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BASIC RESULTS FROM THE PROJECT "INVESTIGATION OF THE GEOMAGNETIC DISTURBANCES PROPAGATION TO MID-LATITUDES AND THEIR INTERPLANETARY DRIVERS IDENTIFICATION FOR THE DEVELOPMENT OF MID-LATITUDE SPACE WEATHER FORECAST"

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Abstract. The project is directed to one of the topical tasks of the solar-terrestrial physics: study of the midlatitude effects of the magnetospheric substorms as a key element of the space weather. The goal of the project was to conduct a comprehensive analysis of the spatiotemporal characteristics of magnetospheric substorms and their effects at midlatitudes depending on space weather conditions. For this purpose, studies of various phenomena related to the development of substorm disturbances and their propagation to midlatitudes were carried out.

For the first time, an original catalog of the variations of the magnetic field at the midlatitude Bulgarian station Panagjurishte (PAG) was created for the period 2007 - 2022. A methodology was developed and universal programs were created for processing data from European stations, for obtaining maps of the spatial distribution of magnetic variations, and for calculating the midlatitude positive bay (MPB) index.

Analyses of events during quiet and disturbed geomagnetic conditions, during slow flows in the solar wind or high speed streams from coronal holes, were carried out. Some cases of supersubstorms have been studied in detail. The hypothesis of the development of an additional substorm current wedge during supersubstorms was confirmed. The morphological features of the polar substorms were also studied. Catalogs of supersubstorms and polar substorms for the past 20 years have been created.

The relationships between the statistical distributions of the MPB index and widely used geomagnetic indices and solar wind parameters were established.

Cases of occurrence of intense geomagnetically induced currents (GIC) during several strong magnetic storms were identified and analyzed.

Introduction

Magnetospheric substorms are important feature of the space weather. The main magnetic disturbances in the earth's magnetosphere are caused precisely by the development of substorms. It is known that magnetic disturbances during a substorm are associated with the formation and development of auroral electrojets in east and west direction which have been studied since 1970s [e.g., *McPherron et al.*, 1973a; *Kisabeth and Rostoker*, 1974]. The magnetic substorms are observed at the earth surface as sharp negative bays in the X component of the magnetic field. Although substorms are a typical phenomenon of auroral latitudes (from ~60° to ~71° geomagnetic latitude), depending on the conditions in the solar wind and the geomagnetic activity substorm disturbances can reach both very high latitudes (polar cap latitudes > 70° GMLAT) [*Pudovkin and Troshichev*, 1972; *Despirak et al.*, 2008], as well as middle (~50° GMLAT) and even low latitudes (< 20° GMLAT). In contrast to the auroral latitudes, at midlatitudes magnetic substorms are observed as positive bays in the X field component, the so-called midlatitude positive bays (MPB) [e.g., *McPherron et al.*, 1973b]. At first it was assumed that the maximum in X is created by the low latitude reverse currents of the westward electrojet [*Akasofu et al.*, 1965], then the occurrence of maxima was explained by the outflowing field-aligned currents [*Meng and Akasofu*, 1969]. Later it was found that the midlatitude positive bays usually observed during the expansion phase of the substorm are related to the substorm current wedge (SCW) [e.g., *McPherron et al.*, 1973b]. It was found that during substorms, the azimuthal (Y) component of the magnetic field at midlatitudes, is positive to the west of the electrojet center, and negative to the east from it. The X and Y variations at the Earth surface have been used in a number of studies of the magnetospheric substorms. For example, the MPB's are a good indicator of the substorm onset [*McPherron and Chu*, 2017], the sign of Y component was used to estimate whether the field aligned currents flow into the ionosphere or out of it at a given longitude [*Meng and Akasofu*, 1969]. A special index has been developed - the midlatitude positive bay index (MPB index) [*McPherron and Chu*, 2017] as an indicator of substorm current wedge characteristics.

The project "Investigation of the geomagnetic disturbances propagation to mid-latitudes and their interplanetary drivers identification for the development of mid-latitude space weather forecast" is a bilateral project Bulgaria – Russia 2019 – 2020, financed by the National Science Fund (project number КП-06-Русия/15) and by the RFBR (project number 20-55-18003Болг_а). The project was directed to one of the topical tasks of the solar-terrestrial physics: study of the midlatitude effects of the magnetospheric substorms as a key element of the space weather. Its main goal was to investigate substorms in Europe at low, mid- and auroral latitudes and their relationships with structures in the solar wind as an element of Space weather, applying the MBP-index concept to a network of European stations.

