Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2024, № 1 (113) https://doi.org/10.33108/visnyk_tntu2024.01
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 520.8

METHOD OF ANALYSIS OF SOLAR ACTIVITY GEOEFFECTIVENESS

Danylo Ivantyshyn

Lviv Polytechnic National University, Lviv, Ukraine

Summary. *The method of analysis of the solar activity geoeffectiveness and assessing its level based on the mining spatiotemporal data of geophysical field disturbances caused by the activity of the Sun is developed. At the first stage of the method, solar activity is analysed. When solar disturbances are detected, the information about solar activity and the geophysical disturbances caused by it are further jointly analysed. Further, the raw data of geophysical fields are cleaned and converted into a format suitable for analysis, as well as their time alignment is carried out, which is crucial when comparing or combining time series from different sources and with different sampling rates. After that, the data is normalized, since the data values of the geophysical fields, which are used to analysis of solar activity geoeffectiveness, are measured on different scales, have different dimensions, which requires their scaling to the conventionally general scale of the comparable range. At the next stage of the method, spatial data aggregation is implemented, which ensures the process of combining the numerical values of a group of resources into one representative value for a given period of time. As a result of aggregation of experimental data of geophysical fields, we obtain a time series of average values of these fields for each moment of time. The analysis of the solar activity geoeffectiveness on the basis of aggregated data makes it possible to estimate its level taking into account the index Dst of the geomagnetic storm, the geomagnetic index of the polar electric current AE, the magnitude of natural atmospheric infrasound and the gradient of the electrical potential of the atmosphere PG. The scale of classification of the solar activity geoeffectiveness is in the range [0, 1]. An event is considered geoeffectiveness if the aggregated signal reaches a threshold value of 0.25 on the geoeffectiveness scale. Geoeffectiveness of solar activity is classified as weak, moderate or strong if the value of the aggregated signal is, respectively,* 0,25≤AS<0,5; 0,5≤AS<0,75; 0,75≤AS≤1,0.

Key words: *solar activity geoeffectiveness, data mining, spatial data aggregation, geoeffectiveness classification.*

https://doi.org/10.33108/visnyk_tntu2024.01.111 *Received 10.01.2024*

Problem statement. Solar activity and associated processes in the near space occur in the form of cyclic variations and dynamic manifestations, induced by powerful and difficult-to-predict sporadic disturbances. The temporal scale of these processes ranges from minutes to years. Dynamic processes with durations up to a month are classified as space weather, while longer-term changes are attributed to space climate. Solar events that cause disturbances in the geospace are referred to as geoeffective. The study of geoeffective manifestations of solar activity, including the assessment of geoeffectiveness level, is one of the important directions in space weather research.

Analysis of known research results. Coronal mass ejections and co-rotating interaction regions formed due to the pressure of high-speed flows of charged particles from coronal holes and slow solar wind under certain conditions cause geomagnetic storms. This influence of solar activity on the Earth's magnetic field is called geoeffective and is most often measured using one of several indices Dst, AE, Kp, Ap. The geoeffectiveness of such structures is considered strong, moderate or weak, if the value of the magnetic storm index is $Dst \leqslant -100\ nT$, $-50\ nT \leqslant Dst < -100\ nT$ and $-30\ nT \leqslant Dst < -50\ nT$ accordingly [1–3].

In the work [4], the geoeffectiveness of a limb coronal mass ejection halo has been investigated. In addition to the Dst index, the $SYM-H$ and $ASY-H$ indices for low latitudes, the *AU* and *AL* indices for high latitudes, and the *am* index for planetary magnetic field disturbances were analyzed. A description of geomagnetic indices is given in [5]. Since threshold values of the magnitude of a magnetic storm for classifying the geoeffectiveness of solar activity events are set only for the Dst index, for other indices the identification of the presence of a disturbance was performed visually. At the same time, the event was considered geoeffective if the Dst index became less than *-50 nT*, or if disturbances above the background level appeared in all analyzed indices.

