CLASSIFICATION OF ISOLATED SUBSTORMS TAKING INTO ACCOUNT GENERATION CONDITIONS AND PHASE CHARACTERISTICS

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A neural network classification of isolated substorms was performed, taking into account the features characterizing the peculiarities of generation of different substorm phases. For this purpose, the following classification features were chosen: the duration of the nucleation phase, the development phase, the recovery phase, and the duration of the substorm as a whole, as well as the behavior of the *Bz* component of the interplanetary magnetic field (IMF). The latter feature is understood as the southward rotation of the *Bz* component of the IMF, which determines the beginning of the nucleation phase of the substorm. These features are adopted as input series for the self-learning neural network models being created. The result of the classification neural networks is the formation of graphical images of the set of the above classification features, each of which contains information on the duration of the phases of the considered substorms. Classification neural network experiments allow us to divide substorms into five classes. The physical features of the selected classes consist in the cause-and-effect relationships between the duration of substorm phases and solar wind parameters and MMP features.

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INTRODUCTION

An important problem in modern heliogeophysics is modeling and forecasting global and substorm activity based on parameters of the near-Earth space environment. It is known that the main cause of intense geomagnetic substorms is a strong and prolonged (more than 3 hours) negative component of the interplanetary magnetic field [1]. It can be contained in one of the numerous solar wind structures or arise as a result of interactions between these structures. However, some structures cause noticeable global disturbances regardless of the presence of a negative component of the interplanetary magnetic field [1-4]. Of particular interest are studies of the characteristics of isolated substorms. Several works propose classification variants of isolated substorm events, taking into account features that characterize the conditions for generating different phases [3]. Such studies consider the generally accepted model of the substorm process, where the accumulation of potential energy in the magnetosphere during the preparatory phase of the substorm is associated with an enhancement of the large-scale westward electric convection field across the magnetospheric tail [5, 6]. This potential energy, in turn, is determined by the kinetic energy of the solar wind [7, 8]. However, the process of its accumulation due to inflow from the solar wind during the preparatory interval of a substorm cannot be accounted for based only on instantaneous values (Bz , N , V), where N is the solar wind flux density, V is the solar wind flow velocity. It can be more accurately estimated by calculating the integral value ΣNV^2], which characterizes the change in the amount of energy entering the magnetosphere from the solar wind in the form of kinetic energy over one hour [1, 9]. The subsequent onset of the active phase of the substorm is usually [3] associated with the explosive conversion of the accumulated potential energy of the magnetospheric magnetic field into the kinetic energy of particles in the radiation belts that ionize the ionosphere. The mechanism of radiation belt formation proposed here is considered as a possible example, and of course there are mechanisms of their formation apart from substorms.

This work explores the possibility of combining all parameters that characterize both the cause, i.e., the structure of the solar wind, and the effect, i.e., the geomagnetic disturbance, through indirect indicators. This is done to create a classification of isolated substorms that takes into account the conditions of generation and characteristics of its various phases. The features used for classification describe the duration of the growth phase, expansion phase, recovery phase, and the duration of the entire substorm. Thus, the object of this study is isolated substorm events of various intensities and durations, which are known to be reflected in the temporal dynamics of the AL -index. For this purpose, the dynamics of the AL -index is investigated during time intervals when the magnetosphere interacts with active solar plasma flows. Since the studied configurations of the AL -index contain information about these flows and the peculiarities of the Earth's passage through them, there is an opportunity to classify the temporal structure of the AL -index taking into account the generation conditions and characteristics of substorm phases. For the classification of substorms, the method of artificial neural networks (ANN) is applied, which allows, based on nonlinear correlation processing of experimental data, to perform intelligent separation of input patterns into classes.

DATA USED AND PARAMETERS OF THE NEURAL NETWORK MODEL

The high interest in neural networks recently is due to the wide range of problems solved with their help, when physical modeling is complicated by considering too many parameters. Currently, the ANN method is actively used in forecasting tasks for various geophysical applications. The high speed of modern computers allows neural networks to be used everywhere, including in solving non-standard problems. Performing classification of significant data arrays, such as image processing and pattern recognition, is now considered a trivial neural network task. This work is devoted to this particular area of ANN application — pattern classification. The peculiarity of our approach to research lies in the subsequent physical interpretation of the obtained results.

The ANN created in the work is built according to the classical principle of self-learning. To solve the classification task, a self-learning ANN was designed and used. The architecture of this network is built on the principle of a Kohonen layer [10-12] and is presented in Fig. 1.

