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CORRELATION OF TOTAL ELECTRON CONTENT VARIATIONS AT MAGNETICALLY CONJUGATED POINTS

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Abstract. In this paper presents the results of the analysis of correlation relationships between magnetically conjugated points of ionosphere. The coordinates of these points were calculated for two approximations of Earth's magnetic field — the dipole and International Geomagnetic Reference Field (IGRF). Correlations were calculated by analyzing the TEC Global Ionosphere Maps (GIM) from the CODE database. The analysis was carried out for the conditions of a strong geomagnetic storm — St. Patrick's storm on March 17, 2015. It is shown that during a storm, areas with high values of the correlation coefficient are concentrated at high latitudes; in the post-storm period, regions with a significant anticorrelation coefficient appear at all latitudes. The paper discusses the influence of a more accurate model of the geomagnetic field on the results obtained.

Introduction

Total Electron Content (TEC) is one of the key sources of information about the state of the ionosphere. The current state of development of receiving and Global Navigation Satellite Systems allows us to build a global distribution of this parameter. This data are widely used to study ionosphere response on different disturbances in global scale [*Blagoveshchensky et al.*, 2018]. In this paper has used GIM of TEC for detection the correlation at magnetically conjugated points, i.e., in points located at the base of the same magnetic-field line. For many problems, the position of the geomagnetic field lines can be calculated in the dipole approximation. Such an approximation will be quite accurate from certain heights above the Earth's surface, and as it approaches the Earth, the dipole lines of force will begin to deviate more and more from the real field. International Geomagnetic Reference Field is widely used model for calculation real Earth's magnetic field. The model applied for study Earth's core field, space weather, local magnetic anomalies and much more, also this model provides the operation satellite system [*Alken et al.*, 2021].

To study global distributions, it is convenient to apply statistical methods, such as correlation analysis. The study of the connection of magnetically conjugate points is also of great interest.

In this paper, were considered the connection of TEC at magnetically conjugate points during the geomagnetic storm of March 17, 2015 — St. Patrick's storm. This work is a continuation of previous studies of TEC variations at magnetically conjugate points [*Timchenko et al.*, 2021, 2022].

Data and method

In this paper were used daily average GIM of TEC CODE (Center for Orbit Determination in Europe) [*Schaer*, 1999], the example of this distribution presented on Fig. 1. The CODE data are defined on a grid from -87,5° to 87,5° by latitude with a step of 2,5° and from -175° to 180° by longitude with a step of 5°, in hourly resolution.

The data were carried out through similar procedures as in previous works: variations were averaged to daily averages, and detrending was also carried out using windowed averaging. After that, the TEC maps given in geographic coordinates were converted into geomagnetic ones, in two approximations: in the dipole and using the IGRF model. For the dipole approximation, each point (λ_m, φ_m) in northern hemisphere was assigned a conjugate point from the southern hemisphere ($-\lambda_m$, φ_m). Using the IGRF model, conjugate points were calculated in a similar way, i.e., for points in the northern hemisphere, conjugates in the southern were calculated. The TEC value at a magnetically conjugate point whose position didn't coincide with a grid node was calculated using bilinear interpolation over four neighboring nodes. The resulting grids, namely the nodes in the northern hemisphere and their corresponding conjugates in the southern hemisphere, are shown in Fig. 2, a — northern hemisphere, b — southern hemisphere in the dipole approximation, c — southern hemisphere according to the IGRF model. The color of the nodes corresponds to the TEC values, the "warmer" the color, the higher the value.

It can be seen from the figure that the position of the polar nodes in both approximations coincides. However, in the dipole approximation, the equatorial maximum is more strongly shifted towards the eastern hemisphere and stretched. In the model, the equator has a greater shift to the south. The main differences in the figure are indicated by red circles.

