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RESPONSE OF THE MID-LATITUDE ATMOSPHERE TO SPORADIC COSMIC RAY VARIATIONS IN THE WESTERN SIBERIAN REGION

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Abstract. The article presents the results of long-term observations of cosmic ray variations and changes in atmospheric parameters at midlatitudes in the Novosibirsk Region. The atmospheric response to Forbush decreases in galactic cosmic rays (CR) and solar proton events is analyzed. The analysis involves 181 Forbush decreases and 18 GLEs (Ground Level Enhancement) for the period 1967–2019. This makes it possible to examine the effect depending on season. The effect of increasing pressure during the Forbush decrease in cosmic rays is more pronounced in the autumn-winter period. Nonetheless, it also occurs in the warm season. For midlatitudes, there is also a tendency for pressure to increase after GLE. At the Forbush decrease front, with a decrease in CR intensity and an increase in atmospheric pressure, an increase in the average mass and surface temperature is observed. In the intensity recovery phase after the Forbush decrease, a decrease in the average mass and surface temperature occurs. The observed variations in atmospheric parameters are assumed to be due to changes in the ionization rate under the influence of cosmic rays in variations in atmospheric transparency and cloudiness.

Keywords: cosmic rays, solar proton events, atmosphere, pressure, temperature.

INTRODUCTION

Over the past decades, many researchers have examined the effect of cosmic rays (CRs) on Earth's weather and climate. One of the first to suggest that air ionization by CRs affects the weather and climate was Ney [Ney, 1959]. As the main source of ionization in the troposphere, CRs cause significant chemical and physical changes in the atmosphere [Dorman, 2004; Harrison, Tammet, 2008]. Ions resulting from air ionization by CRs induce many atmospheric processes: formation of cloudiness [Pudovkin, Veretenenko, 1995; Svenmark, 1998; Marsh, Svenmark, 2000; Pallé et al., 2004; Usoskin, Kovaltsov, 2006], precipitation [Kniveton, 2004], and aerosols [Lee et al., 2003; Lushnikov et al., 2014], changes in atmospheric transparency [Roldugin, Tinsley, 2004; Kudryavtsev, Jungner, 2011] and parameters of the global electric circuit [Ermakov, Stozhkov, 2004; Tinsley, Zhou, 2006], cyclogenesis at middle and high latitudes [Veretenenko, Thejll, 2004; Tinsley, 2012]. Contribution of CRs to atmospheric ionization varies with time due to CR flux modulation in the heliosphere. This indicates that ionization of the troposphere by CRs is one of the mechanisms of solar-atmospheric coupling. The effects of CR variations in the evolution of pressure systems, which were observed in North Atlantic region, were detailed in [Veretenenko, Tile, 2008; Veretenenko, Ogurtsov, 2012]. The works were based on data from stations located on the southeastern coast of Greenland (Tasiilag, 65.5° N, 38° W), on Faroe Islands (Thorshavn, 62° N, 6.5° W), and in Denmark (Jagersborg, 56° N, 12° E). Description of the region, list and characteristics of the stations whose data was used are given in [Veretenenko, 2017]. These latitudes feature low geomagnetic cutoff thresholds allowing precipitation of particles with minimum energies from ~100 MeV. Special attention is paid to the spatial distribution of the atmospheric response to Forbush decreases (FDs) in CRs and to solar proton events (SPEs). Such studies should take into account the spatiotemporal variability in solar-atmospheric coupling. Variations in pressure, temperature, cloudiness, etc. as a response of the atmosphere to certain effects of solar activity can differ significantly depending on the region of interest. Below are the results of long-term observations of cosmic ray variations and changes in atmospheric parameters at midlatitudes (near Novosibirsk).