A comparison of the geoeffectiveness of coronal mass ejections and co-rotating interaction regions at low, middle and high latitudes using the Dst, Ap and AE indices was made in [6]. To assess geomagnetic activity, indices were chosen based on physical interpretation and the ability to relate, in particular, to the ring current and the polar electrojet. It has been shown that coronal mass ejections and corotating interaction regions cause different geomagnetic activity, and their geoeffectiveness is also different at different latitudes. In [2] it was shown that weak and moderate storms can be caused by both the co-rotating interaction region and the coronal mass ejection, while most major magnetic storms are caused by coronal mass ejections. The speed of coronal mass ejections and the location of the solar source are the main factors determining their geoeffectiveness.

In the work [7], an expanded interpretation of the term «geoeffectiveness» is proposed. A phenomenon that causes disturbances in the magnetic field and/or other geophysical fields, including atmospheric infrasound, is considered geoeffective. The driver of infrasound disturbance is high-energy particles, as galactic cosmic rays as well as solar energetic particles. Intense solar proton events are also a source of electric field disturbance, in particular they cause an increase in the atmospheric electric potential gradient [8, 9].

The Objective of the work. To develop a method for analyzing the geoeffectiveness of solar activity and assessing its level for classifying the geoeffectiveness of an event, taking into account both magnetic storms and disturbances of atmospheric infrasound and electric fields.

Presentation of the material. The method of analyzing the geoeffectiveness of solar activity is based on a mining complex data types of disturbances in geophysical fields based on the global geomagnetic Dst index, which is used to measure the magnitude of a geomagnetic storm, the geomagnetic polar electrojet index AE, which is an indicator of a substorm, natural atmospheric infrasound and the atmospheric electric potential gradient PG caused by solar activity.

The main stages of the method for analyzing the geoeffectiveness of solar activity are presented in Fig. 1.

Stage 1. Analysis of solar activity. A wide range of data on solar activity is provided by the Space Weather Prediction Center (SWPC, NOAA), which is the official source of space weather information for the United States. The center, in particular, provides data on the X-ray radiation of the Sun, flows of high-energy particles, coronal mass ejections, access to information is provided through the portal https://www.swpc.noaa.gov/. When solar disturbances are detected, information on solar activity and geophysical disturbances is further analysed jointly. Data on indices of geomagnetic activity are provided by the World Data Center for Geomagnetism (WDC for Geomagnetism), experimental data of the atmospheric electric field are provided by GloCAEM, and atmospheric infrasound data are provided by the Karpenko Physico-Mechanical Institute of the NAS of Ukraine and Lviv Centre of the Institute of Space Research of the NAS of Ukraine and the SSA of Ukraine. Data on solar activity and geophysical disturbances are entered into the database for intellectual system for research of space weather parameters [10].

The time frames of geophysical fields disturbances for analysing the solar activity geoeffectiveness range from minutes to several days, depending on the trigger of solar event.

Stage 2. Data Cleaning. The next step in analysing the solar activity geoeffectiveness involves cleaning and converting raw geophysical fields data into a format suitable for analysis. In the case of data with missing values, such values are filled using statistical computing methods [11, 12]. If there is a significant number of missing values, the data is selected from other sources, if possible, or removed. The next step in data cleaning is to detection and handling outliers based on visualisation or statistical techniques.

