

MULTIVARIATE REGRESSION ANALYSIS OF ATMOSPHERIC TRANSPARENCY INDICATORS DURING POWERFUL MAGNETIC STORMS IN SOLAR CYCLE 25

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Abstract. A multiple linear regression method was employed to assess the degree of influence of solar factors on changes in atmospheric transparency indicators during powerful magnetic storms in March and April 2023. Regression models were constructed using a two-factor linear regression equation, in which the influencing factors were the ionospheric electric potential (EP) contrast and cosmic rays (CRs). It was shown that the determination coefficient increases in the constructed regression models, i.e. the selected factors increase the proportion of explained dispersion in atmospheric transparency characteristics. We assessed the degree of influence associated with each explanatory factor included in the regression models. It was found that CR is the factor that explains the largest proportion of dispersion in cloud parameters in the maximum water vapor layer

(700–500 hPa). It was established that the relative contribution of CRs to the increase in explained dispersion of cloud parameter is equivalent to the contribution of the EP contrast, which explains the largest proportion of the dispersion in the contrast of outgoing longwave radiation. The obtained results illustrate the role of CRs in the electrical mechanism of the nonlinear impact of solar activity on the climate system, whose theoretical foundations are being developed at ISTP SB RAS.

Keywords: solar activity, cosmic rays, ionospheric electric potential, cloud, atmospheric transparency, all-sky camera, climate.

INTRODUCTION

The main feature of the last decade of ongoing global warming is the increased frequency of extreme hydrometeorological phenomena in different regions across the globe [Mokhov, 2023; Rankova et al., 2025; IPCC, 2023]. The deterioration in living conditions necessitates searching for additional factors that, along with carbon dioxide, can contribute to the observable environmental changes. Solar activity (SA) is one of these factors belonging to the group of minor impacts on the climate system. Features of this group include the small amount of direct impact, the nonlinear nature of the impact, and the heterogeneous spatio-temporal pattern of the response to the impact. These features underlie the question concerning the physical mechanism behind the SA impact on the climate system. The research aimed at studying solar-tropospheric relations through instrumental measurements has been carried out for about 150 years [Georgieva, Veretenko, 2023]. Their first surge was observed in the second half of the XX century. It was associated with exploration of outer space and active formation of a ground-based observation network. Systematization of new data made it possible to detect an increase in near-surface temperature on the planet, which began in the mid-1970s and intensified in the 1990s. In the early 2000s, satellite information

became available due to the development of the Internet and the widespread use of personal computers in Russia; therefore, under the ongoing global warming there was a resurgence of interest in studying the effect of solar processes on the lower atmosphere. Nowadays, modern technologies and collected data allow us, along with monitoring the global climate change, to tackle the problem of improving its forecasting. To increase the reliability of both the short-term weather forecast and the forecast of climate changes for periods from several decades to hundreds of years, it is necessary to include additional parameterizations in the climate models that describe the interaction between atmospheric layers in the SA—magnetosphere—ionosphere—lower atmosphere system. The latter condition requires in-depth study of the physical processes occurring in outer space between the Sun and Earth. A detailed review of the mechanisms behind the impact of galactic and solar energetic particles on processes in all atmospheric layers is presented in [Mironova et al., 2015]. In addition to corpuscular radiation, solar wind (SW) and interplanetary magnetic field (IMF) variations leading to changes in the global electric circuit (GEC) and to the formation of clouds in the troposphere, which regulate incoming solar radiation into the lower atmosphere, are thought to have an effect on the atmosphere [Tinsley, 2000; Harrison, Lockwood, 2020]. The electrical mechanism be-

hind the nonlinear impact of SA on the troposphere, whose theoretical foundations are being developed at ISTP SB RAS, causes a change in the outgoing portion of the radiation budget of the climate system [Zherebtsov et al., 2005]. According to this mechanism, SA variations through changes in SW and IMF parameters lead to changes in GEC, thereby restructuring the vertical profile of the volume electric charge, which affects the cluster composition of water vapor. An increase in the number of dimers and larger clusters of water in the molecular composition of water vapor brings about an increase in its absorptivity in the infrared range [Molodykh et al., 2020]. Since it is known that the main ionizer of the atmosphere is cosmic rays (CRs), which, on the one hand, enhance its conductivity and, on the other hand, can affect the cloud formation in the troposphere, it is important to answer the question about the role of CRs in the proposed mechanism of SA impact on the climate system.