DATA AND ANALYSIS

Data from aerological sounding of the atmosphere (for every hour) over Novosibirsk has been taken from the database [http://crsa.izmiran.ru/phpmyadmin], which also contains the results of the US National Center for Environmental Prediction (NCEP) [https://www.nco.ncep.noaa.gov/pmb/products/gfs]. CR variations were obtained from continuous observations of the count rate of the neutron monitor 24NM-64 at the station Novosibirsk [http://193.232.24.200/nvbk/main.htm]; atmospheric pressure measurements were carried out there simultaneously with CR observations. We employed hourly and daily average values of the neutron monitor count rate and atmospheric pressure. The main parameters of the observation station are presented in Table 1.

The response of the atmosphere to Forbush decreases in galactic cosmic rays (GCRs), as well as to solar proton events, was analyzed using the method of superimposed epochs. For the study, FDs with an amplitude

Table 1

Parameters of the observation station

latitude φ	longitude λ	Geomagnetic latitude (quasi-dipole) Φ	Geomagnetic cutoff rigidity R_c	Altitude H_0	Atmospheric pressure h_0
54.84°	83.00°	51.59°	2.91 GV	163 m	995 mb

Table 2

Distribution of the number of Forbush decreases

Time interval	Number of FDs with amplitude			FDs in total
	2.5÷4.5 %	5÷7 %	≥8 %	
fall (September–November)	24	10	11	45
winter (December–February)	22	21	4	47
spring (March–May)	20	14	5	39
summer (June–August)	22	20	8	50
the whole period	88	65	28	181

of at least 2.5 % were selected from data from the neutron monitor of the station Novosibirsk, for which no other event (FD or SPE) was observed at an interval ±10 days relative to zero days of the event considered. In 1967–2019, 181 FDs were selected; 54 of them were not accompanied by geomagnetic storms: 44 events with an amplitude 2.5÷4.5 %; 7 events, 5÷7 %; 3 events, ≥8 %. Distribution of the number of FDs depending on season and their amplitude is shown in Table 2.

The onset of a CR intensity decrease in FDs was taken as zero reference. Relative to this moment, variations in both atmospheric pressure $\Delta h = h - h_0$ and CR intensity $\Delta I = \frac{I - I_0}{I_0} \cdot 100\,\%$ were examined Here h, I are the current values of the parameters, h_0, I_0 stand for the time zero. Figure 1 illustrates pressure variations during FDs for different seasons at midlatitudes.

For all seasons, an increase in atmospheric pressure is observed during FDs: during the decay, minimum, and initial recovery phase of the CR intensity. Before FD, atmospheric pressure decreases, while the lowest values are noted on the zero day. On the first day after zero, the pressure begins to increase, and on the 4÷6 day it peaks. For high latitudes, the maximum pressure is recorded on the third day [Pudovkin et al., 1997]. With further recovery of the CR intensity, the pressure drops (see Figure 1). The duration of this atmospheric response is on average ~12 days and almost coincides with the duration of CR FD. In [Veretenenko, Pudovkin, 1993; Pudovkin et al., 1997; Veretenenko, Tejll, 2008], events were selected only for the cold season (October–March), and those for the warm half-year were ignored. Artamonova and Veretenenko [2011, 2014] have analyzed 48 FDs for 1980–2006. This paper delves into 181 FDs (see Table 2) for 1967–2019, which allows us to examine the effect as a function of season. Using the method of superimposed epochs, variations in atmospheric pressure Δh relative to the pressure at the zero moment of the event are studied. Estimates of the statistical significance of the results are given for the level <0.05. These are rather stringent conditions, and in practice the results are considered valid. The level ≤0.05 corresponds to a confidence interval of ±3σ. Standard deviations $\sigma = \sqrt[2]{\frac{1}{n}\sum_{i=1}^{n}\left(\Delta h_i - \overline{\Delta h}\right)^2}$ were found independently for each point of the obtained distributions. There is a spread of σ values for different seasons: 0.253÷0.52 mb for fall, 0.29÷0.56 mb for winter, 0.33÷0.6 mb for spring, 0.506÷0.73 mb for summer. Boundaries of the ±3σ confidence intervals are indicated by curves 3 and 4 in Figure 1. The effect of increasing pressure is better manifested in the fall-winter period (Figure 1, *a*, *b*). The depth of the effect is far from being identical at an equal amplitude of a sporadic variation in CRs and largely depends on atmospheric conditions at a given time. The effect can also occur in the warm season (Figure 1, *c*, *d*) since the low statistical significance of the effect does not mean its absence. Variations in CR intensity and atmospheric pressure during FDs, averaged over 181 events, are illustrated in Figure 2.

