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Functional Dependence of the Critical Frequency of the Ionospheric F2-layer on Geomagnetic Activity

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Abstract.

This paper presents the functional dependence of the ionospheric characteristic foF2, representing the critical frequency of the ionospheric F2-layer, on the geomagnetic activity produced by regression analysis. The data for the ionosphere were obtained from the ionosonde station at Sofia (National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences) for the period of 1995-2014. The geomagnetic activity is represented by the planetary Kp-index derived from the NOAA. Some examples defining the use of both filtered Kp values and relative deviations of foF2 are shown in this study. The results of the obtained seasonal dependencies demonstrate that the response in winter is weaker than that in summer and equinoxes. The considered dependencies are significantly nonlinear, requiring a third-degree polynomial approximation. It is noted that the range of the geomagnetic activity variation is different in different months; this does not allow reliable values of the average response to strong geomagnetic disturbances to be obtained in some cases. The differences found by using the regression analysis between the ionosphere responses in day and night conditions necessitate the generation of an empirical foF2 model separately for day and night conditions. These results can be used to establish an empirical model for predicting the state of the ionosphere over Bulgaria.

Introduction

The ionospheric structure and variability are related to changes in solar radiation and geomagnetic activity, together with the subsequent response of the thermosphere-ionosphere system [*Roble*, 1995]. The ionosphere also varies in response to neutral winds [*Schunk et al*., 2009], electrodynamical coupling with the overlying plasmasphere and magnetosphere [*Huba et al.*, 2005], and dynamical coupling with the underlying atmosphere particularly effective during low solar activity conditions [*Mendillo et al*., 2002; *Rishbeth*, 2006]. Geomagnetic storms are generated through the interaction between coronal mass ejections and the Earth's magnetic field. Such disturbances can lead to a significant perturbation of the "quiet-time" ionosphere due to large variability in the electron density distribution, total electron content (TEC) and the ionospheric current system [*Prölss*, 1995].

The midlatitude F2-layer response to geomagnetic storms is mainly based on storm-induced changes in the neutral atmosphere, which are primarily a consequence of a strong Joule heating in the auroral thermosphere. At lower heights the role of the ionization and photochemical processes increases due to shorter electron lifetimes. The altitude dependence of the ionospheric response is due to the differences in physical mechanisms responsible for the changes of the electron concentration. While in the E and D regions the primary reason for the electron concentration changes is the variation of the ionization rate because of corpuscular intrusions, in the F2 layer the electron density variations are predominantly caused by such factors as neutral composition changes and dynamical processes.

There is one more difference in the electron concentration behavior in various ionospheric regions. All "disturbances" in the lower ionosphere (poststorm effects, auroral absorption, polar cap absorption (PCA)) are actually an increase of electron concentration above some “quiet-time” background level. Contrary to that, the F2-layer response to a geomagnetic disturbance (so called ionospheric storm) consists of effects of both signs. Both the depletion and enhancement of the electron density relative to the background level are observed during storms and are called "negative" and "positive" phases of the storm, respectively.

The latitude and longitude, season, as well as both the storm onset time and maximum are the main factors which define the positive/negative response [*Mukhtarov et al*., 2013; *Mukhtarov and Bojilova*, 2017].

The ionospheric storms are usually manifested by variations of the electron concentration in a wide altitude range from about 200 km to 800-1000 km. Therefore, the basic feature of the storms is also the TEC variations observed from the satellite-to-ground radio wave propagation.

The basic aim of this study is to find a relationship between the critical frequency of the F2-layer and the geomagnetic activity represented by the Kp-index. The requested functional dependence between the considered parameters is obtained by applying regression analysis. The regressions of the seasonal dependencies are presented separately for day and night conditions and a proper justification for this is made. The results also confirm the expediency of introducing the relative deviation of the critical frequencies of the F2-layer from the geomagnetic activity as a third degree polynomial. All these results can be used for producing an empirical model for forecasting the state of the ionosphere over Bulgaria.

Data and methods

The geomagnetic activity, described by the planetary Kp-index is provided from: https://omniweb.gsfc.nasa.gov/. The foF2 values are derived from the ionosonde station Sofia-SQ143 (42.4°N, 23.2°E) that belongs to the National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences.