The purpose of this work is to assess the contribution of CRs to the electromagnetic interaction between components of the SA—magnetosphere—ionosphere—troposphere system during powerful geomagnetic storms.

DATA AND ANALYSIS TECHNIQUE

Our study has been carried out through the example of two powerful geomagnetic storms recorded in March and April 2023 of solar cycle (SC) 25. SC 25 began in January 2020 and is noted for decreased SA. The dynamics of sunspot activity during its growth phase corresponds to average cycles according to the Gnevyshev—Ohl rule. Its maximum phase began in November 2023. The minimum of SC 25 is expected in the first half of 2031 [Yermolaev et al., 2023; Yazev et al., 2023; Ishkov, 2024]. The magnetic storm on March 23 was characterized by a decrease in Dst to -163 nT, and during the geomagnetic storm on April 23, Dst was -213 nT according to WDC Kyoto [<https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>]. The mid-latitude geomagnetic index K_p was as high as 8 in both cases. The geomagnetic storms were accompanied by a Forbush decrease in the CR neutron component, which exceeded 6 %, as derived from NMDB Event Search Tool (NEST) data [nmdb.eu/nest/].

As initial data we use the electric potential (EP) of the ionosphere, calculated by the advanced Weimer semi-empirical model 2005 [Weimer, 2005]. The data on the interplanetary medium and geomagnetic activity indices with hourly resolution was taken from the OMNI database [https://omniweb.gsfc.nasa.gov/html/ow_data.html]. A solar wind energy indicator in the magnetosphere is the geomagnetic activity index PCN , which measures the geomagnetic activity in the polar cap of the Northern Hemisphere under changes in the solar plasma velocity and density and IMF [Troshichev, Sormakov, 2021]. The CR data was obtained by the neutron monitor of the high-latitude station Norilsk (69° N, 88° E), with hourly values corrected for pressure [<http://cgm.iszf.irk.ru/>]. Cloud parameters are the ball of

cloudiness, Liquid Water Path, and Ice Water Path. The ball of cloudiness characterizes the amount of clouds as a percentage of sky cover. The liquid/ice water paths are the mass of water droplets/ice particles in the entire cloud column per unit surface area. Outgoing longwave radiation (OLR) is represented by the observable broadband heat flow at the upper boundary of the troposphere ($h \sim 20$ km). We employ hourly values of meteorological parameters in a $1.0^\circ \times 1.0^\circ$ grid from the CERES satellite data set [Wielicki et al., 1996; <https://ceres.larc.nasa.gov/data/>].

The ionospheric EP contrast, averaged for latitudes above 60° N, is utilized as a heliogeophysical parameter related to variations in SW parameters. The EP contrast is the difference between potential anomalies averaged over regions of the same sign. The anomalies were calculated from the average over seven days before the day of onset of a magnetic storm. EP was computed using the Weimer model from hourly values of interplanetary medium parameters: SW velocity, plasma proton density, IMF B_y and B_z components, as well as geomagnetic activity index AL . The CR variations are represented by anomalies of the relatively quiet period from March 16 to March 22 for the March 23, 2023 magnetic storm and from April 11 to April 17 for the April 23, 2023 geomagnetic storm. For all the meteorological parameters analyzed in this work, we have calculated contrast of the value representing the difference between positive and negative anomalies, which were obtained as deviations from the average over seven days before the day of onset of a magnetic storm.

Statistical analysis of the data was made using the multiple linear regression (MLR) method, employed to predict one dependent variable from two or more independent variables. The linear model is constructed applying the ordinary least squares to minimize errors in fitting data to observable values of a single variable. The MLR method allows us to assess the contribution of each explanatory factor, excluding the influence of other explanatory factors included in the model. The regression model is based on the two-factor linear regression equation

$$y = a + b_1 x_1 + b_2 x_2, \quad (1)$$

where a is the coefficient showing how the variable y will look like in the case when the explanatory factors $x_1, x_2 = 0$; b_1, b_2 are coefficients that describe the degree of dependence of the variable y on x_1, x_2 .

