize the magnitude of geomagnetic storms. Kp is an excellent indicator of disturbances in the Earth's magnetic field and is used to decide whether geomagnetic alerts and warnings need to be issued for users who are affected by these disturbances. The Dst index is an index of magnetic activity derived from a network of near-equatorial geomagnetic observatories that measures the intensity of the globally symmetrical equatorial electrojet (the "ring current"). The Dst index shows the effect of the globally symmetrical westward flowing high altitude equatorial ring current, which causes the "main phase" depression worldwide in the H-component field during large magnetic storms.

Fig. 1 shows the variation of Kp and Dst, which are used to determine main phases of the storm. Data for both indices were obtained from https://omniweb.gsfc.nasa.gov/. The figure shows that the storm started around 18UT on November 3 through the following changes in both parameters: a) Kp- index exceeds 6 (which is an indication of geomagnetic disturbance), b) the other index Dst reacts with a positive change up to 20nT, followed by a sharp drop in the index to -120nT. The graph shows that the changes in the two indices occur sharply, which may define the considered event as a storm with a sudden commencement. The maximum of the storm is around noon on 4 November. In the hours around 12UT the Kp index exceeds 7.67 and Dst reaches its minimum. After 18UT on November 4, the Kp index returns to quite condition, which is characterized by values below 4, and the Dst index gradually begins to recover. The duration of the storm according to the considered global indices turns out to be one day from 18 UT on 3 November to the same hour on 4 November 2021.

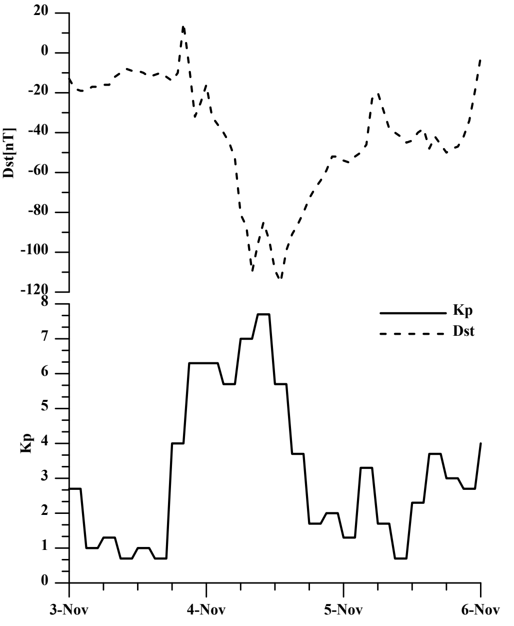

Fig. 1. Global indices of geomagnetic activity Kp (continuous line) and Dst (dash line)

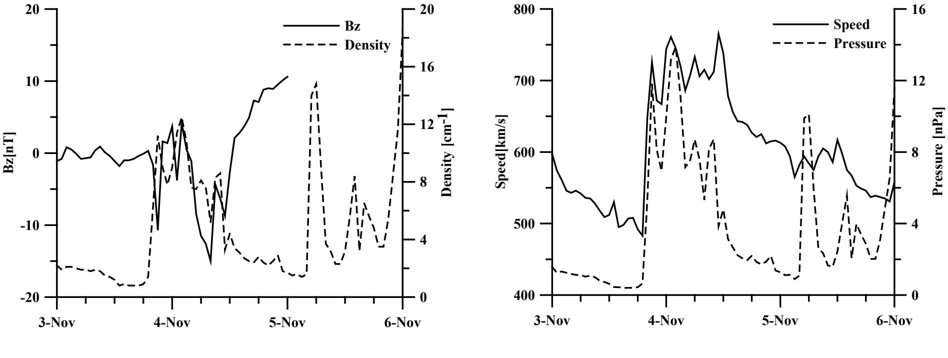

Fig. 2. Solar wind parameters: Bz component of interplanetary magnetic field (continuous line; left panel) and solar wind density (dash line; left panel), Speed (continuous line; right panel) and Pressure (dash line; right panel).