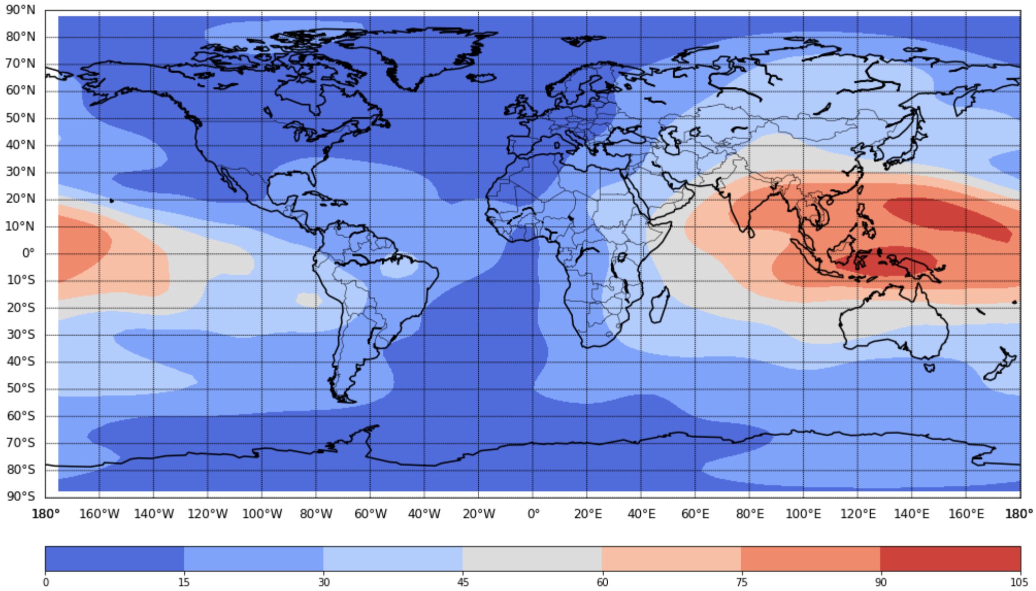

Figure 1. Global Ionospheric Map daily average distributions of Total Electron Content by CODE.

Based on the obtained data, the Pearson correlation coefficient was calculated using the formula:

$$\mathbb{R}(\lambda,\varphi,\lambda_c,\varphi_c) = \frac{\sum_{t=1}^{N}(TEC_d(\lambda,\varphi) - \langle TEC_d(\lambda,\varphi)\rangle)(TEC_d(\lambda_c,\varphi_c) - \langle TEC_d(\lambda_c,\varphi_c)\rangle)}{\sqrt{\sum_{t=1}^{N}(TEC_d(\lambda,\varphi) - \langle TEC_d(\lambda,\varphi)\rangle)^2 (TEC_d(\lambda_c,\varphi_c) - \langle TEC_d(\lambda_c,\varphi_c)\rangle)^2}}, \quad (1)$$

where N — the numbers of day under consideration; λ, φ — latitude and longitude in geographic coordinate system (CS); λ_c, φ_c — latitude and longitude magnetically conjugated point in geographic CS; $\langle TEC_d \rangle$ — average value of TEC_d variations for the considered period.