The coefficient of determination is the main indicator of the quality of the regression model that describes the relationship between dependent and independent variables of the model. The coefficient of multiple determination demonstrates how much of the dispersion of the dependent variable is due to the influence of changes in the explanatory factors included in the model. Statistical reliability of the regression equation and coefficient of determination is estimated with Fisher's F -test. The null hypothesis H_0 consists in simultaneous equality of all regression coefficients to zero for explanatory variables, i.e. none of the explanatory variables included in the regression has a significant effect on the dependent variable. The hypothesis H_1 suggests that the sample

coefficient of determination is not zero. Acceptance of H_1 means that at least one of the explanatory variables included in the regression has a significant effect on y . To assess the significance of the coefficient of determination, we employ the statistics having F -distribution (right-side test) with $f_1=m-2$ and $f_2=n-m-1$ degrees of freedom. The calculated value of the F statistics is compared with its critical value F_{cr} , found from Table presented in [Foerster, Renz, 1983] at a given significance level α and the corresponding number of degrees of freedom. If $F > F_{cr}$, the calculated coefficient of determination is significant with a probability $1-\alpha$ [Foerster, Renz, 1983; Chavro, Dymnikov, 2000].

Reliably assessing the degree of dependence of meteorological parameters on solar factors with the MLR method requires a condition for weak linear relationship between independent variables, namely, the EP contrast and CR anomalies during disturbances, which holds in the given cases (Figure 1). During the disturbed period, which lasted for 26 hrs in both cases, the correlation coefficient between the explanatory factors was -0.23 for the March storm and -0.25 for the April storm. In the temporal dynamics of solar activity characteristics, there is a high correlation between EP contrast and PCN variations.

RESULTS

At the first stage of the study, we calculated paired correlation coefficients of contrast of cloud parameters in the troposphere, such as ball of cloudiness and liquid/ice water paths, with solar factors — EP contrast, PCN, and CR anomalies (Table 1).

Analysis of the correlation coefficients has revealed that in the maximum water vapor layer (700–500 hPa) there is a positive correlation between CRs and all cloud parameters during the March 23 magnetic storm and a negative linear relationship between CRs and cloud parameters during the April 23 geomagnetic storm. Thus, two physical mechanisms of CR impact on the troposphere are illustrated. Under the premise that CRs are the main ionizer of the atmosphere, they, on the one hand, can affect the formation of clouds in the troposphere. As the CR intensity increases, the concentration of ions in the troposphere goes up, which promote the growth of water clusters and hence the formation of clouds. Conversely, as during the March 23 magnetic storm, with decreasing CR intensity, the contrast of the cloud parameters (its ball and liquid/ice water paths) lowers.

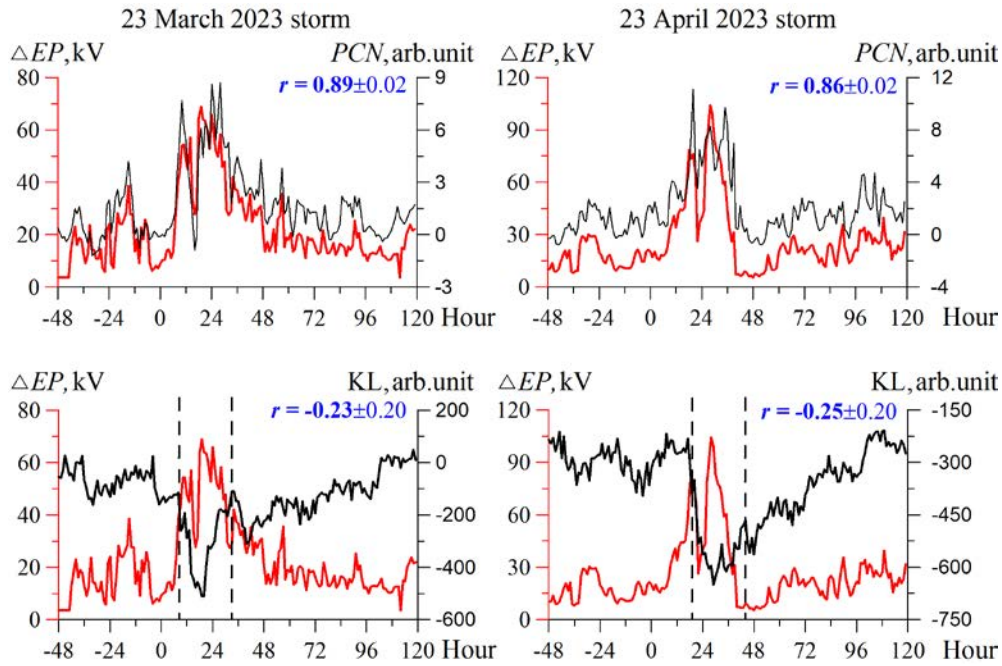


Figure 1. Variations in the EP contrast, averaged for latitudes above 60° N (red line), in the geomagnetic index PCN (gray line), and CR anomalies (black line). Zero on the X-axis is 00 UT of the day of onset of the geomagnetic storm. The disturbed period is shown by vertical dashed lines