Shown in Fig. 2 parameters of the solar wind show that at 18 UT on 3 November the increase in the density of the solar wind (dash line), which reaches about 11 cm^{-1}. The component Bz of the interplanetary magnetic field - IMF (continuous line; left panel) has negative values, reaching about -10nT, which allow for coupling between the solar wind and the Earth's magnetosphere. The speed (continuous line; right panel) and pressure (dash line; right panel) of the solar wind also increased sharply at 18 UT on 3 November, which is another confirmation besides the global indices of geomagnetic activity (see Fig.1) that we have a storm with a sudden commencement. By 12 UT on 4 November Bz has negative values (about -15nT) and then turns into positive values (above 10nT). This means that the coupling between the solar wind and the Earth's magnetosphere ceases around 12UT on 4 November, when the density and speed of the solar wind begins to decline. This also causes rapid decline in the Kp-index (see Fig. 1).

The MAK model (Andonov et al., 2004) presents estimated Kp values (marked in Fig. 3 as Kpm) as a function of the inert system-modified Bz values, the speed and pressure of solar wind. Fig. 3 shows the variation of Kpm, obtained by the model (continuous line), compared to the variation of Kp values. During the storm the values of Kpm are close enough to the actual values of Kp (dash line), which are determined from data from geomagnetic stations of the world network (Muhtarov and Andonov, 2000; Andonov et al., 2004).

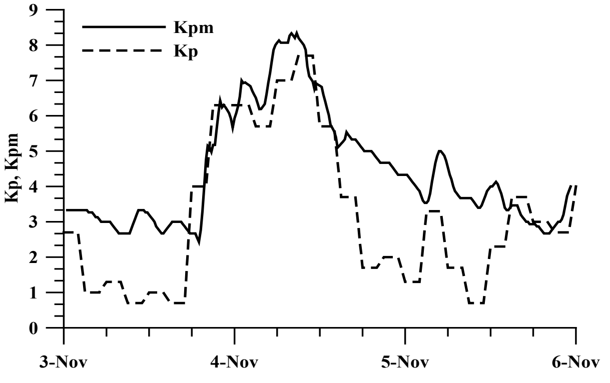

Fig. 3. Comparison between the model values of the Kp-index, calculated from the MAK model (continuous line) and the actual (dash line).

Total Electron Content is the integral of the ionospheric electron density for the entire ionosphere along a line vertical at a point on the Earth`s surface. The TEC quantity is important for determining the so-called ionospheric correction to using Global Navigation Satellite Systems (GNSS). The radio waves used in satellite navigation are with a very high frequency and they are not reflected by the ionosphere, but when pass through it they get an additional delay, which introduces errors in determining the coordinates of the receiver. Knowing of the TEC values makes it possible to correct the values of the devices.

In Fig. 4 the TEC values for the point with coordinates 42.7°N и 23.4°E calculated from the CODE data by interpolation are shown. Shown with dotted lines relative deviation (Mukhtarov et al., 2018) describes the deviation of the TEC values from the steady state presented by the TEC hourly medians for November 2021. When using a relative deviation, the diurnal, seasonal and solar course of the respective ionospheric characteristics is eliminated. The short-period variations caused by geomagnetic disturbances are clearly distinguished. The figure shows that during the considered storm both the TEC values and the relative deviation have a predominance of positive values, which means an increase in the electron density of the ionosphere. A similar reaction is typical for the winter season (Bojilova and Mukhtarov, 2020; Bojilova and Mukhtarov, 2020a). Weak negative reaction in TEC is observed only in the initial phase of the storm (on the night of 3 to 4 November) in the values of relative TEC (dash line). In daytime conditions on 4 November, a positive response of relative TEC of about 0.5 was observed, which means an increase of TEC by 50% compared to the calm state this month. An increase of up to 30 TECU was again observed in the raw TEC values.

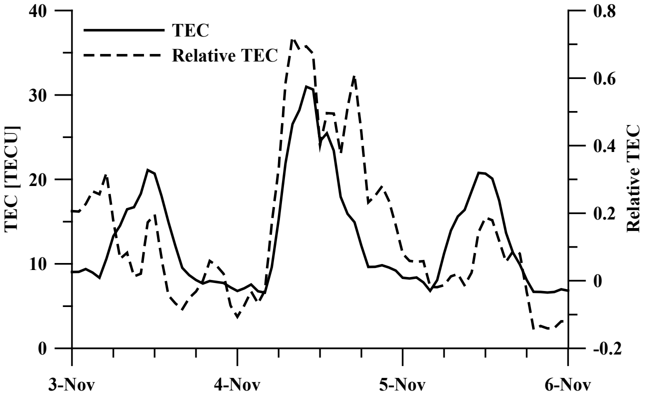

Fig. 4. TEC values for Bulgaria (continuous line) and their relative deviation from the steady state (dash line).