Atmospheric pressure reaches a maximum on the fifth day after the onset of the FD and averages 6–7 mb relative to the reference value. Before the event, atmospheric pressure decreases for 2 days. Tinsley et al. [1989] have suggested that this is a separate effect of a solar flare itself resulting in a Forbush decrease (the so-called "early" and "late" flare effects). The duration of the observed effect in atmospheric pressure variation depends on the duration of FD (see Figure 2).

Along with FDs, sporadic phenomena in cosmic rays include solar cosmic ray (SCR) flares, which are more often called solar proton events (SPEs). Particle energy in these fluxes is usually not high (of the order of hundreds of MeV), and they are not recorded near Earth's surface. The atmospheric response to such SPEs is observed mainly at high latitudes [Veretenenko, Tejll, 2008]. SPEs containing particles with an energy of 1 GeV or higher are recorded as ground level enhancements (GLEs) in solar cosmic rays [https://gle.oulu.fi/]. GLEs are relatively

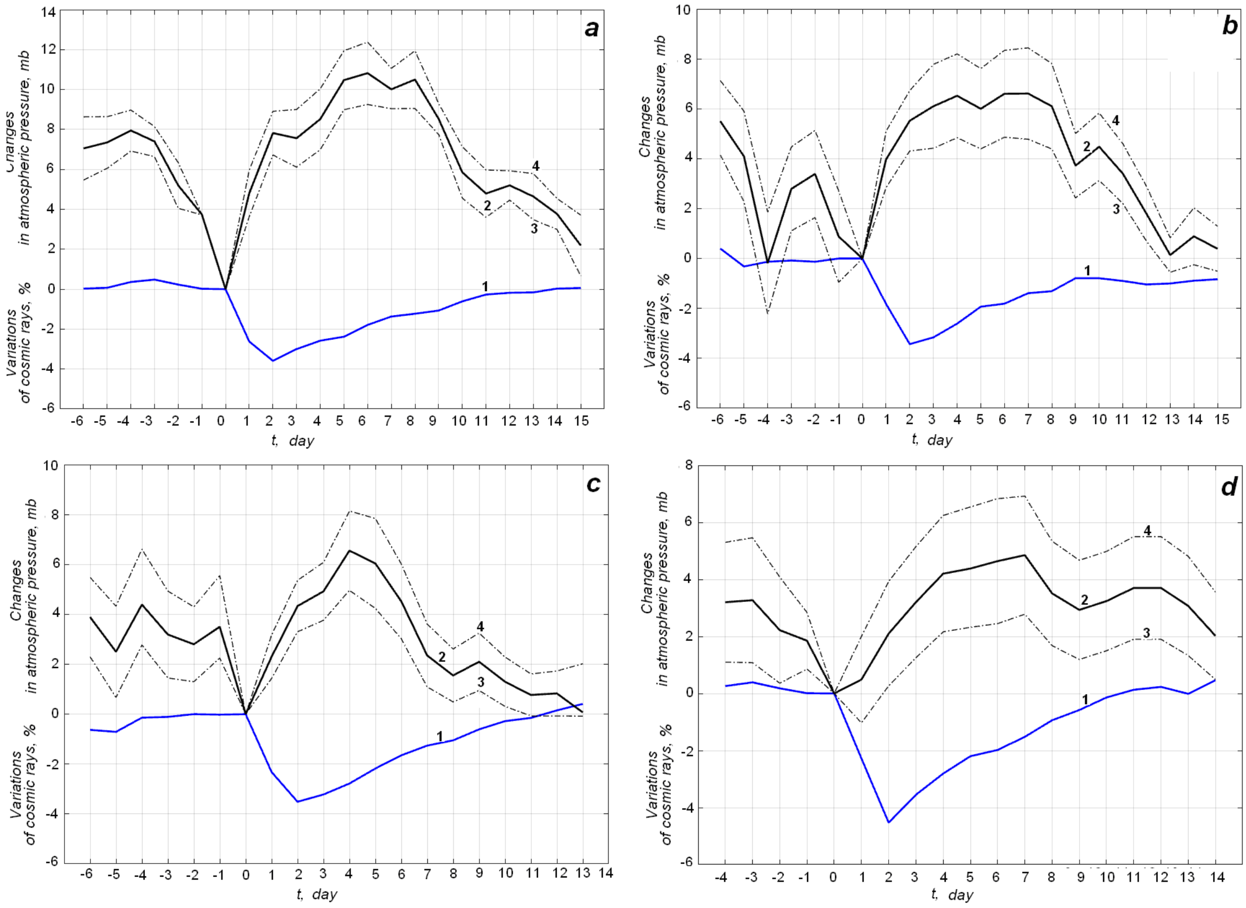

Figure 1. Variations in CR intensity (curve 1) and atmospheric pressure (curve 2) during FDs observed in fall (*a*), winter (*b*), spring (*c*), and summer (*d*). Curves 3 and 4 denote boundaries of the ±3σ confidence interval

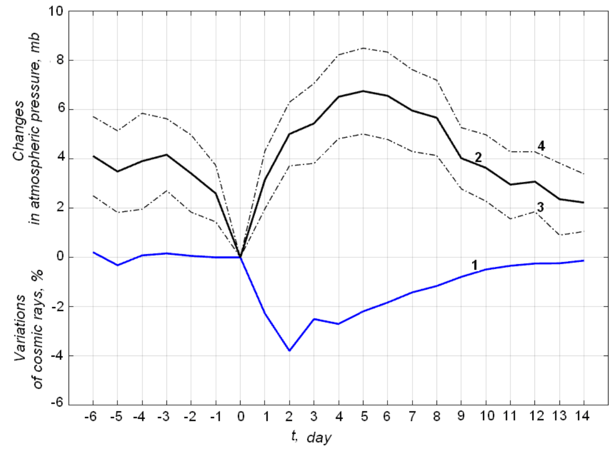

Figure 2. Variations in CR intensity (curve 1) and atmospheric pressure (curve 2), averaged over 181 events, during FDs. Curves 3 and 4 denote boundaries of the ±3σ confidence interval