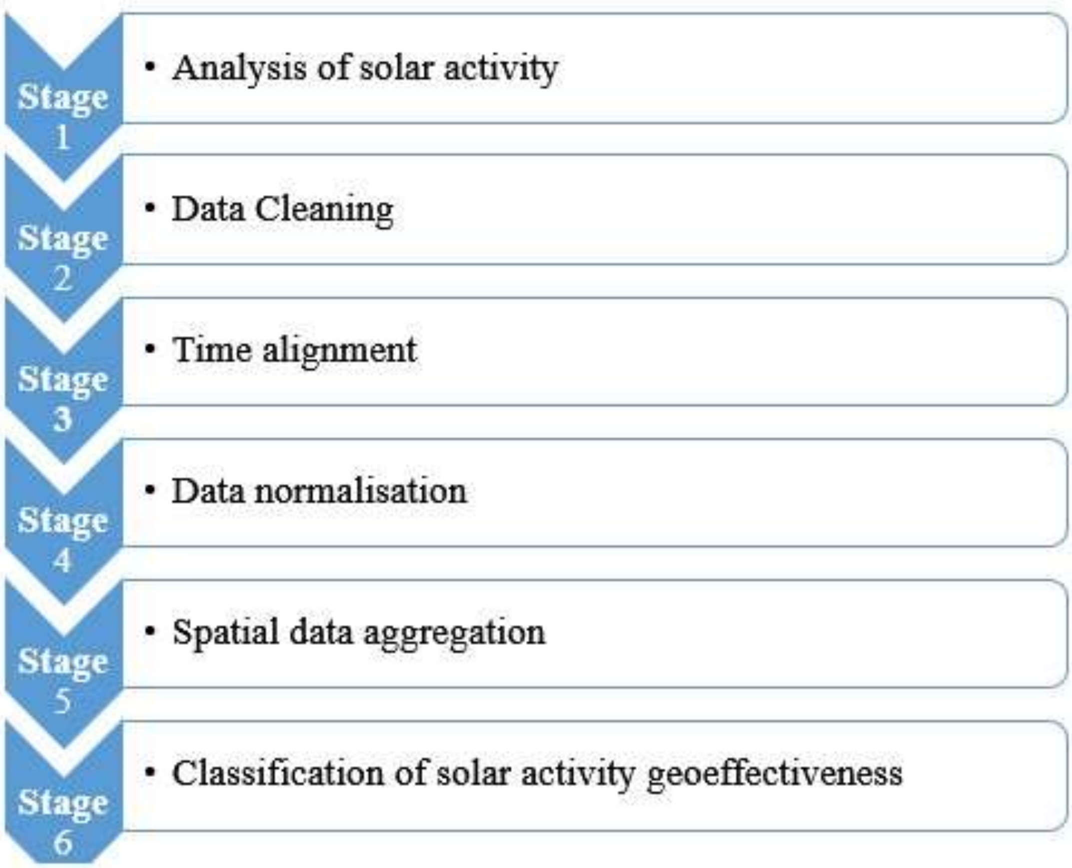

Figure 1. Stages of the method of analysis of solar activity geoeffectiveness

Stage 3. Time alignment. At the next stage, time alignment of data from different sources and with different sampling rates is carried out, which is of crucial importance when comparing time series or when combining them. First of all, resampling of time series data is carried out, which can include both increasing the sampling frequency (interpolation) and decreasing it – decimation. Next, it is necessary to make sure that the time indexes of the data of different time series are aligned. If necessary, time indexes are adjusted. This ensures that data samples from different time series correspond to the same time samples.

For example, experimental records after data preprocessing of disturbances of the polar electric current AE, the geomagnetic index Dst, natural atmospheric infrasound, and the gradient of the electrical potential of the atmosphere PG caused by solar activity are presents in Fig. 2. The extreme solar event occurred 61 h after the start of recording the experimental data (first vertical bar in figure). About 18 h after the start of the solar activity (second vertical strip), the maximum flow of high-energy particles was registered, and about 5 h after that, the beginning of disturbance of the natural atmospheric infrasound and the electric field was registered (panels 3 and 4, respectively) in the form of an increase in their magnitudes by ~ 3–5 times. About 53 h after the start of the solar activity (third vertical strip) the coronal mass ejection reached the Earth and caused a weak geomagnetic storm and substorm. The value of the AE index reached the magnitude of 1280 nT, and the decrease of the Dst index reached the magnitude of -55 nT (panels 1 and 2, respectively).

Stage 4. Data normalisation. The values of geophysical fields data used to analyse the solar activity geoeffectiveness are measured on different scales, which requires their scaling to a conventionally general scale.