The physical explanation for the observed positive response may be the result of some of the main mechanisms: the F2-layer uplifting due to vertical drift, plasma fluxes from the plasmasphere, and downwelling of the gas as a result of the storm-induced thermospheric circulation (Danilov and Lastovicka, 2001).

In the physics of the ionosphere, the following values are of the greatest interest: foF2 and MUF3000, which together with the value foE allow to calculate the main parameters of a given radio path. The task for calculating a radio path contains the determination of the range of frequencies on which a radio communication can occur at a given distance between the two radio communication points. The frequency range is limited by the minimum and maximum usable frequencies, which depend on the distance of the radio path and the state of the ionosphere at the time. To solve this problem, it is necessary to know the altitude profile of the electron density of the ionosphere to the maximum in the layer of reflection of radio waves. The model named after its creators, the profile of Di Giovanni-Radicella, is based on the presentation of the electronic profile with hyperbolic sequence functions (Di Giovanni and Radicella, 1990). The values of the three critical frequencies are sufficient to calculate the model altitude profile for heights up to the height of the maximum of the F- layer. After calculating the electron profile, the model ionogram is calculated. After determining the model ionogram, the calculation of the model inclined ionograms at a given distance of the radio communication is started.

Therefore, the values of foF2 and MUF3000 were chosen in the present work to illustrate the ionosphere response. Two points were selected to compare the behavior of ionospheric parameters. One point is ionosonde station San Vito, and the other is the point with coordinates close to Sofia.

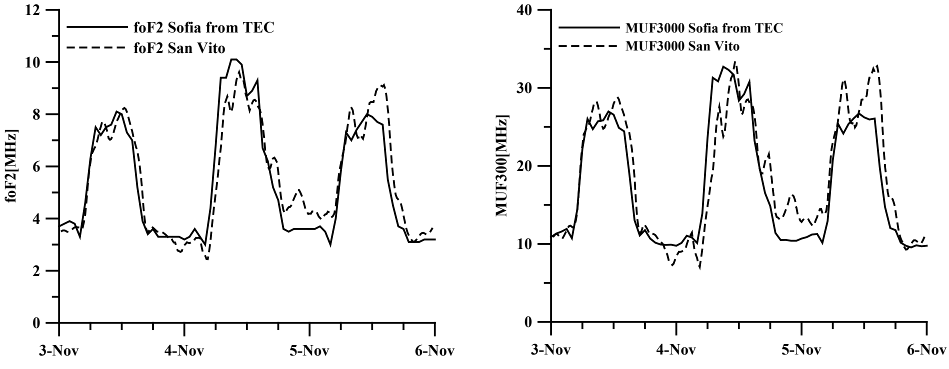

Fig. 5. Variations of the critical frequencies of the ionosphere over Bulgaria during the storm calculated according to the TEC data (continuous line). For comparison with dotted line the measured values from a similar coordinate ionospheric station San Vito are shown.

Fig. 5 shows the values of the critical frequency with vertical propagation foF2 (left panel; continuous line) and the maximum usable frequency of radio communication at a distance of 3000km (right panel; continuous line) obtained from an empirical model that makes it possible to calculate both critical frequencies through TEC data (Bojilova and Mukhtarov, 2021; Mukhtarov and Bojilova, 2021a). For comparison, the measured values of these quantities from a nearby ionospheric station San Vito (40.6°N, 17.8°E) are shown. Fig. 5 makes it evident that the values of the critical frequencies during the storm increase in comparison to the values on quite days. During the day on 4 November (the maximum of the storm) foF2 for Sofia exceeds 10MHz, and the same value on 3 November and 5 November (quite conditions) has values around 8 (see Fig. 5; left panel; continuous line). The other ionospheric quantity MUF3000 has analogous increase in values during the storm (see Fig. 5; right panel; continuous line). From the parameters shown at the San Vito ionospheric station in fig. 5 (right and left panel; dash line) a similar situation with the behavior of the ionosphere on the territory of Bulgaria is clearly visible. In conclusion, we can say that in the studied ionospheric stations at almost the same latitude in the territories of Bulgaria and Italy there is a positive response in the behavior of critical frequencies during the studied event on 4 November, 2021. The positive storm effects, especially at midlatitudes, remain the most unpredictable feature of the ionospheric storms. Besides an increase in the neutral density ratio O/N2 as possible candidate for the positive storm occurrence, storm time thermospheric winds, prompt penetration, and disturbance dynamo electric fields, as well as plasmaspheric downward fluxes, have been reported to be the main causes of the storm time increases in the ionospheric plasma density (Astafyeva et al., 2015; Fuller-Rowell et al., 1996; Richmond and Lu, 2000; Förster and Jakowski, 2000; Huang et al., 2005; Crowley et al., 2006; Danilov, 2013, Gadzhev et al., 2013). A positive response to the critical frequencies of the ionosphere means that during this storm there are no conditions for disruption of radio communications.