Fig. 1. Architecture of the Kohonen layer type ANN

The purpose of the neural network is to classify graphical images of a set of classification features. Each such image contains information about the ratio of the durations of the phases of the considered substorms. The features used for classification describe the duration of the initiation phase (parameter P 1), the duration of the development phase (parameter P 2), the recovery phase (parameter P 3), and the duration of the entire substorm as a whole (parameter P 4). The beginning of the substorm initiation phase was determined by the southward turning of the Bz -component of the IMF. The listed classification features characterize the peculiarities of the generation conditions of various phases of the studied substorms. They are accepted as input series for the created self-learning neural network models.

The result of neural network experiments is the determination of the number of classes that best corresponds to the information contained in the used data. Classification parameters within each analyzed combination are normalized, which allows presenting the entire data array on a single scale for the neural network, while preserving information about the intensity of events. In this paper, we propose a demonstration of data arrays using graphics in the form of polygons. Examples of visualization of parameter combinations involved in classification are shown in Fig. 2. These are images in the form of polygons. The numbers in the figure (Fig. 2 *a*) indicate different phases (initiation, development, and recovery) of the substorm, the radius value for each triangle peak corresponds to the relative duration of the phase. It is also possible to use a combination of different phases, such as the quadrilateral in Fig. 2 *d*.

Fig. 2. Examples of visualization of parameter combinations

The following criteria were used for the selection of isolated substorms:

- time interval from the previous disturbance of at least 3 hours;
- magnetic bay intensity at the maximum 250 nT $<$ Max$|AL|$ $<$ 1300 nT;
- substorm duration $<$ 3 hours;
- end of the substorm: UT time, after which the disturbance magnitude $|AL|$ $<$ 0.2 Max$|AL|$.

Preliminary selection of substorms according to these criteria was carried out by visual inspection of daily variations of the AL -index, more precisely the beginning of the substorm development phase and the duration of its phases were determined by a program specially developed for this purpose. An additional sign of the substorm appearance was the presence of corresponding variations in the magnetic activity indices SYM/H(D) or ASYM/H(D). According to the criteria, 106 isolated substorm events of various intensities were selected for the period from 1994 to 2012 based on NASA catalog data (http://cdaw.gsfc.nasa.gov). The strict requirements for the analyzed events significantly reduced their number and left only unobscured ones. The assessment of substorm activity and phase duration was performed using minute data of the AL index.

NEURAL NETWORK RESULTS OF NUMERICAL CLASSIFICATION EXPERIMENTS

The classification features describe the duration of the growth phase, the duration of the expansion phase, the recovery phase, and the entire substorm. Thus, the result of the classification neural network was the formation of graphical images (Fig. 3) of a set of classification features. Each such image contains information about the duration of the phases of the considered substorms. In the presented image (Fig. 3), the vertex of the quadrilateral at 12 o'clock characterizes the relative duration of the entire substorm, and then clockwise follow the relative periods of the growth phase duration, expansion phase, and recovery phase. As a result of neural network experiments, the considered substorms were classified into five classes.

Fig. 3. Visualization of combinations of classification parameters. Relative values of parameters are demonstrated: duration of the initiation phase (parameter *P* 1), development phase (parameter *P* 2), recovery phase (parameter *P* 3) and the duration of the entire substorm as a whole (parameter *P* 4). In this example, the current value of parameter *P* 2 coincides with the maximum possible *P* 2 max in the considered sample of substorm events.

Visual inspection of the classification results in the form of polygon groups (Fig. 4–8) is consistent with the conclusions proposed by the ANN. Analysis of the obtained data allows us to formulate the following features of the obtained classes.

<u>Class 1</u> – substorms with prolonged development and recovery phases and with a shortened initiation phase (Fig. 4)

<u>Class 2</u> – substorms with a prolonged initiation phase (Fig. 5)

<u>Class 3</u> – substorms with phases of equal magnitude (Fig. 6)

<u>Class 4</u> – substorms with a prolonged development phase (Fig. 7)

<u>Class 5</u> – substorms with a short recovery phase (Fig. 8)

Fig. 4 Class 1

Fig. 5 Class 2

Fig. 6 Class 3

Fig. 7 Class 4

Fig. 8 Class 5

CONCLUSION

The uniqueness of the neural network tool lies in the absence of analytical approaches and explicit models. Despite this, neural network conclusions fully correspond to real physical phenomena and demonstrate the most compact and at the same time meaningful result. The physical nature of the results obtained is ensured by the problem statement, the data used, and the interpretation of neural network responses.