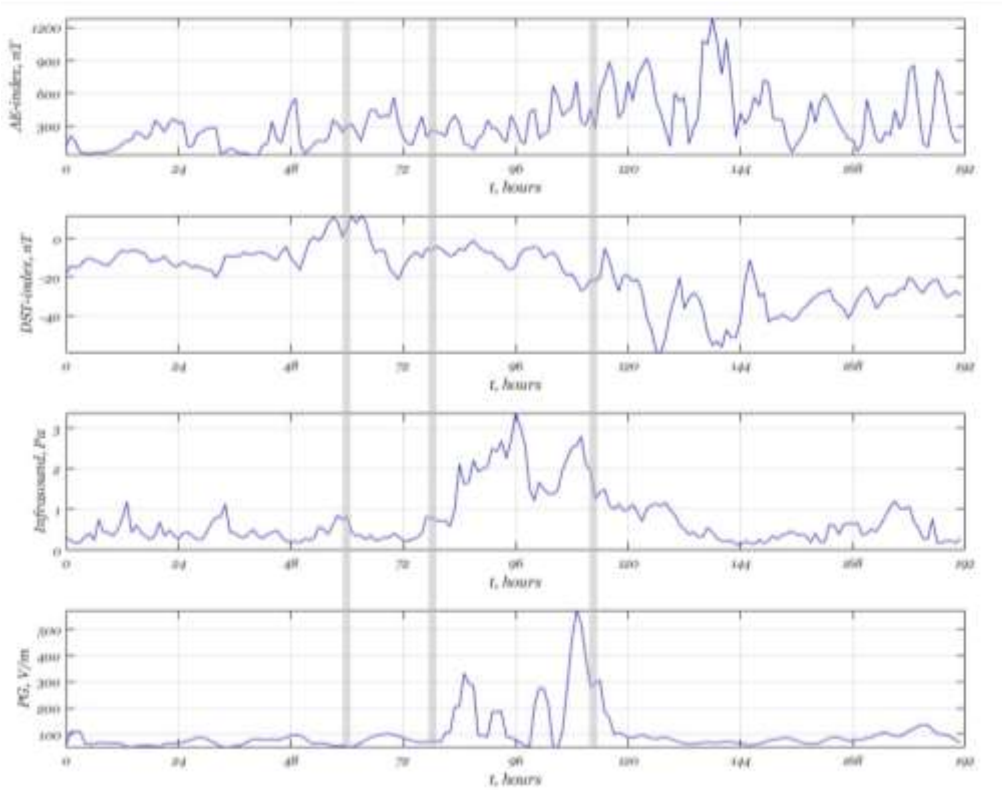

Figure 2. Experimental records of disturbances of the polar electric current AE, geomagnetic index Dst, natural atmospheric infrasound and atmospheric electric potential gradient PG

Two approaches to the normalisation of time series data $\{x(t), t = 0, 1, 2 ...\}$ are used:

- for time series data, the values of which are within the limits $x \geq 0$, we apply relative normalisation according to by the formula

$$x_{ni} = x_i / \max(x_i),$$

- for time series data, the values of which take both negative and positive values, we apply Savage normalisation

$$x_{ni} = (\max(x_i) - x_i)/(\max(x_i) - \min(x_i)),$$

where x_{ni} – is the normalised value of the ith term of the time series, x_i – is the actual value of the ith term of the time series, $\max(x_i)$ and $\min(x_i)$ – is the maximum and minimum value of the time series data, respectively.

As a result, we receive data in the range [0, 1] for further processing.

Stage 5. Spatial data aggregation. Spatial data aggregation provides the process of combining for a given period of time the numerical values of a group of resources into one representative value for the purpose of further analysis. The AVERAGE aggregation function is used for aggregation. As a result of the aggregation of experimental data of geophysical fields, we obtain a time series of average data values of these fields for each moment of time. The analysis of the solar activity geoeffectiveness based on aggregated data allows one to estimate its level in the expanded interpretation of the term geoeffectiveness, that is, taking into account the index Dst of the geomagnetic storm, the geomagnetic index of the polar electric current AE, the magnitude of natural atmospheric infrasound and the gradient of the electrical potential of the atmosphere PG.

In Fig. 3 presents the normalized data of disturbances of the polar electric current AE, the geomagnetic index Dst, natural atmospheric infrasound, and the gradient of the electrical potential of the atmosphere PG (respectively, the first four panels), as well as the aggregated signal (bottom panel).