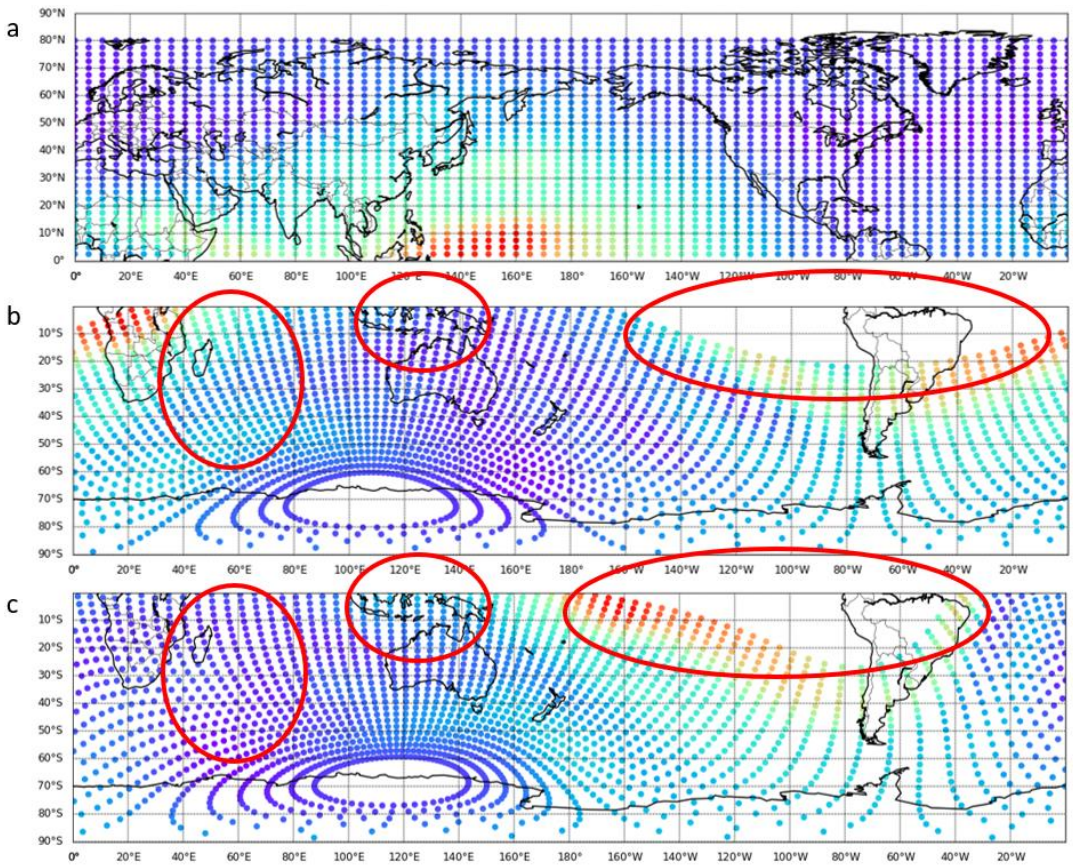

Figure 2. Grid nodes of the northern hemisphere, in which the TEC map (a) and its conjugate nodes in the southern hemisphere are specified: dipole approximation (b) and IGRF model (c).

Results

On Fig. 3 shows the values of the correlation coefficient of TEC variations of magnetically conjugate points: a — using the IGRF model and b — in the dipole approximation of the geomagnetic field, during the geomagnetic storm on March 17, 2015. Azimuth maps present the significant (0.75–0.9) and the high (>0.9) values of the coefficient in the northern hemisphere of the Earth. Shades of blue indicate anti-correlation relationship, red — positive. During a storm, the number of open magnetic-field lines increases, but the correlation in TEC variations remains and is determined by the similar behavior of disturbance sources in these areas.