rare events, not more than 5 % of all SPEs. On average, one event is recorded per year. The CR variations observed with neutron monitors during GLEs can exceed the 11-year CR variation and the largest Forbush decreases by more than an order of magnitude. The response of neutron monitors at high and middle latitudes to GLEs differs due to the geomagnetic cutoff rigidity. In Novosibirsk, the 24NM-64 neutron monitor has recorded 18 GLEs over the entire observation period. The events significantly varied in intensity: 5 events had an amplitude 2.5–4.5 %; 5, 4.6–5.5 %; 3, 5.6–9.5 %; 2, 10–15 %; 2, 20–30 %; and one event, 127 %. They were grouped for the cold (November to March) and warm (April to October) seasons, with 9 GLEs for each period. When examining the atmospheric pressure response to GLEs by the method of superimposed epochs, the day when the solar cosmic ray flare was maximum was taken as zero. The result is presented in Figure 3.

Before GLE, there is a decrease in atmospheric pressure; and after the flare, its increase with a depression on the second day. Veretenenko and Tejll [2008] for SPEs with ≥90 MeV particle fluxes observed a decrease in pressure at high latitudes on the first day after zero in the cold season (October–March). In order to carefully trace the behavior of atmospheric pressure in the zero and first days, we have used initial data with 1 hr resolution. The hour corresponding to SCR flare maximum was taken as zero. Atmospheric pressure variations with 1 hr resolution are depicted in Figure 4.