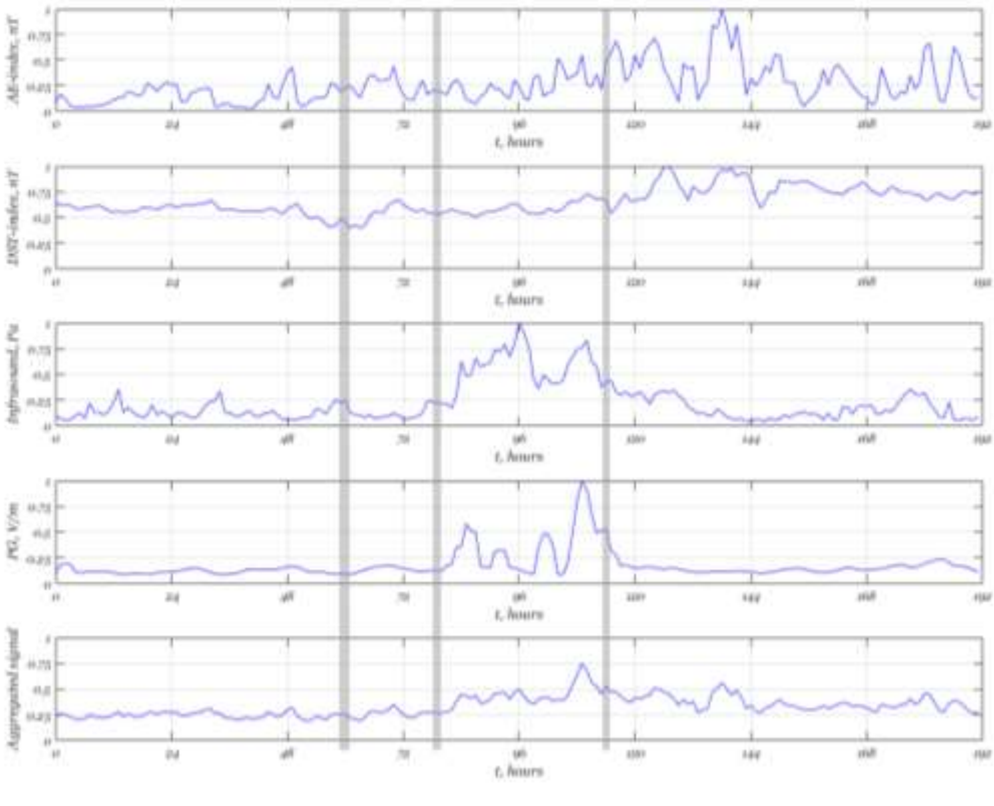

Figure 3. Normalised data of disturbances of polar electric current AE, geomagnetic index Dst, natural atmospheric infrasound and atmospheric electric potential gradient PG

Stage 6. Classification of solar activity geoeffectiveness. The assessment of the solar activity geoeffectiveness events is based on the aggregated signal, the numerical values of which are shifted by the minimum value of the magnitude, which makes it possible to obtain a minimum value equal to zero. The scale of classification of the geoeffectiveness of the activity of the Sun is in the range [0, 1]. An event is considered geoeffective if the aggregated signal reaches a threshold value of 0.25 on the geoeffectiveness scale. Geoeffectiveness of solar activity is classified as weak, moderate or strong if the value of the aggregated signal is, respectively, $0{,}25 \leq AS < 0{,}5$; $0{,}5 \leq AS < 0{,}75$; $0{,}75 \leq AS \leq 1{,}0$.

In Fig. 4 shows the aggregated signal of the geophysical fields considered above. As can be seen from the figure, the contribution of magnetic field disturbances to the aggregated signal (in the interval of 120–144 hours from the start of the recording) is in the range of weak geoeffectiveness, while the infrasound and electric field disturbances in the aggregated signal caused by high-energy particles exceeded the threshold value of moderate geoeffectiveness. Thus, the geoeffectiveness of this event, taking into account the Dst index of the geomagnetic storm, the geomagnetic index of the polar electric current AE, the magnitude of natural atmospheric infrasound and the gradient of the electrical potential of the atmosphere PG, is classified as moderate.