The present work is meant to report briefly the results of the work on the project. They are grouped in three sections, following the work packages of the project: development of a catalog of the magnetic variations at the Panagjurishte station, study of midlatitude substorms, and analysis of events of extreme intensity and related phenomena.

Catalog of the magnetic variations at the Panagjurishte station

For the first time, an original catalog of magnetic field variations at the midlatitude Bulgarian magnetic station Panagjurishte (PAG) (~37° GMLat, ~97° GMLon) has been created. The catalog takes in data from 2007 to the end of 2022. It is located on the website of the Space Research and Technology Institute, BAS, and is available at: http://space.bas.bg/Catalog_MPB/. A concept was worked out for the type, structure and content of the catalog, which developed with the progress of the work [*Guineva et al.*, 2021a; *Guineva et al.*, 2021b; *Guineva et al.*, 2023]. In the current version, the catalog consists of three main sections: Magnetic field data, Data about MPB and Catalog publications. In the section Magnetic field data the processed X and Y magnetic components and the calculated horizontal power of the magnetic field at PAG (Data Files subsection) are stored as well as their plots (Graphs subsection). The second section, Data about MPB, consists of four subsections: Fast Look Daily Graphs, Yearly Lists, MPB Parameters, and MPB Graphs. Fast Look Daily Graphs are composite plots including the *IL* index calculated for the IMAGE PPN-SOR and PPN-NAL station chains, X-component variations, and horizontal power of the magnetic field. The Yearly lists include data on cases where significant variations (midlatitude positive bays - MPB) are observed during substorms, verified by the *IL* index. The MPB parameters and MPB graphs sections present the defined main MPB parameters for the cases from the Yearly MPB lists and graphs representing the MPB maximum and the minima indicating the start and end of the MPB. The Catalog Publications section provides access to articles describing the catalog or using data from it for some research.

A methodology was developed and original programs were created for processing data from ground-based magnetic observations and calculating the midlatitude positive bays index (MPB index), which were used to analyze data from geomagnetic observations at more than 50 European stations at mid- and auroral latitudes, including from the Bulgarian station Panagjurishte [e.g., *Werner et al.*, 2021; *Guineva et al.*, 2022, 2023a, 2023b]. The processing tools to build the catalog and investigate the substorm disturbances can be grouped in three data processing and visualization modules. The first module involves processing the raw magnetic field data, the second module includes processing tools to obtain the data about MPB. The third module comprises programs, related to the computing and presentation of the spatial distribution of the magnetic disturbances.

Study of midlatitude substorms

To study the spatial distribution of the magnetic field components variations during substorms, chosen cases of isolated substorms have been used. Different kinds of substorms have been examined, namely usual, expanded and polar substorms, during different interplanetary conditions: quiet or disturbed [e.g., *Guineva et al.*, 2021c, 2021d, 2023b]. For the studies purposes, the X and Y variations due to the substorms were computed for more than 50 stations based on the developed programs.

Basic parameters of the substorm appearance at midlatitudes can be derived from the variations distributions and the profiles. Maps of the X magnetic component in the range 38°÷73° LAT, 10°÷ 32° LON and of the Y component in the range 38° ÷ 55° LAT, -10° ÷ 35° LON and longitudinal and latitudinal profiles for the time of the maximal substorm developments at Panagjurishte (PAG) and some other moments of the substorm development have been constructed. In Fig.1 the map of the used stations and an example of the X and Y distributions at chosen times of the substorm development on 22.03.2013 are presented.

Some characteristics as the line of sign conversion latitude, the central meridian, the longitudinal and latitudinal extent of the positive bays and the latitudinal and longitudinal dependence of the variations have been estimated: the latitudinal dependence of the X variations in all examined cases is as follows: after the sign conversion latitude X increases, reaches a maximum close to it, and decreases gradually. The sign conversion latitude during expanded substorms is higher (~60-67°MLAT) than during usual substorms (~53-60°MLAT), and it is highest for polar substorms (~68-70°MLAT); the maximal MPB amplitude in latitudinal direction is very small for the polar substorms, higher for the usual substorms, and greatest for the expanded substorms; the same result is obtained for the horizontal power of the magnetic field; the obtained MPB duration for the studied substorms is the shortest for the polar substorms, it appears some longer for the usual substorms, and most continued are the expanded substorms; the latitudinal and longitudinal extent increase up to the maximal substorm development; at the maximal development, the longitudinal and latitudinal extent are higher for expanded substorms. For the first time, European MPB index was introduced, which reflects the substorm appearance at European midlatitudes. The obtained results coincide very well with the results about the global MPB index for the same substorms by *Chu et al.* (2015) (Fig.2).