The pressure slightly decreases during the first 12 hrs after the SCR flare, but in the warm season. During the first 1.5 days, the behavior of atmospheric pressure variations differs in the cold and warm seasons. In [Veretenenko, Tejll, 2008], for midlatitudes a tendency is also observed for the pressure to increase after SPE in the middle troposphere and lower stratosphere.

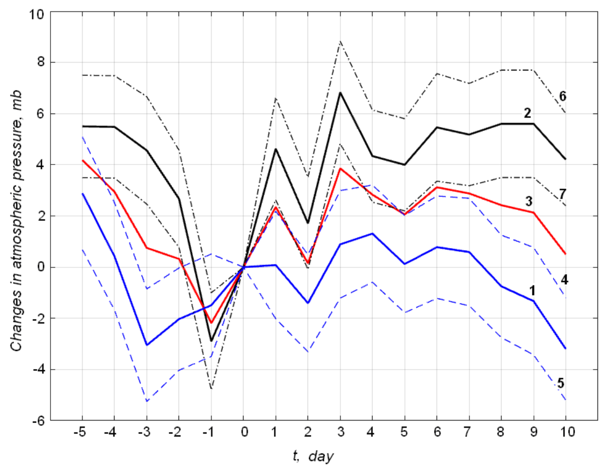

Figure 3. Atmospheric pressure variations during GLE in warm (curve 1) and cold (curve 2) seasons and on average per year (curve 3). Curves 4, 5 and 6, 7 designate boundaries of the ±3σ confidence interval

The atmospheric response to solar activity phenomena, as noted in a number of works [Mustel, 1974; Tinsley, Deen, 1991; Veretenenko, Thejll, 2013], is more pronounced in the cold season when there is an increase in cyclonic activity at midlatitudes due to an increase in temperature contrasts in the troposphere. The seasonal variation in temperature gradients at middle and high latitudes of the Northern Hemisphere occurs due to good warming of the continental surface in summer and strong cooling in winter.

Let us examine the behavior of the average mass and surface temperatures of the atmosphere during FDs for cold and warm seasons. The average mass temperature is the mass-weighted average temperature of the atmosphere

$$T_{\text{см}} = \sum_{i=1}^{n} T_i \Delta h_i \Big/ \sum_{i=1}^{n} \Delta h_i ,$$

where T_i is the temperature of the ith atmospheric layer (isobar); $\Delta h_i = h_{i\max} - h_{i\min}$ is the difference between the h values defining boundaries of the layer for the ith isobar. Since the atmospheric pressure at each level is equal to the weight of the overlying column of air, i.e. proportional to the mass of air in this column, Δh_i will characterize the mass of the layer of the ith isobar. The surface temperature is the temperature of the atmospheric surface layer (h–950 mb). Information on the temperature conditions in the atmosphere has been taken from the hourly database [http://crsa.izmiran.ru/phpmyadmin], which contains NCEP results [https://www.nco.ncep.noaa.gov/pmb/products/gfs]. We have analyzed 47 FDs observed since 2000: 27 were recorded in the warm season (April–September); 20, in the cold season (October–March); 11, in winter (December–February). Figure 5 shows variations in the average mass and surface temperatures during FDs at midlatitudes for winter, as well as for the cold and warm seasons.