Table 1

Correlation coefficients of the contrast of cloud parameters with solar factors — EP contrast, PCN, and CR anomalies — during powerful magnetic storms

	General			1000–700 hPa			700–500 hPa			500–300 hPa			300 hPa – tropopause		
	Ball	LWP	IWP	Ball	LWP	IWP	Ball	LWP	IWP	Ball	LWP	IWP	Ball	LWP	IWP
March 23, 2023															
ΔEP	0.005	-0.05	-0.29	0.06	-0.20	-0.55	0.32	0.003	-0.34	-0.05	-0.18	-0.02	0.33	0.32	0.40
PCN	0.26	0.02	-0.38	0.09	-0.16	-0.51	0.60	0.50	0.15	-0.02	0.27	0.36	0.40	0.13	-0.10
CR	0.29	0.11	0.02	0.09	-0.02	-0.09	0.56±0.17	0.79±0.13	0.76±0.13	-0.02	0.67±0.15	0.72±0.14	0.04	-0.28	-0.84
April 23, 2023															
ΔEP	-0.38	0.33	0.51	-0.20	0.33	0.12	-0.09	0.44	0.25	0.05	0.13	-0.06	0.42	0.02	0.24
PCN	-0.04	0.50	0.44	-0.09	0.44	0.20	-0.05	0.49	0.25	0.27	0.17	-0.10	0.49	0.04	-0.09
CR	0.22	0.07	-0.45	0.10	-0.26	-0.12	-0.10	-0.61±0.16	-0.63±0.16	-0.44±0.18	0.30±0.19	-0.37±0.19	0.23	0.63	-0.66

On the other hand, CRs alter the conductivity of the troposphere. With decreasing ion concentration, air conductivity goes down in cloudless regions of the troposphere, thereby increasing the ionosphere—Earth potential difference. In accordance with the mechanism developed at ISTP SB RAS, this causes an increase in concentration of water clusters and hence in clouds, mainly of high-level. This effect manifested itself during the April 23 geomagnetic storm when a decrease in CRs was followed by an increase in the contrast of cloud parameters.

The MLR method was employed to estimate the degree of dependence of cloud parameters on solar factors during the powerful magnetic storms from the calculated parameters: r^2 — the coefficient of paired determination; b_1 and b_2 — the calculated coefficients describing the degree of dependence of cloud parameters on explanatory factors in the regression equation; R — the multiple correlation coefficient; R^2 — the coefficient of multiple determination; F — the calculated value of the statistics having F -distribution to assess the significance of R^2 (Table 2). The critical value of the F_{cr} statistics, found from Table presented in [Foerster, Renz, 1983], was 3.42 at a significance level of 5 % and 5.66 at $\alpha=1$ %. The EP contrast was applied in the calculations as the first factor influencing the cloud parameters in the maximum water vapor layer, except for the calculation of the dependence of the ball of cloudiness on solar factors during the April magnetic storm, in which the first factor was the geomagnetic index PCN .

We have established that in the constructed regression models the square of the multiple correlation coefficient, or coefficient of determination, increases, i.e. this set of variables consisting of the EP contrast and CRs allows us

to increase the proportion of explained dispersion of the dependent variables — the ball of cloudiness and liquid/ice water paths. The increment in explained dispersion through each factor is estimated by analyzing the coefficients describing the degree of dependence of the cloud parameters on the explanatory factors (ΔEP and CR) in regression equations. We have found that CRs explain the largest proportion of dispersion of cloud parameters in the maximum water vapor layer (Figure 2).

Along with cloudiness, OLR can be considered as a characteristic of atmospheric transparency. The correlation coefficients of the OLR contrast with solar factors — EP contrast, PCN , and CR anomalies — during the magnetic storms in March and April 2023 are presented in Table 3.