This article demonstrates the capabilities of a tool created by the authors for classifying isolated substorms, taking into account generation conditions and phase characteristics. The applied classification neural network revealed patterns in the relationship between the duration of substorm phases for the considered isolated substorms. The physical phenomena leading to high-latitude geomagnetic manifestations are taken into account. Graphical images of classification feature sets have been formed. Each image contains information about the duration of phases of the considered substorms caused by the impact of solar wind plasma flows on the Earth's magnetosphere. As a result of neural network experiments, such substorm images were classified. The fact that substorms can be divided into classes reflects the specific states of the high-latitude magnetosphere.

Analysis of the obtained results allowed formulating the features of the five obtained classes and drawing the following physical conclusions. Class 1 assumes prolonged development and recovery phases of a substorm with a shortened growth phase; class 2 indicates a prolonged growth phase; class 3 demonstrates substorm phases of equal duration; class 4 is associated with a prolonged development phase; class 5 contains substorms with a short recovery phase. The physical features of the discovered classification are determined by the cause-and-effect relationships between the duration of substorm phases and the parameters of the solar wind and IMF. That is why the features of the discovered classes will form the basis for further research on the physics of cause-and-effect relationships between the duration of substorm phases and the parameters of near-Earth space.

IMF parameters, solar wind plasma, and magnetic activity indices were taken from the pages http://wdc.kugi.kyoto-u.ac.jp/ and http://cdaweb.gsfc.nasa.gov/ .

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REFERENCES

1. *Barkhatov N.A., Vorobyev V.G., Revunov S.E., Yagodkina O.I* . Manifestation of solar wind parameter dynamics on the formation of substorm activity // Geomagnetism and Aeronomy. 2017. Vol. 57. No. 3. P. 273–279.
2. *Barkhatov N.A., Gromova L.I., Dremukhina L.A., et al.* Accounting for the energy budget of the magnetosphere in the problem of classification of magnetospheric activity sources // Bulletin of the Russian Academy of Sciences: Physics. 2006. V. 70. No. 10. P. 1535–1537.
3. *Vorobyev V.G., Yagodkina O.I., Antonova E.E., Zverev V.L* . Influence of solar wind plasma parameters on the intensity of isolated magnetospheric substorms // Geomagnetism and Aeronomy. 2018. V. 58. No. 3. P. 311–323.
4. *Vorobjev V.G., Antonova E.E., Yagodkina O.I* . How the intensity of isolated substorms is controlled by the solar wind parameters // Earth, Planets and Space. 2018. V. 70. Iss. 148 doi.org/10.1186/s40623-018-0922-5.
5. *Lynch B., Zurbuchen T., Fisk L. et al* . Internal structure of magnetic clouds: Plasma and composition // J. Geophys. Res. 2002. V 08. Iss. A6. Art.ID. 1239.
6. *Newell P.T., Sotirelis T., Liou K. et al.* A nearly universal solar wind-magnetosphere coupling function inferred from 10 magnetospheric state variables // J. Geophys. Res. 2007. V. 112. Art.ID. A01206.
7. *Crooker N.U., Kahler S.W., Gosling J.T. et al* . Evidence in magnetic clouds for systematic open flux transport on the Sun // J. Geophys. Res. 2008. V. 113. Art.ID. A12107. doi:10.1029/2008JA013628.
8. *Kilpua E.K.J., Li Y., Luhmann J.G. et al.* On the relationship between magnetic cloud field polarity and geoeffectiveness // Ann. Geophys. 2012. V. 30. P. 1037–1050. DOI:10.5194/angeo-30-1037-2012.
9. *Barkhatov N.A., Vorobyev V.G., Revunov S.E. et al.* Substorm activity and orientation of the shock front of an interplanetary magnetic cloud // Geomagnetism and Aeronomy. 2019. V. 59. No. 4. P. 427–436.
10. *Barkhatov N.A., Revunov S.E.* Neural network classification of discontinuities in space plasma parameters // Solar-Terrestrial Physics. 2010. Iss. 14(127). P. 42–51.
11. *Barkhatov N.A., Vorobjev V.G., Revunov S.E. et al* . Neural network classification of substorm geomagnetic activity caused by solar wind magnetic clouds // J. Atmospheric and Solar–Terrestrial Physics. 2020. V. 205. Art.ID. 105301.

12. *Barkhatov N.A., Vorobyev V.G., Revunov S.E. et al* . Neural network classification of cause-effect relationship between substorm activity and structural elements of solar wind magnetic clouds // Proceedings of the Russian Academy of Sciences. Physics Series. 2022. Vol. 86. No. 3. P. 329–334.