Summary

Empirically modeled values of the geomagnetic activity index Kp presented in this paper, calculated from satellite data of the solar wind, allow to predict with satisfactory accuracy through the website of the National Institute of Geophysics Geodesy and Geography the occurrence of geomagnetic storms with a delay of not more than 15 minutes. This is a definite advantage over the three-hour estimated values published by the world data centers.

The model, which calculates the estimated values of the critical frequencies of the ionosphere over Bulgaria (foF2 and MUF3000) provides, in the absence of a working ionospheric station, a way to control the state of the ionosphere over Bulgaria. The results of the model allow to predict the ionospheric characteristics with satisfactory accuracy not only in quiet conditions, but also during disturbances of geomagnetic origin and to make short-term and medium-term prediction.

This study presents the second geomagnetic storm of class G3 for 2021, which occurs on November 3-4, 2021.From the considered geophysical parameters it can be seen that the models providing monitoring at the National Institute of Geophysics, Geodesy and Geography describe in great detail and accuracy the behavior of the basic quantities used to study the behavior of the ionosphere in geomagnetic and ionospheric disturbances, namely: i) the Kp-index by MAK model, ii) the critical frequency of the F2 layer, iii) the maximum usable frequency at a distance of 3000 km and iv) the TEC quantity.

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References

Kamide, Y. Baumjohann, W. Daglis, I. A Gonzalez, W. D. Grande, M. Joselyn, J. A. McPherron, R. L. Phillips, J. L. Reeves, E. G. D. Rostoker, G. Sharma, A. S. Singer, H. J. Tsurutani, B. T. Vasyliunas, V. M., 1998. Current understanding of magnetic storms: Storm-substorm relationships, J. Geophys. Res., 103, No. 8, 17,705-17,728.

Tsurutani, B., W. Gonzalez, 1997. The interplanetary causes of magnetic storms: A review, in Magnetic Storms, Geophys. Monogr. Ser., vol. 98, edited by B. Tsurutani et al., p. 77, AGU, Washington, D.C.

National Space Weather Program Implementation Plan, 2000. 2nd Edition, Washington.

Muhtarov, P. and Andonov, B., 2000. Improved relationship between the Interplanetary Magnetic Field component B z and Kp index. *Bulgarian Geophysical Journal*, *26*, pp. 1-4.

Andonov, B., Muhtarov, P., and Kutiev, I., 2004. Analogue model, relating Kp index to solar wind parameters. Journal of atmospheric and solar-terrestrial physics, **66**(11), 927-932.

Bojilova, R., and Mukhtarov, P., 2021. RECONSTRUCTION OF IONOSPHERIC CRITICAL FREQUENCIES BASED ON THE TOTAL ELECTRON CONTENT OVER BULGARIA. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, 74(1), 110-119.

Mukhtarov, P., and Bojilova, R., 2021a). Accuracy Assessment of the Ionospheric Critical Frequencies Reconstructed by TEC over Bulgaria. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, **74**(2), 250-259.

Mukhtarov, P., Andonov, B., and Pancheva, D., 2018. Empirical model of TEC response to geomagnetic and solar forcing over Balkan Peninsula. Journal of Atmospheric and Solar-Terrestrial Physics, 167, 80-95.

Bojilova, R., & Mukhtarov, P., 2020. LOCAL TIME DEPEDENCE OF THE IONOSPHERIC RESPONSE TO GEOMAGNETIC DISTURBANCES OVER BULGARIA. International Multidisciplinary Scientific GeoConference: SGEM, 20(1.2), 615-622.