It has been revealed that during the March 23 magnetic storm the CR mechanism associated with cloud formation in the troposphere prevails, and an increase in the EP contrast occurs with a decrease in the OLR contrast. During the April 23 geomagnetic storm, CRs are an additional factor reducing the conductivity of the troposphere, and as the EP contrast rises, so does the OLR contrast. Figure 3 illustrates the temporal dynamics of average EP for latitudes above 60° N during the geomagnetic storms. Analysis of variations in average EP during the powerful magnetic storms has revealed that the EP contrast correlates with the OLR contrast under disturbed conditions during the April magnetic storm when positive potential anomalies prevail. Accordingly, the response of the OLR contrast to EP contrast variations depends on changes in positive potential anomalies during a disturbance.

Table 2

Calculated parameters for estimating the degree of dependence of contrast of cloud parameters on explanatory factors — EP contrast (1) and CR anomalies (2)

	r^2_1	r^2_2	b_1	b_2	R	R^2	F
March 23, 2023							
Ball	0.1024	0.3136	0.48	0.67	0.73	0.5329	13.12
LWP	0.0324	0.4489	-0.025	0.67	0.675	0.46	9.60
IWP	0.1156	0.5776	-0.175	0.72	0.78	0.6084	17.87
April 23, 2023							
Ball	0.0729	0.1936	0.24	-0.43	0.50	0.25	3.83
LWP	0.1936	0.3721	0.31	-0.54	0.685	0.4692	10.17
IWP	0.0625	0.3969	0.095	-0.61	0.64	0.4096	7.98

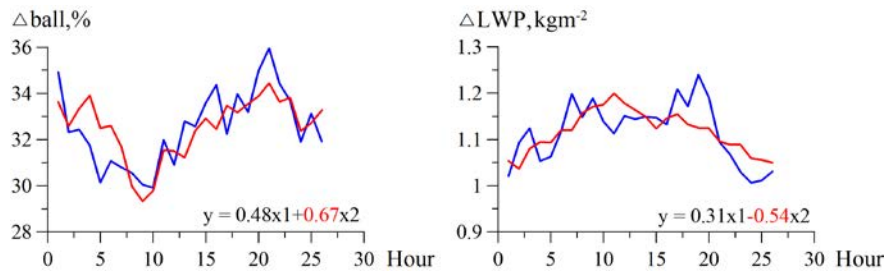


Figure 2. Variations in the contrast of the ball of cloudiness during the magnetic storm on March 23 (left) and the LWP contrast during the geomagnetic storm on April 23 (right): the blue line indicates initial values; the red line, values calculated from regression equations.

Table 3

Correlation coefficients of OLR contrast
with EP contrast, *PCN*, and CR anomalies during powerful magnetic storms

	March 23, 2023	April 23, 2023
ΔEP	-0.68 ± 0.15	0.76 ± 0.13
<i>PCN</i>	-0.43 ± 0.18	0.77 ± 0.13
CR	0.32 ± 0.19	-0.34 ± 0.19

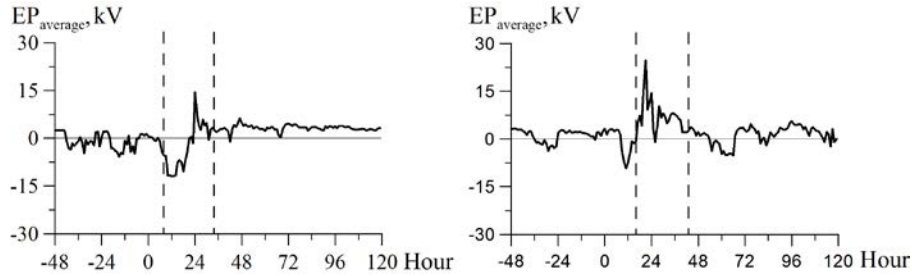


Figure 3. Variations in average EP for latitudes above 60° N during the geomagnetic storms on March 23 (left) and April 23 (right), 2023. Zero on the X-axis is 00 UT of the day of onset of the geomagnetic storm. The disturbed period is shown by vertical dashed lines

We assessed the degree of dependence of the OLR contrast on the EP contrast and CR anomalies during the geomagnetic storms, using the MLR method (Table 4). It appeared that the coefficient of determination rises during disturbances, i.e. the selected solar factors can enlarge the proportion of explained dispersion of the OLR contrast. The estimate of the increment in explained dispersion by each factor has shown that the EP contrast explains the largest proportion of OLR contrast dispersion. Regression models are presented in Figure 4.