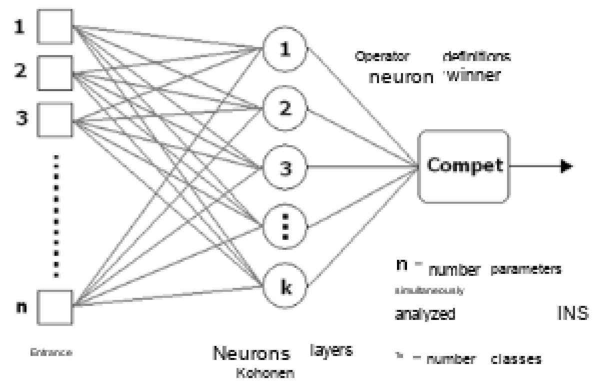


Fig. 1. Architecture of ANN of Kohonen layer type

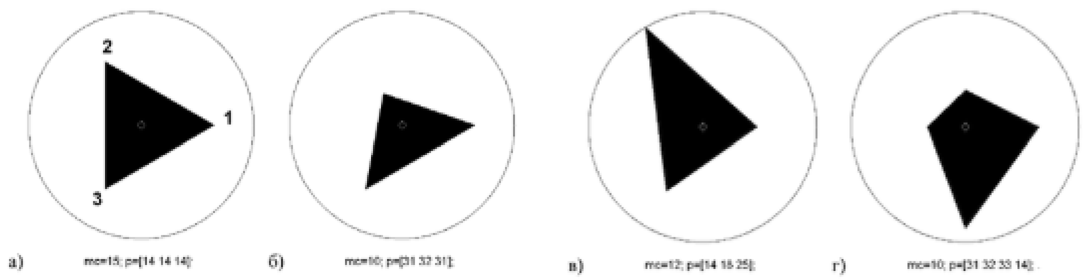


Fig. 2. Examples of parameter combinations visualization

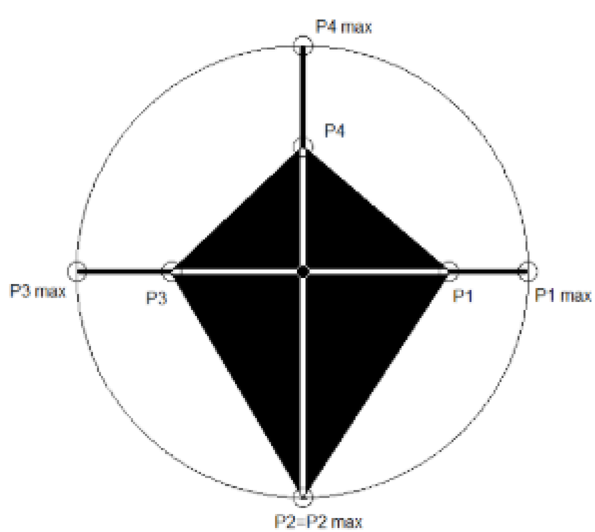


Fig. 3. Visualization of classification parameter combinations. Relative parameter values are shown: duration of the initiation phase (parameter P 1), development phase (parameter P 2), recovery phase

(parameter P 3) and duration of the entire substorm (parameter P 4). In this example, the current value of the parameter P 2 coincides with the maximum possible P 2 max in the considered sample of substorm events.