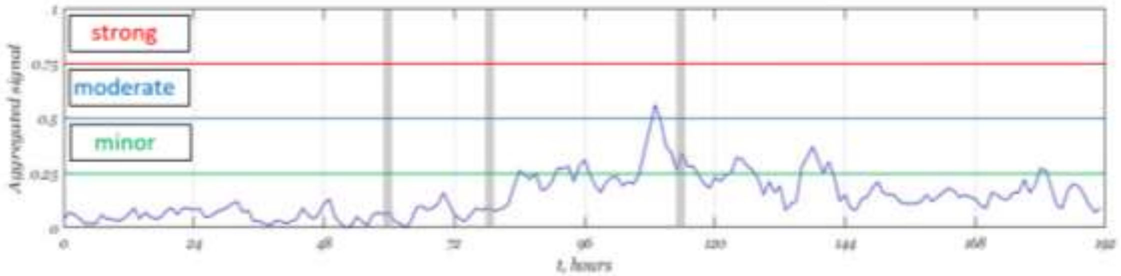

Figure 4. Aggregated signal of perturbations of polar electric current AE, geomagnetic index Dst, natural atmospheric infrasound, atmospheric electric potential gradient PG

Conclusions. Based on the analysis of the state of the problem, it is shown that solar activity under certain conditions causes geomagnetic storms, disturbances of infrasound and atmospheric electric fields.

However, one of several geomagnetic indices Dst, AE, Kp, Ap is most often used to analyse the geoeffectiveness of solar activity, and for the classification of geoeffectiveness threshold values of the magnetic storm are specified only for the Dst index, for other indices an event when the disturbance exceeds the background level is considered geoeffective.

Based on the mining spatiotemporal data of geophysical fields disturbances caused by the solar activity is developed a method for analysing of the solar activity geoeffectiveness and assessing its level. Spatial data aggregation implemented within the method provides the process of combining the numerical values of a group of resources into one representative value for a given period of time. As a result of aggregation of experimental data of geophysical fields, we obtain a time series of average values of these fields for each moment of time.

The analysis of the solar activity geoeffectiveness on the basis of aggregated data makes it possible to estimate its level taking into account the index Dst of the geomagnetic storm, the geomagnetic index of the polar electric current AE, the magnitude of natural atmospheric infrasound and the gradient of the electrical potential of the atmosphere PG. The scale of classification of the solar activity geoeffectiveness is in the range [0, 1]. An event is considered geoeffectiveness if the aggregated signal reaches a threshold value of 0.25 on the geoeffectiveness scale. Geoeffectiveness of solar activity is classified as weak, moderate or strong if the value of the aggregated signal is, respectively, $0{,}25 \leq AS < 0{,}5$; $0{,}5 \leq AS < 0{,}75$; $0{,}75 \leq AS \leq 1{,}0$.

References

1. Gopalswamy N. Solar connections of geoeffective magnetic structures. Journal of Atmospheric and Solar-Terrestrial Physics. 2008. Vol. 70. P. 2078–2100. https://doi.org/10.1016/j.jastp.2008.06.010
2. Gopalswamy N., Yashiro S., Akiyama S. Geoeffectiveness of halo coronal mass ejections. J. Geophys. Res. Earth Surf. 2007. Vol. 112.. https://doi.org/10.1029/2006JA012149