The current intensive technological development makes it possible to obtain higher-level data and is attended with both the refinement of old data processing techniques and the emergence of new ones. This allowed us to apply the MLR method to high temporal resolution data. Due to the improvement of ground-based instruments, in particular all-sky cameras for re-

cording airglow, and modifications made in the technique for processing their images [Syrenova et al., 2021], it became possible to use the number of stars in the sky as an indicator that indirectly describes the transparency conditions throughout the atmosphere. The all-sky cameras are located at the ISTP SB RAS Geophysical Observatory (Tory village, Republic of Buryatia), whose instruments are included in the National Heliogeophysical Complex of the Russian Academy of Sciences. A decrease was detected in the number of stars relative to their average number in the sky (1200) in images captured by an all-sky camera under conditions of the severe magnetic storm on May 10–11, 2024, during which there was a Forbush decrease in galactic CRs, and solar CRs increased during its recovery phase [Makhmutov et al., 2025; Yasyukevich et al., 2025].

Table 4

Calculated parameters for assessing the degree of influence of explanatory factors
on dependent variable (OLR contrast, number of stars)

	r_1^2	r_2^2	b_1	b_2	R	R^2	F
March 23, 2023							
OLR	0.4624	0.1024	-0.64	0.17	0.70	0.49	11.05
April 23, 2023							
OLR	0.5776	0.1156	0.72	-0.16	0.78	0.6084	17.87
May 11, 2024							
Number of stars	0.1325	0.0144	0.43	0.11	0.38	0.1444	5.82

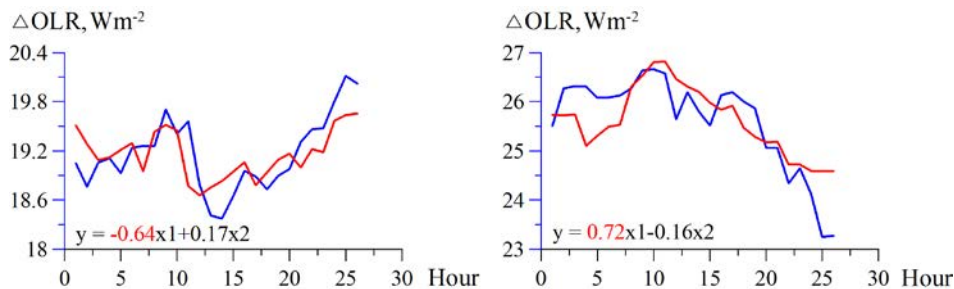


Figure 4. Variation in the OLR contrast during the geomagnetic storms on March 23, 2023 (left) and April 23, 2023 (right): the blue line denotes initial values; the red line, values calculated from regression equations.

Let us assess the degree of dependence of the number of stars on solar factors, such as *PCN* and CR anomalies. The correlation between the explanatory factors was -0.55 ± 0.08 , i.e. the condition of weak linear relationship between explanatory factors holds and the MLR method can be applied in this case. The geomagnetic index *PCN* with one-minute temporal resolution is presented on the website [<https://pcindex.org>]. Information on CRs was gained from the Irkutsk CR spectrograph database that contains pressure corrected data from the neutron monitor of the Irkutsk station [<http://cgm.iszf.irk.ru/>]. We analyzed data obtained on May 11, 2024 from 14 to 19 UT with a temporal resolution of 5 min. The F_{cr} value, found from Table, was 3.13 at a significance level of 5 % and 4.92 at $\alpha=1$ %. Using the MLR method to estimate the degree of dependence of the number of stars on *PCN* and CR anomalies, we detected an increase in the coefficient of determination during the disturbance. The estimate of the increment in explained dispersion by each factor has shown that *PCN* explains the largest proportion of dispersion of the number of stars in the sky (see Table 4). Consequently, the decrease in atmospheric transparency is caused by the electromagnetic interaction between all atmospheric layers during the heliogeophysical event.

Let us illustrate this finding, drawing on the example of the dynamics of the average ball of cloudiness in the 500–300 hPa layer and the total relative contribution of both factors, calculated for the entire disturbed period from 16 UT on May 10 to 05 UT on May 12 (Figure 5). As clear from Figure 5, upper cloudiness varies with a shift of 3 hrs about relative variations in the influencing factors with a correlation coefficient of 0.55 ± 0.14 . Thus, harnessing the fairly general characteristic of atmospheric transparency (the number of stars) over the limited period, but with high temporal resolution data allowed us to obtain regression coefficients and calculate the relative contribution of explanatory factors on the entire time interval of the disturbance, which made it possible to compare it with a change in the accepted cloud parameter.