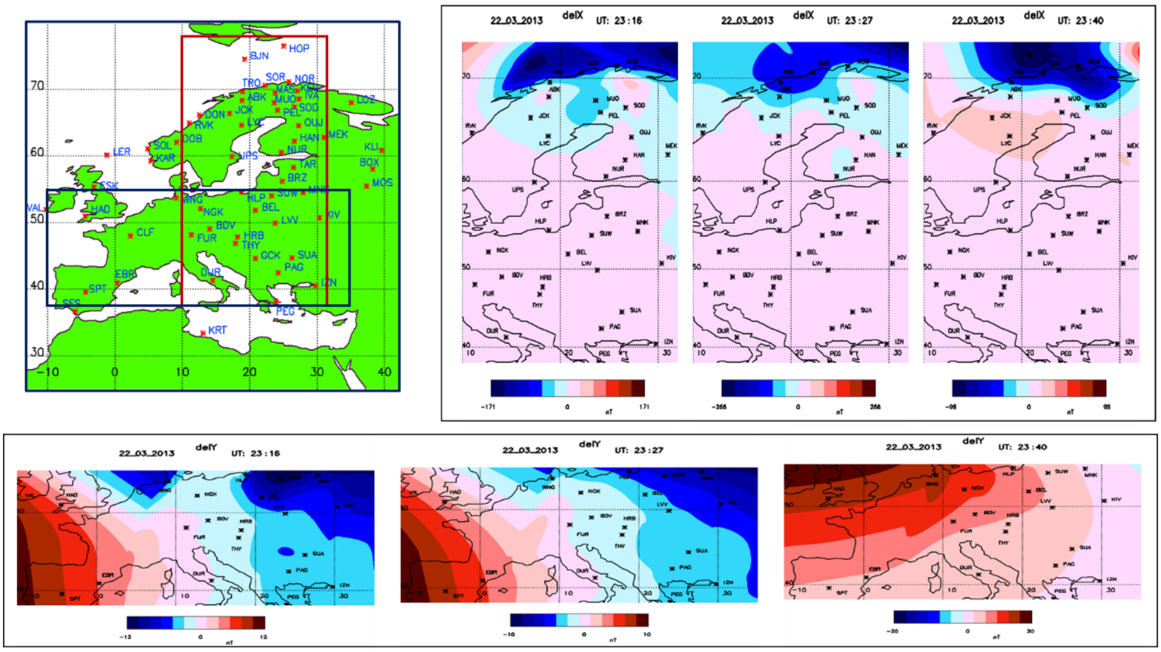


Figure 1. Examples of maps of the X and Y distributions. Upper left panel: Stations, used to compute the distribution of the magnetic variations on the Earth surface. The rectangular frames in the figure indicate the regions for which maps of the spatial distribution of X (red line) and Y (blue line) are constructed. Upper right panel: Maps of the X magnetic variations at three typical moments during the substorm development on 22.03.2013: at 23:16 UT, 23:27 UT (maximal development), and at 23:40 UT. The sign conversion boundary is clearly seen. Bottom panel: Maps of the Y magnetic variations at the same three moments during the substorm development. The central meridian of the substorm arises in the Y-maps, close to the sign conversion in Y.