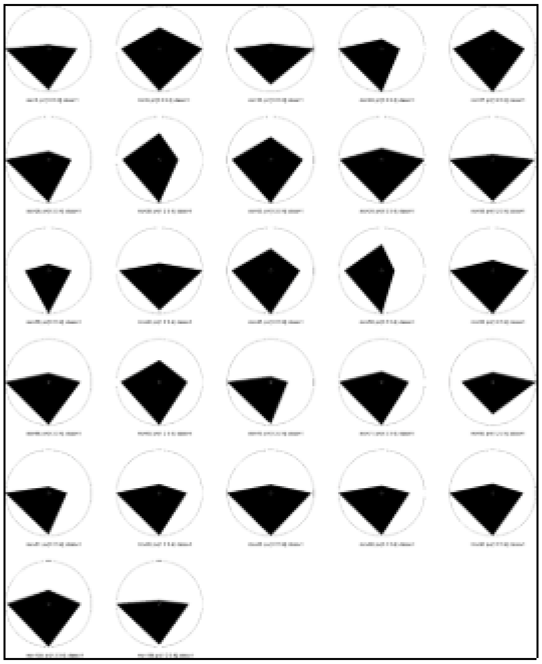
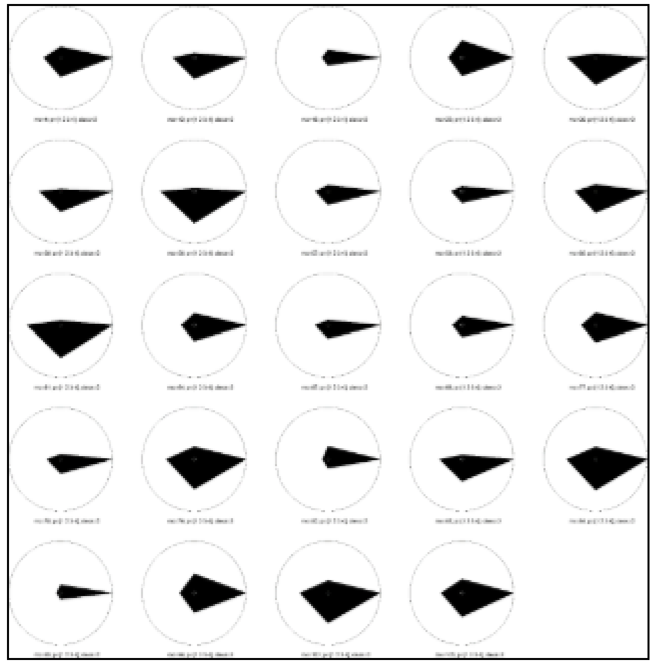


Fig. 4 Class 1



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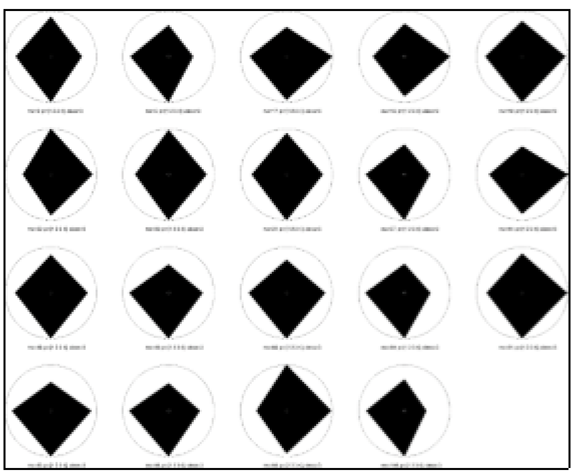

Fig. 6 Class 3

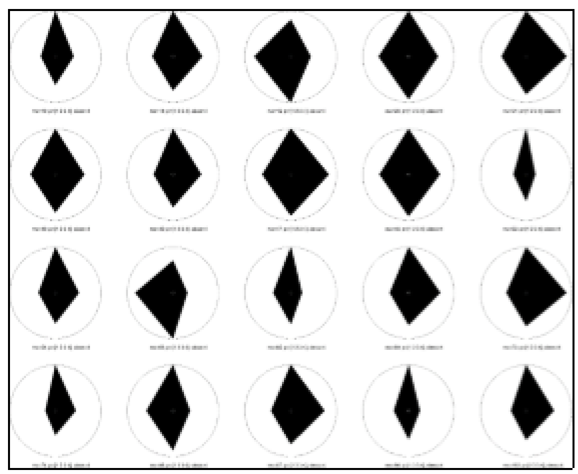

Fig. 7 Class 4

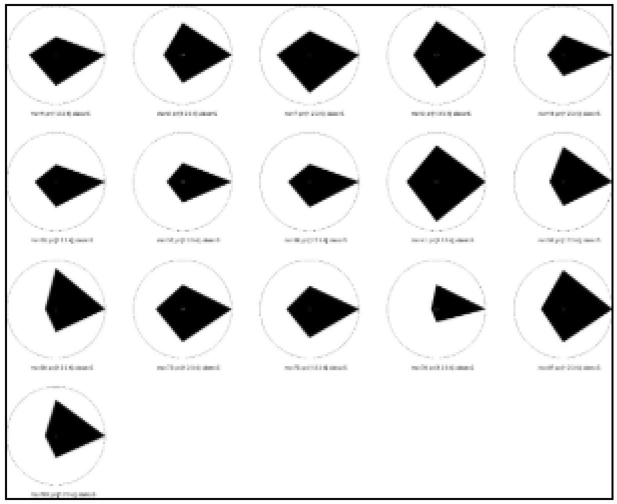

Fig. 8 Class 5