To find the dependence of the ionospheric characteristics on the geomagnetic activity it is convenient to use not the specific values of these characteristics, which have a strong daily and seasonal course, but their relative deviations from the sliding medians. The relative deviations of the critical frequencies of the F2-layer are obtained using the formula:

$$rfoF2(t) = \frac{foF2(t) - foF2med(UT)}{foF2med(UT)}$$

From the value of the critical frequency of the F2-layer measured at some moment *t* (noted by *foF2 (t)*), subtract the median value measured at the same universal time for an interval of 15 days centered to the current day (marked as $foF2_{med}(UT)$) and the difference is divided by the same median value.

The filtered Kp (*filt_Kp*) is calculated by subtracting from each value in the time series the average one obtained for a segment of time with a length of 27 days and centered on the current time. This conversion ensures that the variations in the Kp-index with a time scale greater than 27 days are removed. This is very useful procedure because the relative values of the ionospheric characteristics do not contain variations with a time scale longer than 27 days.

A criterion used to determine whether an hour belongs to day- or night-time is the cosine of the Sun's zenith angle; the negative values indicate night-time conditions. The cosine values of the zenith angle χ are determined by using the simplified astronomical formula:

$$\cos\chi = \sin\left(\frac{\pi}{180}\varphi\right)\sin\varphi_0 + \cos\left(\frac{\pi}{180}\varphi\right)\cos\varphi_0\cos\left(\frac{\pi}{180}\left(15\left(UT-12\right)-\theta\right)\right)$$

$$\varphi_0 = \frac{\pi}{180}23.45\sin\left(\frac{2\pi}{365}\left(DOY-21\right)\right)$$

The formula includes the latitude and longitude of the station φ and θ respectively, the universal time UT, and the serial number of the day of the year, counted from January 1, DOY.

Results

This section illustrates some examples of the group regressions between the relative values of the critical frequencies of the F2-layer and the filtered Kp-index, presented in Fig. 1, for selected calendar months representing winter (January, upper row of plots), summer (July, middle row of plots) and equinoxes (September, bottom row of plots) as the regressions are given for day- (red color, left column of plots) and night-time (blue color, right column of plots) conditions.

A careful inspection of the regression dependencies shown in the Fig. 1 reveals a significant nonlinear relationship between the considered parameters, requiring a third-degree polynomial approximation. It is noted that the range of variation of geomagnetic activity is different in the different months, which does not allow in some cases (January) reliable values of the average response to strong geomagnetic disturbances to be obtained. This is due to the insufficient statistical material available for this study.

A characteristic feature of the anomalies of geomagnetic origin is the amplification of the deviations mainly in the negative direction, i.e. nonlinearity of the reaction is enhanced during strong magnetic storms, especially during the summer months. The comparison between the forms of the regressions separately for day- and night-time conditions indicates significant differences, especially during the winter months. For example, in January, the day-time dependence shows a positive (increasing) change with respect to the average values of the geomagnetic activity, whereas at night conditions, opposite, at high geomagnetic activity values, a negative change is observed. This can be explained by the predominance of the positive ionospheric response to geomagnetic storms in day-time winter conditions [*Bojilova and Mukhtarov*, 2019].