Analysis of events of extreme intensity and related phenomena

Statistical studies

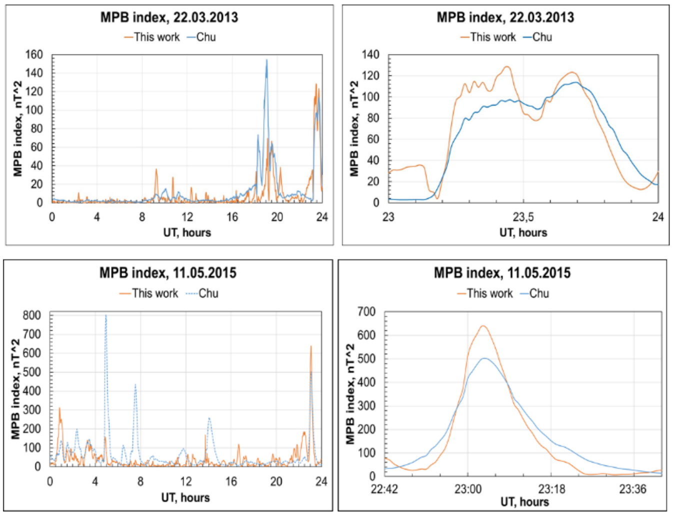
For the first time we statistically analyzed the substorm activity at auroral latitudes for 2007–2020 and its relationship with the magnetic disturbances at middle latitudes based on the *IL* index (similar to the *AL* index, but according to IMAGE data). INTERMAGNET, SuperMAG, and IMAGE magnetometer data have been used [*Werner et al.*, 2023a].

We selected events near the meridian of the IMAGE network, in the night sector (21-03 MLT). Two samples of events were used: (1) $IL < -200$ nT for at least 10 min, with an additional criterion for the presence or absence of positive bays at the Panagjurishte station in Bulgaria, and (2) isolated substorms observed on the IMAGE meridian according to the list of *Ohtani and Gjerloev* (2020).

The distributions of the *IL* index, as well as the empirical and theoretical cumulative distribution functions, are obtained, and the occurrence of extreme events is also estimated.

It is shown that, in general, the *IL* distributions are described well by exponential functions, and out of all events, events accompanied by midlatitude positive bays were observed in ~65% of cases while their fraction increased with increasing disturbance intensity. Events accompanied with MPB and isolated substorms were better described by the Weibull distribution for extreme events (Fig.3a). The intensity of the flow of events was determined: the frequency of occurrence of events with $IL < -1500$ nT is ~0.35 events/year (Fig.3b).

From both distributions, annual and semi-annual variations were identified: annual variations have a summer minimum and a winter maximum, and semiannual variations have maxima near the equinoxes, which is most likely due to the Russell-McPherron effect. The semi-annual variation is also shown to be more pronounced for events with accompanying midlatitude positive bays.



Comparison of our results with the results of Chu et al. [29]

Date	Quantity	This work	Chu et al. (2015)
22.03.2013	MPB_{max1}, nT^2	128.4	97.47
	UT_{max1}	23:27	23:28
	MPB_{max2}, nT^2	123.18	113.77
	UT_{max2}	23:41	23:42
11.05.2015	MPB_{max}, nT^2	639	502
	UT_{max}	23:03	23:02

MPB_{max} – maximum of the MPB index
UT_{max} – time of the obtained maximum

Figure 2. MPB index obtained by *Chu et al.* (2015) and us for 22.03.2013 (upper left panel) and 11.05.2015 (bottom left panel). The middle panels display the MPB index during the substorms developed over Europe (noticeable maxima in MPB indices) in the same days. The table to the right shows some numerical results about the MPB index maxima.

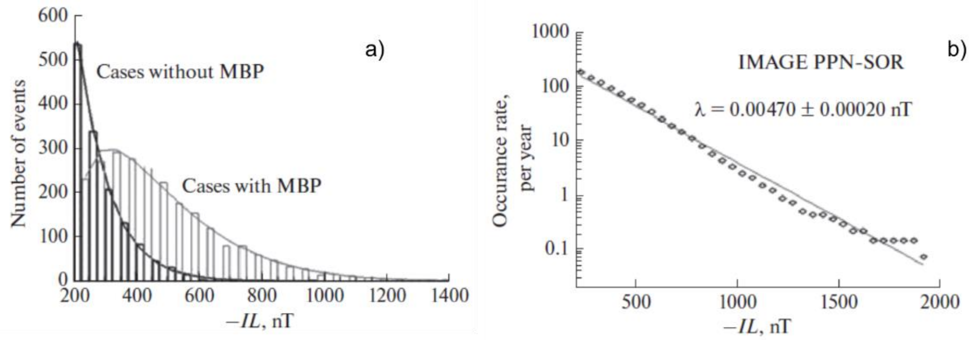


Figure 3. *IL* index distribution histograms for events with a positive bay (MPB) in Panagjurishte (grey) and without a positive bay (black). The solid lines show the histograms approximation by the Weibull distribution (a). Rate of events per year for PPN-NAL. The empirical dependence is shown by circles, and the theoretical approximation is shown by a solid line. It is seen that the occurrence of extreme events with *IL* < –1500 nT is ~0.35 events/year (b).