Bojilova, R., & Mukhtarov, P., 2020a). Relationship between the Critical Frequencies of the Ionosphere over Bulgaria and Geomagnetic Activity. COMPTES RENDUS DE L ACADEMIE BULGARE DES SCIENCES, 73(8), 1113-1122.

Danilov, A. D., & Lastovicka, J., 2001. Effects of geomagnetic storms on the ionosphere and atmosphere. International Journal of geomagnetism and aeronomy, 2(3), 209-224.

Di Giovanni, G., & Radicella, S. M., 1990. An analytical model of the electron density profile in the ionosphere. Advances in Space Research, 10(11), 27-30.

Astafyeva, E., Zakharenkova, I. and Förster, M., 2015. Ionospheric response to the 2015 St. Patrick's Day storm: A global multi-instrumental overview. Journal of Geophysical Research: Space Physics, 120(10), pp. 9023-9037.

Fuller-Rowell, T. J., M. V. Codrescu, H. Rishbeth, R. J. Moffett, and S. Quegan, 1996. On the seasonal response of the thermosphere and ionosphere to geomagnetic storms, J. Geophys. Res., 101(A2), 2343-2353, doi:10.1029/95JA01614.

Richmond, A., and G. Lu, 2000. Upper-atmospheric effects of magnetic storms: A brief tutorial, J. Atmos. Sol. Terr. Phys., 62, 1115-1127.

Förster, M., and N. Jakowski, 2000. Geomagnetic storm effects on the topside ionosphere and plasmasphere: A compact tutorial and new results, Surv. Geophys., 21, 47-87.

Huang, C. S., J. C. Foster, L. P. Goncharenko, P. J. Erickson, W. Rideout, and A. J. Coster, 2005. A strong positive phase of ionospheric storms observed by the Millstone Hill incoherent scatter radar and global GPS network, J. Geophys. Res., 110, A06303, doi:10.1029/2004JA010865.

Crowley, G., Hackert, C.L., Meier, R.R., Strickland, D.J., Paxton, L.J., Pi, X., Mannucci, A., Christensen, A.B., Morrison, D., Bust, G.S. and Roble, R.G., 2006. Global thermosphere-ionosphere response to onset of 20 November 2003 magnetic storm. Journal of Geophysical Research: Space Physics, 111(A10).

Danilov, A. D., 2013. Ionospheric F-region response to geomagnetic disturbances, Adv. Space Res., 52(3), 343–366, doi:10.1016/j.asr.2013.04.019.

Gadzhev, G., Ganev, K., Prodanova, M., Syrakov, D., Atanasov, E. and Miloshev, N., 2014. Multi-scale atmospheric composition modelling for Bulgaria. In Air Pollution Modeling and its Application XXII (pp. 381-385). Springer, Dordrecht.

G3 (силна) геомагнитна буря през 25-тия слънчев цикъл на 3-4 ноември 2021

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Резюме: В настоящата статия е анализирана реакцията на йоносферата над България по време на G3 (Strong) геомагнитна буря от 3-4 Ноември 2021 на базата на данните от постоянно действащия мониторинг на състоянието на йоносферата в Национия Институт по Геофизика, Геодезия и География – Българска академия на науките. Представени са глобалните геомагнитни индекси (Kp and Dst), характеризиращи протичането на бурята и данните за слънчевия вятър. Моделните стойности (МАК модел работещ на интернет страницата на NIGGG) на глобалния индекс на геомагнитната активност, които се изчисляват в реално време по данните на слънчевия вятър показват добро съответствие с дефинитивните стойности на този индекс от световните центрове за данни. Представени са стойностите на Total Electron Content (TEC) за България по време на бурята и прогнозните стойности на критичните честоти на йоносферата (foF2 and MUF3000), които се изчисляват на базата на TEC и служат за изготвяне на ежедневни прогнози за разпространенението на радиовълните на територията на България. Отчетено е много добро съвпадение между моделните стойности и измерените такива. Като резултат е проследена реакцията на йоносферата, която в разглеждания интервал от време 3-5 ноември и в условията на геомагнитна буря е положителна. Предложено е и обяснение за набюдаваното поведение на критичните честоти на йоносферата. Всички дискутирани параметри в тази работа са обект на мониториновата дейност по Project "National Geoinformation Center (NGIC)".