"Physics of Auroral Phenomena", Proc. XLIV Annual Seminar, Apatity, pp. 130-132, 2021

Polar Geophysical Institute

DOI: 10.51981/2588-0039.2021.44.030

SEASONAL FEATURES OF THE CORRELATION OF THE TOTAL ELECTRON CONTENT AT MAGNETICALLY CONJUGATE POINTS

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Abstract. The paper presents the results of studies of the seasonal variability of statistical relationships between Magnetoconjugated Points (MCP) of the ionosphere. The analysis is based on the calculation of the correlation coefficients between the variations in the Total Electron Content (TEC) at points located on the same field line of the dipole magnetic field on both sides of the geomagnetic equator. Global TEC maps were used as initial data. For the four seasons of 2009 and 2015, the values of the Pearson's correlation coefficient between the variations in the Total Electron Content in the MCP were calculated. For two levels of solar activity, we examined the seasonal features of statistical relationships between TEC variations at points located on the same field line of the dipole magnetic field on both sides of the geomagnetic equator. Pearson's correlation coefficient was calculated for the mean daily TEC variations. It was shown in the work that during the period of low solar activity, the correlation between the TEC variations in the MCP regions is weak or absent, except for autumn. In 2015, a significant correlation between magnetoconjugated regions is observed during all seasons, while in winter and summer they are localized at low latitudes and in spring and autumn at high and middle latitudes.

Introduction

An important source of information on the state of the ionosphere is the Total Electron Content. The availability of this integral characteristic of the ionosphere for researchers, a large number of receivers providing good spatial coverage, the high temporal resolution of measurements, made TEC a kind of indicator of the state of the ionosphere and a convenient parameter for studying the dynamics of ionospheric processes. To study the response of the Total Electron Content to various disturbing factors, statistical methods are traditionally used, including correlation analysis. The expansion of the network of ground stations of the Global Navigation Satellite System (GNSS), the development of satellite observations made it possible to move from measuring the Total Electron Content in local areas to the construction of Global Ionospheric Maps of TEC (GIM TEC). The use of two-dimensional maps made it possible to move on to the study of large-scale processes in the ionosphere, including the TEC response to disturbances of various nature. In particular, many researchers have considered the features of the ionospheric response to strong earthquakes. For example, Li and Parrot, 2018 showed that the response of the ionosphere to an earthquake is observed not only above its epicenter but also at its conjugate point. Shim Ja, 2009 in his work carried out a study of the correlation between TEC variations at different spatial points on the GIM TEC. Among the many pairs of GIM TEC points, a good correlation was observed in MCP. Shuo L. et al, 2018 considered the local and spatial morphology of daytime TEC variations. They noted the presence of a significant correlation between variations at Magnetoconjugated Points of the equatorial anomaly. Yue et al, 2007 conducted a study of the correlation between diurnal TEC variations and incoherent scatter radar data. One of the results of the study is the conclusion about a significant correlation of variations in the Total Electron Content at high latitudes, which can exceed 0.8 at Magnetoconjugated Points.

It is clear that due to the existing geomagnetic connections between the sources, which determine the daily TEC variability, higher correlation values should be expected in MCP. At the same time, the problem of the variability of this correlation over longer time intervals, in particular, the dependence on the season, remains unexplored.

In this work, we investigated the change in the correlation coefficient between TEC variations at Magnetoconjugated Points for four seasons in 2009 and 2015.

Data and Method

As data we used GIM TEC set on a spatial grid from –87.5° to 87.5° in latitude, with a step of 2.5° and from –180° to 180° in longitude, with a step of 5°, with a time resolution of 1 hour. These maps are available on the IZMIRAN website: https://www.izmiran.ru/ionosphere/weather/.

We have selected TEC maps for 2009 and 2015, corresponding to the minimum and maximum levels of 24 solar activity cycles. When analyzing the data for the winters of 2009 and 2015, the data for December 2008 and 2014 were also used, respectively. Data preparation for correlation analysis was as follows. The original GIM TEC data is generated in a geographic coordinate system, which we have converted to a geomagnetic dipole coordinate system. For each point of the TEC map in the northern geomagnetic hemisphere with coordinates (θ_d, φ_d), there was a point in the southern geomagnetic hemisphere ($-\theta_d$, φ_d). Here θ_d and φ_d are geomagnetic latitude and longitude, respectively. After that, the obtained coordinates were again converted into a geographic coordinate system. Strictly speaking, not all points selected in this way can be called magnetically conjugated: from their set, those related to open lines of force should be excluded. Nevertheless, "conjugation" in the extended sense can be justified by the symmetry of the geophysical factors perturbing the high-latitude ionosphere in the dipole coordinate system.

The GIM TEC values were averaged to daily values, and then the trend and periodic component were removed from the time series of daily means using window averaging. The window size was 27 days. The Pearson correlation coefficient was calculated between the TEC variations prepared in this way in the Magnetoconjugated Points, and the length of the time series was limited to 30 days, and the series itself was centered on the solstices or equinoxes.

$$\mathbb{R}(\theta,\varphi,\theta_c,\varphi_c) = \frac{\sum_t (TEC_d(\theta,\varphi)_t - \langle TEC_d(\theta,\varphi)\rangle)(TEC_d(\theta_c,\phi_c)_t - \langle TEC_d(\theta_c,\phi_c)\rangle)}{\sqrt{\sum_t (TEC_d(\theta,\varphi)_t - \langle TEC_d(\theta,\varphi)\rangle)^2 (TEC_d(\theta_c,\phi_c)_t - \langle TEC_d(\theta_c,\phi_c)\rangle)^2}}$$

Where $TEC_d(\theta,\varphi)_t$ and $TEC_d(\theta_c,\varphi_c)_t$ – are values of the average daily TEC in t-day at the point with geographic coordinates (θ, φ) and the magnetoconjugate to it point with coordinates (θ_c, φ_c).