The occurrence of magnetic substorms and their activity have been described with the help of extreme value distributions. Statistical studies of the substorm occurrence in the following time sectors: morning (3–9 MLT), day (9–15 MLT), evening (15–21 MLT), and night (21–3 MLT) sectors for the auroral zone (PPN-SOR IMAGE chain) and for high latitudes (BJN-NAL chain) have been performed [*Werner et al.*, 2023b]. The histograms, the empirical cumulative distributions and the occurrence rates were computed. It was shown that the empirical distributions could be well approximated with exponential distributions. The distribution parameters were determined from the occurrence rates. Three classes were discovered, which differ significantly by the respective distribution parameters. Structural changes in the distributions were found in the morning sector at both auroral and high latitudes.

The relationship between the occurrence rate of magnetic disturbances with *IL* < −1000 nT and the frequency of occurrence of geomagnetically induced currents was highlighted. It was found out that in Scandinavia events (totaled across all sectors) which could induce currents (GICs) in gas pipelines stronger than 10 A occur about seven times a year. In contrast, such events are to be expected only half as often at Svalbard.

The statistical distributions of various geomagnetic indices (*MPB*, *SML*, *SYM/H*, *ASY/H*, *AL*, *AE* and *PC(N)*) and solar wind parameters (B_T, B_X, B_Y, B_Z, V, T, P_{dyn}) are obtained for the period from 1991 to 2019. It was found that the MPB index, which characterizes the intensity of geomagnetic disturbances at midlatitudes, increases with an increase in the level of geomagnetic activity, as well as with an increase in the interplanetary magnetic field, the speed of the solar wind and the dynamic pressure, but to a lesser extent depends on its density and temperature [*Lubchich et al.*, 2023].

Study of supersubstorms

A kind of very intensive substorm disturbances, the so called “supersubstorms”, when the index *AL* < -2000 nT, and their manifestation at midlatitudes have been studied. Usually supersubstorms develop during magnetic storms. A catalog of supersubstorms recorded at the global network of ground stations over the past 20 years (1999-2019) has been compiled.

Several of the most striking events - April 5, 2005, May 28, 2011 (Fig.4a) and December 20, 2015 have been examined in detail [e.g., *Despirak et al.*, 2022a, 2022b, 2022c]. Study of the spatial-temporal dynamics of the supersubsorms was performed by means of analysis of ground-based magnetograms, instantaneous maps of magnetic field vectors by data from the SuperMAG network, and maps of the global distribution of magnetic field variations and field aligned currents from AMPERE project. It is shown that the peculiarity of the planetary distribution of ionospheric currents during supersubstorms is that the westward and eastward electrojets develop on a global scale, surrounding the Earth from different sides. The development of these global currents was accompanied by intense midlatitude positive bays and significant leaps in the MPB index (~ 4000-6000 nT^2).

At the same time, a significant strengthening of the eastward electrojet occurred in the evening sector (~15-18 MLT), i.e. in the same sector where the appearance of an additional ring current was observed, which confirms the hypothesis of an additional substorm current wedge arising during supersubstorms on the evening side (Fig.4b).

Additionally, rare supersubstorm events that were recorded in non-storm conditions (*SYM/H* > -50 nT) were studied. It is shown that these events are also characterized by the development of ionospheric currents on a global scale and the formation of a strong eastward current in the evening sector. It is shown that such events were observed either at the very beginning of a storm caused by a coronal mass ejection (SHEATH or MC storm), or in the late recovery phase of a moderate magnetic storm caused by the CIR region of high-speed solar wind stream (HSS), or in the absence of a magnetic storm, but at high solar wind speeds ~600-700 km/sec.