3. D.-C. Talpeanu, S. Poedts, E. D’Huys and M. Mierla. Study of the propagation, in situ signatures, and geoeffectiveness of shear-induced coronal mass ejections in different solar winds. A&A. 2022. Vol. 658. A56. https://doi.org/10.1051/0004-6361/202141977
4. Cid C., Cremades H., Aran A., Mandrini C., Sanahuja B., Schmieder B., Menvielle M., Rodriguez, L., Saiz E., Cerrato Y., et al. Can a halo CME from the limb be geoeffective? J. Geophys. Res. 2012. Vol. 117. A11102. https://doi.org/10.1029/2012JA017536
5. Menvielle M., Marchaudon A. Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather. Space Weather. Astrophysics and Space Science Library. 2007. Vol. 344. Springer. Dordrecht. P. 277–288. https://doi.org/10.1007/1-4020-5446-7_24
6. Verbanac G., Živković S., Vršnak B., Bandić M. and Hojsak T. Comparison of geoeffectiveness of coronal mass ejections and corotating interaction regions. A&A. 2013. Vol. 558. A85. https://doi.org/10.1051/0004-6361/201220417
7. Koshovyy V., Ivantyshyn O., Mezentsev V., Rusyn B., Kalinichenko M. Influence of active cosmic factors on the dynamics of natural infrasound in the Earth’s atmosphere. Rom. Journ. Phys., 2020. Vol. 65. 813. URL: https://rjp.nipne.ro/2020_65_9-10/RomJPhys.65.813.pdf.
8. Tacza J., Odzimek A., Tueros Cuadros E., Raulin J.-P., Kubicki M., Fernandez G., & Marun A. Investigating effects of solar proton events and Forbush decreases on ground-level potential gradient recorded at middle and low latitudes and different altitudes. Space Weather. 2022. Vol. 20. e2021SW002944. https://doi.org/10.1029/2021SW002944
9. Elhalel G., Yair Y., Nicoll K., Price C., Reuveni Y., Harrison RG: Influence of short-term solar disturbances on the fair weather conversion current. J. Space Weather Space Clim. 2014. 4, A26. https://doi.org/10.1051/swsc/2014022
10. Ivantyshyn D., Burov Ye. Rozroblennia bazy danykh dlia intelektualnoi systemy doslidzhennia parametriv kosmichnoi pohody. Visnyk Informatsiini systemy ta merezhi. 2023. No. 13. P. 329–337. [In Ukrainian].
11. Han J., Kamber M., Pei J. Data mining: concepts and techniques. Elsevier Science. 2012. 3rd ed. p. cm. ISBN 978-0-12-381479-1. P. 744.
12. F. Cheng, C. Meiling, W. Xinghua, W. Jiayuan, H. Bufu. A Review on Data Preprocessing Techniques Toward Efficient and Reliable Knowledge Discovery From Building Operational Data. Frontiers in Energy Research. 2021. Vol. 9. https://doi.org/10.3389/fenrg.2021.652801

Список використаних джерел

1. Gopalswamy N. Solar connections of geoeffective magnetic structures. Journal of Atmospheric and Solar-Terrestrial Physics. 2008. Vol. 70. P. 2078–2100. https://doi.org/10.1016/j.jastp.2008.06.010
2. Gopalswamy N., Yashiro S., Akiyama S. Geoeffectiveness of halo coronal mass ejections. J. Geophys. Res. Earth Surf. 2007. Vol. 112. URL: https://doi.org/10.1029/2006JA012149.
3. D.-C. Talpeanu, S. Poedts, E. D’Huys and M. Mierla. Study of the propagation, in situ signatures, and geoeffectiveness of shear-induced coronal mass ejections in different solar winds. A&A. 2022. Vol. 658. A56. https://doi.org/10.1051/0004-6361/202141977
4. Cid C., Cremades H., Aran A., Mandrini C., Sanahuja B., Schmieder B., Menvielle M., Rodriguez, L., Saiz E., Cerrato Y., et al. Can a halo CME from the limb be geoeffective? J. Geophys. Res. 2012. Vol. 117. A11102. https://doi.org/10.1029/2012JA017536
5. Menvielle M., Marchaudon A. Geomagnetic Indices in Solar-Terrestrial Physics and Space Weather. Space Weather. Astrophysics and Space Science Library. 2007. Vol. 344. Springer. Dordrecht. P. 277–288. https://doi.org/10.1007/1-4020-5446-7_24
6. Verbanac G., Živković S., Vršnak B., Bandić M. and Hojsak T. Comparison of geoeffectiveness of coronal mass ejections and corotating interaction regions. A&A. 2013. Vol. 558. A85. https://doi.org/10.1051/0004-6361/201220417
7. Koshovyy V., Ivantyshyn O., Mezentsev V., Rusyn B., Kalinichenko M. Influence of active cosmic factors on the dynamics of natural infrasound in the Earth’s atmosphere. Rom. Journ. Phys., 2020. Vol. 65. 813. URL: https://rjp.nipne.ro/2020_65_9-10/RomJPhys.65.813.pdf.
8. Tacza J., Odzimek A., Tueros Cuadros E., Raulin J.-P., Kubicki M., Fernandez G., & Marun A. Investigating effects of solar proton events and Forbush decreases on ground-level potential gradient recorded at middle and low latitudes and different altitudes. Space Weather. 2022. Vol. 20. e2021SW002944. https://doi.org/10.1029/2021SW002944
9. Elhalel G., Yair Y., Nicoll K., Price C., Reuveni Y., Harrison RG: Influence of short-term solar disturbances on the fair weather conversion current. J. Space Weather Space Clim. 2014. 4, A26. https://doi.org/10.1051/swsc/2014022
10. Івантишин Д., Буров Є. Розроблення бази даних для інтелектуальної системи дослідження параметрів космічної погоди. Вісник Інформаційні системи та мережі. 2023. № 13. С. 329–337.
11. Han J., Kamber M., Pei J. Data mining: concepts and techniques. Elsevier Science. 2012. 3rd ed. p. cm. ISBN 978-0-12-381479-1. P. 744.