DISCUSSION

The first quarter of the 21st century is characterized by an increase in the frequency of dangerous phenomena wreaking havoc in different regions across the globe. Increasing the reliability of their prediction on a time scale from several days to several decades will help reduce the material costs of recovery efforts and enhance the quality

of life. To solve the prediction problem, we should examine in detail not only the internal variability in the climate system, but also the effect of the processes external to the system. The latter includes solar activity (SA) that refers to physical phenomena occurring on the Sun. In this paper, we handled the question concerning the role of CRs in the electrical mechanism of the nonlinear impact of SA on the climate system, the theoretical model of which is being developed at ISTP SB RAS.

The MLR method was used to assess the degree of dependence of atmospheric transparency indicators on solar factors during the powerful magnetic storms in March and April 2023. It is shown that in the constructed regression models a set of independent variables consisting of the EP contrast and CRs allows us to increase the proportion of explained dispersion of dependent variables — ball of cloudiness, liquid/ice water paths, and OLR (see Figures 2, 4). The results illustrate two mechanisms of CR effect on the troposphere: on the one hand, the CR effect mechanism associated with cloud formation in the troposphere during the magnetic storm on March 23 prevails; on the other hand, CRs are an additional factor reducing the conductivity of the troposphere during the geomagnetic storm on April 23, which is consistent with the results obtained in [Petukhova et al., 2023]. Note that the relative contribution of CRs to the increment in explained dispersion of cloud parameters is equivalent to the contribution of the EP contrast, which explains the largest proportion of OLR contrast dispersion.

Thanks to the improvement of ground-based optical instruments and the creation of databases with high temporal resolution, we can use the number of stars in this study as an indirect characteristic of atmospheric transparency. For the limited time period, we obtained regression coefficients by the MLR method, which allowed us to calculate the relative contribution of explanatory factors for the entire time interval of the disturbance and compare it with the change in the average ball of upper cloudiness in a particular region (see Figure 5). Thus, updating the data processing techniques of modern optical instruments contributes to the appearance of additional atmospheric characteristics that can be applied in follow-up studies in the absence of observations of meteorological parameters with high temporal resolution.

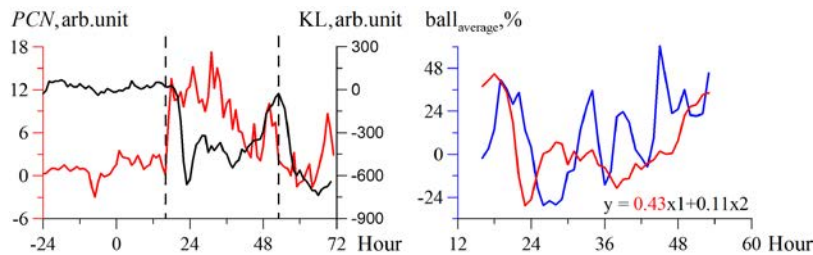


Figure 5. The left panel plots variations in *PCN* (red line) and CR anomalies (black line) during the powerful magnetic storm on May 10–11, 2024; vertical dashed lines mark the disturbed period; in the right panel is the dynamics of the average ball of cloudiness in the 500–300 hPa layer (blue line) and the regression model (red line) during the disturbed period

CONCLUSIONS

Analysis of the influence of solar factors (EP contrast and CRs) on changes in atmospheric transparency during powerful magnetic storms by the MLR method yielded the following results.

An increase has been revealed in the coefficient of determination in the constructed regression models, i.e. the selected factors (ΔEP and CR) enlarge the proportion of explained dispersion in atmospheric transparency characteristics.

It has been found that CRs are a factor that explains the largest proportion of dispersion of cloud parameters in the maximum water vapor layer (700–500 hPa) during powerful geomagnetic storms.

The estimate of the increment in explained dispersion by the two solar factors has shown that the EP contrast explains the largest proportion of OLR dispersion.

It appeared that the positive linear response of the OLR contrast to EP contrast variations is determined by changes in positive potential anomalies during heliogeophysical disturbances.

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