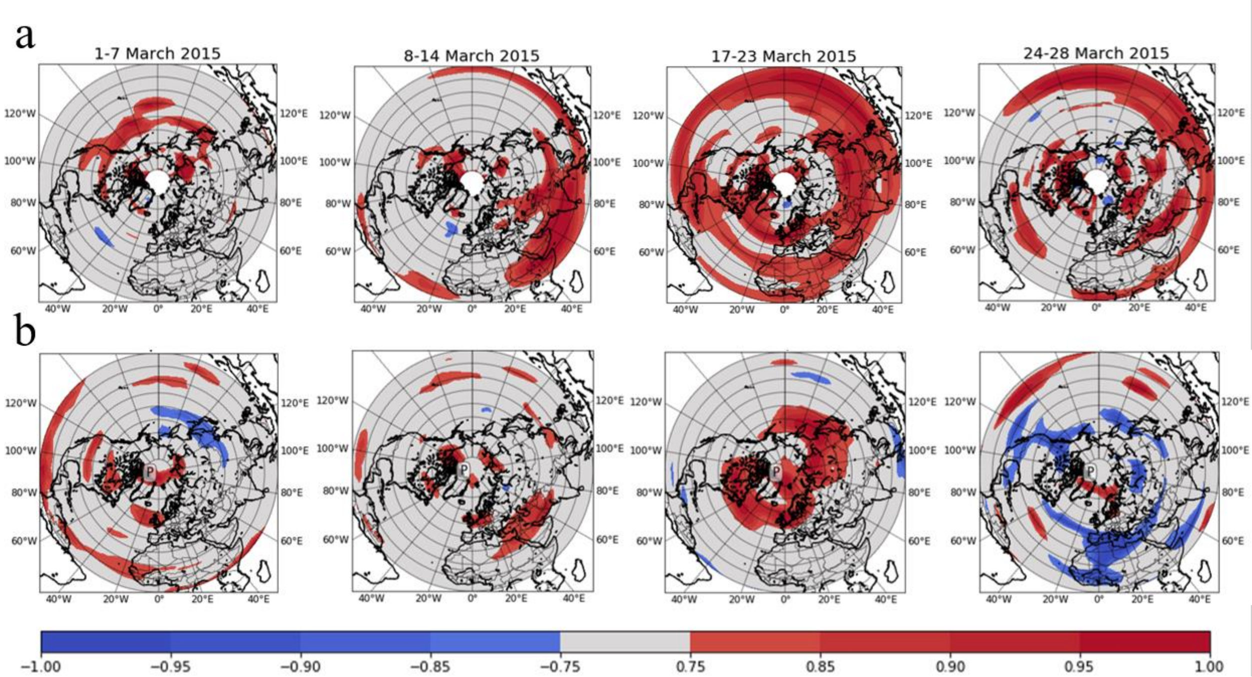

Figure 3. Correlation coefficient values calculated from TEC CODE maps. (a) is the geomagnetic field calculated using the IGRF model, (b) is the dipole approximation of the geomagnetic field.

This distribution of the correlation coefficient calculated for the dipole approximation present that during a storm, the correlation increases and is localized in the polar region. After the storm, during the recovery phase, on the contrary, the anticorrelation relations between hemispheres increase [*Timchenko et al.*, 2022].

In the case when magnetically conjugate regions are searched by the IGRF model, the positive correlation between the hemispheres is more pronounced. This is especially noticeable during a storm, where a positive correlation is present at all latitudes. It is also noted in IGRF that the behavior of the correlation coefficient in the pre-storm week coincides with the behavior in the recovery phase. In addition, during these two weeks, a positive correlation appears at equatorial latitudes, which was not in the dipole. Common to the two approximations of the geomagnetic field is an increase the anticorrelation relationship during the recovery phase after the storm.

The real Earth's magnetic field on ionospheric altitudes significant deviate from the dipole approximation. Total Electron Content calculated for an electron column at altitudes from 100 to 20 000 km. Ehe main contribution to TEC is made by electrons at heights from 100 to 500 km, in this reason, the IGRF should better reproduce correlations between magnetically conjugate regions of the ionosphere. But, high values of correlation coefficients at middle latitudes in the variant with IGRF require additional studies. It is possible that the results obtained are influenced by the method of constructing TEC maps: the selection of values, the methods of filling in map areas in which there are no GPS receivers. This issue remains open and requires separate consideration.

Conclusion

In this article, the values of the correlation coefficient TEC at magnetically conjugate points, calculated in the dipole approximation of the geomagnetic field and using the IGRF model, during the St. Patrick geomagnetic storm were considered.

It is shown that in the dipole approximation, during the storm, the positive correlation in the region of the poles increases. After the storm, the negative correlation increases.

The correlation obtained for the field calculated using the IGRF model increases during the storm at all latitudes. After the storm, the negative correlation also increases, but much weaker than in the dipole approximation.

Acknowledgment

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