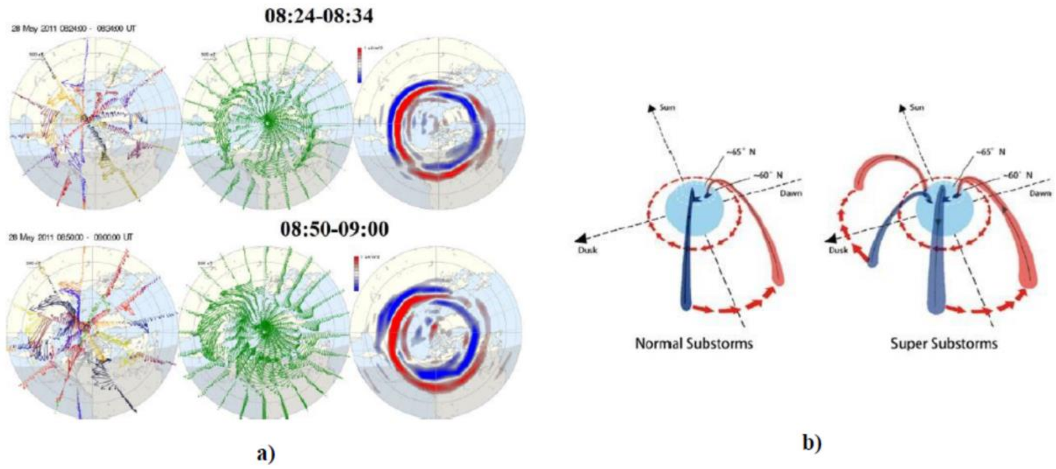


Figure 4. Distribution of magnetic disturbance vectors, their spherical harmonic analysis and field-aligned current distribution for two moments (at ~ 08:30 UT and ~ 08:55 UT) on May 28, 2011 according to AMPERE data (a); models of substorm current wedge (SCW) for normal substorm and for supersubstorm (b).

Study of geomagnetically induced currents (GIC)

Development of of intense (>20 A) geoinduced currents (GIC) on a meridional profile from subauroral to high latitudes (from ~60º to ~ 69º) was traced out using two systems for recording GIC in ground networks: at substations of main electrical networks in the North-West of Russia, located in the auroral zone, and on a gas pipeline near the city of Mantsala (Finland), located in the subauroral zone.

Several cases of the appearance of intense GICs were studied in detail: during the magnetic storms in March 2012 and 2013, and during a complex space weather event in September 2017 [*Despirak et al.*, 2022d; *Setsko et al.*, 2023]. Several moderate to very intense substorms (supersubstorms) have been recorded against the background of these magnetic storms. It was shown that the appearance of intense GICs at different latitudes occurred in accordance with the development of the fine spatiotemporal structure of the substorm, corresponding to the poleward movement of individual substorm activations. It has been established that the main sources of GIC growth at auroral latitudes are the intensification and poleward movement of the westward electrojet during the expansion phase of the substorm, as well as Pc5 pulsations, usually observed during the recovery phase of the substorm. A good relationship was found between the appearance of GIC and an increase in the geomagnetic indices *IL* and *Wp*, which characterize the substorm activity.

Summary

The goal of the project was to conduct a comprehensive analysis of the spatiotemporal characteristics of magnetospheric substorms and their effects at midlatitudes depending on space weather conditions.

For the first time, an original catalog of the variations of the magnetic field at the midlatitude Panagyurishte station (PAG) was created for the period 2007-2022. The variations of the horizontal components of the magnetic field and the main characteristics of the midlatitude positive bays (MPB) were determined. The catalog is available on the Internet (http://space.bas.bg/Catalog_MPB/).

Universal programs were created for data processing, obtaining maps of the spatial distribution of magnetic variations, and for calculating the MPB index. For the first time, a Central European MPB index has been introduced, which provides information on the development of substorms over Europe.

Substorms were analyzed during different conditions in the solar wind. The spatiotemporal characteristics of different types of substorms: regular, extended, and polar were identified and compared.

An algorithm and program for detecting substorms based on variations in the *IL* index were developed, a statistical analysis of substorm activity at auroral latitudes and its relationship with midlatitude magnetic disturbances for the period 2007–2020 was performed. For the first time, distributions of simultaneous geomagnetic disturbances at PAG and on the IMAGE meridian were obtained.

The statistical distributions of various geomagnetic indices and solar wind parameters for the period from 1991 to 2019 were obtained and their relationship with the MPB index was established.

Research has been conducted on supersubstorms and polar substorms. The hypothesis of an additional substorm current wedge on the evening side during supersubstorms is confirmed.

Cases of intense geoinduced currents (GIC), which often lead to damage in terrestrial electrical networks, have been analyzed. The main sources of the GIC were found to be the poleward motion of the westerly electrojet and geomagnetic pulsations Pc5.

The results are presented at 18 conferences with 48 presentations and 39 papers on the subject of the project have been published. Research on the project is topical and will be continued based on the results obtained.

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