12. F. Cheng, C. Meiling, W. Xinghua, W. Jiayuan, H. Bufu. A Review on Data Preprocessing Techniques Toward Efficient and Reliable Knowledge Discovery From Building Operational Data. Frontiers in Energy Research. 2021. Vol. 9. https://doi.org/10.3389/fenrg.2021.652801

УДК 520.8

МЕТОД АНАЛІЗУ ГЕОЕФЕКТИВНОСТІ СОНЯЧНОЇ АКТИВНОСТІ

Данило Івантишин

Національний університет «Львівська політехніка», Львів, Україна

Резюме. *Розроблено метод аналізу геоефективності сонячної активності й оцінювання її рівня на основі аналізу просторово-часових даних збурень геофізичних полів, викликаних активністю Сонця. На першому етапі методу проведено аналіз сонячної активності. При виявленні сонячних збурень надалі сумісно аналізовано інформацію про сонячну активність і геофізичні збурення, викликані нею. Надалі проведено очищення та перетворення неопрацьованих даних геофізичних полів у формат, придатний для аналізу, а також їх часове вирівнювання, що має вирішальне значення при порівнянні або під час об'єднання часових рядів з різних джерел і з різною частотою дискретизації. Після цього проведено нормалізацію даних, оскільки значення даних геофізичних полів, які використовуються для аналізу геоефективності сонячної активності виміряні за різними шкалами, мають різну розмірність, що вимагає їхнього масштабування до умовно загальної шкали співставного діапазону. На наступному етапі методу реалізовано просторову агрегацію даних, яка забезпечує процес об'єднання для заданого проміжку часу числових значень групи ресурсів в одне репрезентативне значення. В результаті агрегації експериментальних даних геофізичних полів отримано часовий ряд середніх значень цих полів для кожного моменту часу. Аналіз геоефективності сонячної активності на основі агрегованих даних дозволяє оцінювати її рівень з урахуванням індексу Dst геомагнітної бурі, геомагнітного індексу полярного електроструму AE, величини природного атмосферного інфразвуку та градієнта електричного потенціалу атмосфери PG. Шкала класифікації геоефективності активності Сонця знаходиться в діапазоні [0, 1]. Подія вважається геоефективною, якщо агрегований сигнал досягає порогового значення 0,25 шкали геоефективності. Геоефективність сонячної активності класифікується як слабка, помірна або сильна, якщо величина агрегованого сигналу складає відповідно* $0{,}25 \le AS < 0{,}5$; $0{,}5 \le AS < 0{,}75$; $0{,}75 \le AS \le 1{,}0$.

Ключові слова: *геоефективність сонячної активності, аналіз даних, просторова агрегація, класифікація геоефективності.*

https://doi.org/10.33108/visnyk_tntu2024.01.111 *Отримано 10.01.2024*