Results and Discussions

The correlation coefficients in the spatial maps form are shown in Fig. 1. The first four maps correspond to the winter, spring, summer, and autumn seasons of 2009 (a–d), the next four – 2015 (e–h). The maps show the northern hemisphere of the Earth, against the background of which the isolines of the correlation coefficient are plotted, taking values from –1 to 1. The scale of isolines is selected in such a way that only significant (from 0.75 to 0.9) and strong (more than 0.9) the value of the correlation coefficient.

As it could be seen, in 2009, in all seasons, except for autumn, there are no correlations between the hemispheres. In autumn 2009, a small spatial region appears at polar latitudes with high values of the correlation coefficient. In 2015, areas with significant correlation coefficients are observed during all four seasons. The localization of correlated zones during equinoxes and solstices is different: in winter and summer, areas of significant correlation are located in low and equatorial latitudes, and in spring and autumn in polar and high latitudes. Moreover, in the autumn equinox, areas of high and significant correlation expand to middle and low latitudes.

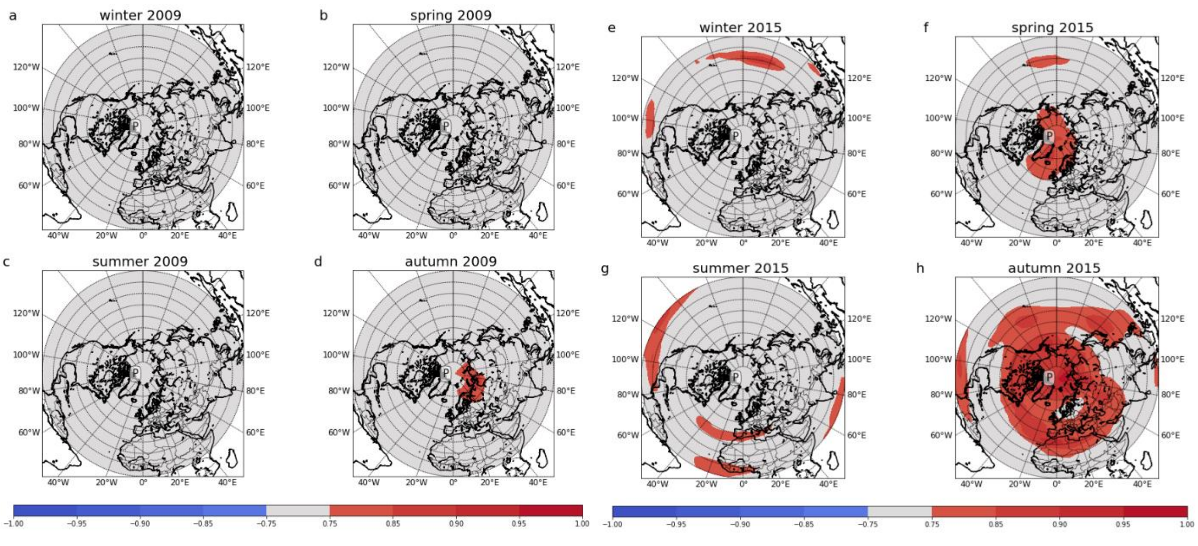

Figure 1. Distribution of the correlation coefficient of magnetoconjugate points for four seasons: winter, spring, summer and autumn 2009 (a-d) and 2015 (e-h), respectively.

Thus, the results of the analysis of TEC variations showed that under the condition of anomalously low geomagnetic activity in 2009, there is no correlation in the ionosphere between the geomagnetic hemispheres, except for the autumn season. On the opposite, high solar activity in 2015 was accompanied by a large number of geophysical disturbances. For example, in March and June 2015, there were very strong geomagnetic storms. A high level of disturbance also led to a significant correlation in MCP of the ionosphere, and during the solstices, TEC variations correlate at low and equatorial latitudes, and at the spring and autumn equinoxes, a significant correlation is manifested at high and circumpolar latitudes.

An important result of the analysis is also a clear predominance of correlations in the autumn period, which took place both in 2009 and 2015. This seasonal asymmetry requires further research.

Conclusion

The paper presents the results of a study of the seasonal variability of correlations in Magnetoconjugated Points of the ionosphere for two levels of solar activity, calculated from the data of the GIM TEC for 2009 and 2015. It is shown that in 2009, which was characterized by anomalously low values of solar and geomagnetic activity, a significant correlation between MCP was observed only in autumn in a limited longitudinal sector of high latitudes. In the case of high solar activity in 2015, areas with high values of interhemispheric correlation are observed in all seasons. At the same time, during the solstice periods, a significant correlation prevails at low and equatorial latitudes, and during the spring and autumn equinoxes — at high and middle (autumn) latitudes. A common pattern for two years is the predominance of a high level of interhemispheric TEC correlation in the autumn season.

Acknowledgments

This investigation was performed with the financial support of the Russian Science Foundation Grant No. 21-17-00208.

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