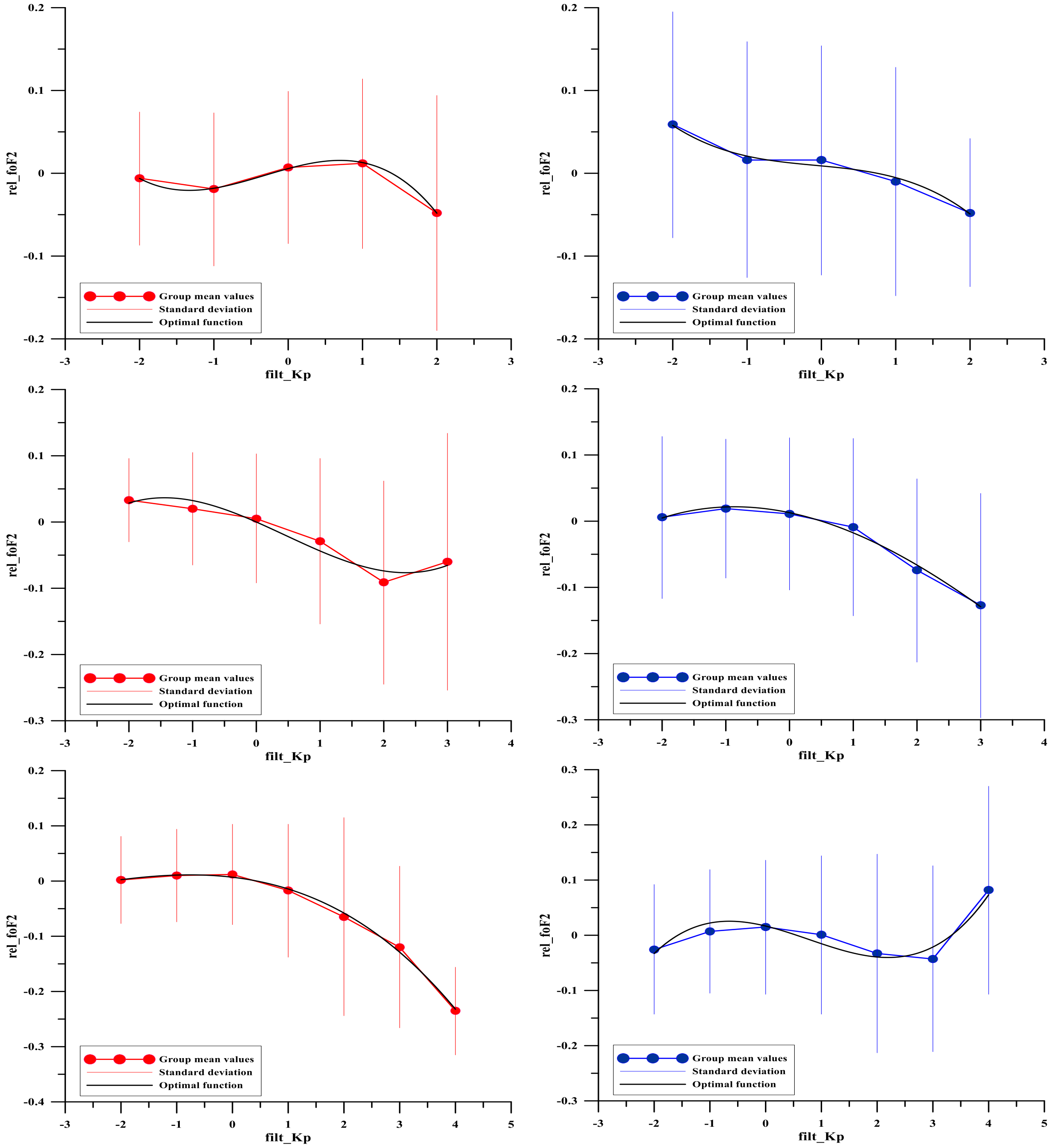

Fig. 1 Comparison of the monthly group regressions between the filtered values of the geomagnetic activity Kp-index and the relative values of foF2 as the regressions are divided for day (left panel) and night (right panel), as well as their optimal approximations. The following months are shown: January (upper row of panels); July (middle row of panel) and September (bottom row of panel). The error bars are represented by the standard devisions.

There is no significant difference between day and night regressions in the summer and equinoctial months which have a definite negative course. This result reflects the known fact that the geomagnetic storms cause mainly negative reactions of the F2-layer critical frequencies in summer and equinoxes.

The results obtained will be used for producing of an empirical model intended to predict the F2-layer critical frequencies of the ionosphere over Bulgaria.

Conclusions

The presented results in this study justify the use of both the relative values of the critical frequency of the F2-layer and the filtered the Kp-index. The necessity of introducing a third degree polynomial dependence of the relative deviation of the critical frequency of the F2-layer on the geomagnetic activity is also confirmed. The differences between the response of the F2-layer critical frequency in the day and night conditions demonstrated in the presented regression analysis justify the necessity to synthesize an empirical model for forecasting the ionosphere separately for day and night. The results obtained will be used to establish an empirical model intended to predict the state of the ionosphere over Bulgaria.

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