With a decrease in the CR intensity, the atmospheric pressure, average mass and surface temperatures go up. At the same time, the average mass temperature rises by almost a degree (ΔT_{am}=+0.84 °C); and the surface temperature, by two degrees (ΔT_{surf}=+2.38 °C). At an FD minimum (after +2 days), the temperature stops increasing. With an increase in the CR intensity, the temperature begins to decrease during the FD recovery phase: the average mass temperature is the lowest (ΔT_{am}=–1.9 °C) on the seventh day; the surface temperature (ΔT_{surf}=–2.03), on the ninth day. With a further increase in the CR intensity during the FD recovery phase, the Δh, ΔT_{am}, and ΔT_{surf} variations approach zero. Variations in the average mass and surface temperatures of the atmosphere during FDs are more pronounced in winter

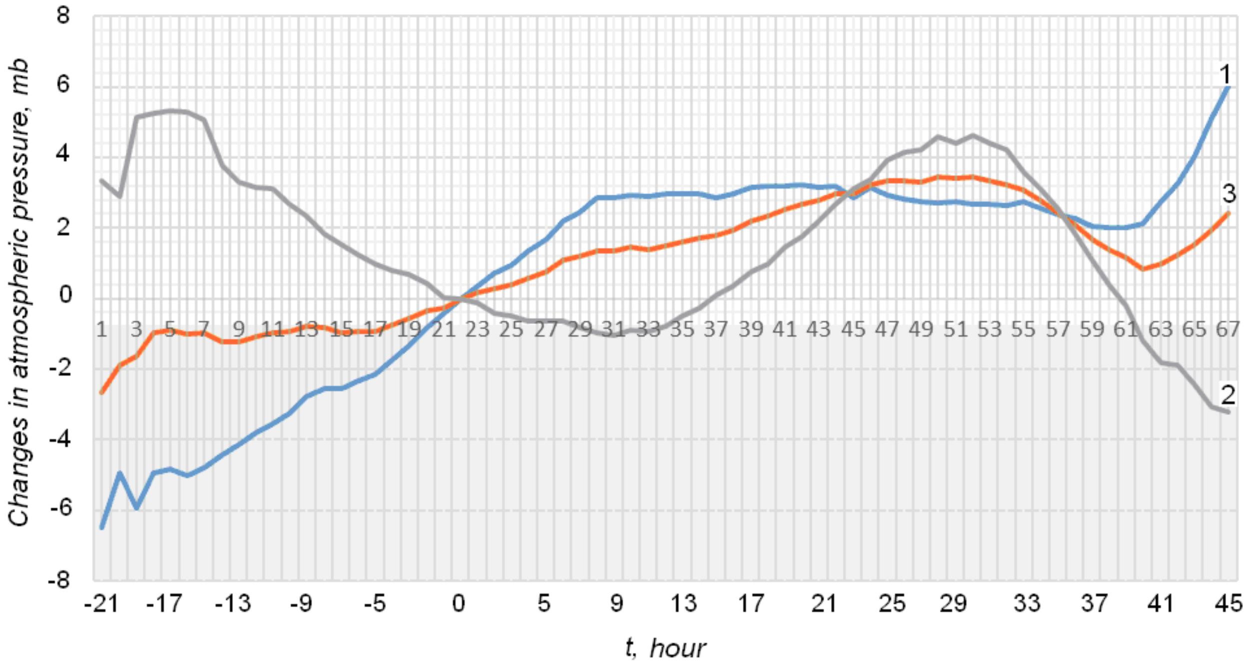

Figure 4. Atmospheric pressure variations (with 1 hr resolution) during GLEs in cold (curve 1), warm (curve 2) seasons, and on average per year (curve 3)

(December–February) (Figure 5, *a*), as well as in the cold season (October–March) (Figure 5, *b*). In all the cases (Figure 5, *a*–*c*), atmospheric temperature variations are wavelike.

Ionization of the atmosphere by CRs alters its chemical and aerosol composition [Pudovkin, Raspopov, 1993] without significant time delay [Shumilov et al., 1996]. Changes in the chemical composition of the atmosphere (concentrations of minor components of H_2O, O_3, NO_2, etc.), concentrations and sizes of aerosol particles cause changes in the atmospheric transparency and cloud cover. As a result, the solar energy flux entering the lower atmosphere is modulated. Thus, changes in the radiation-thermal balance of the troposphere are determined by the

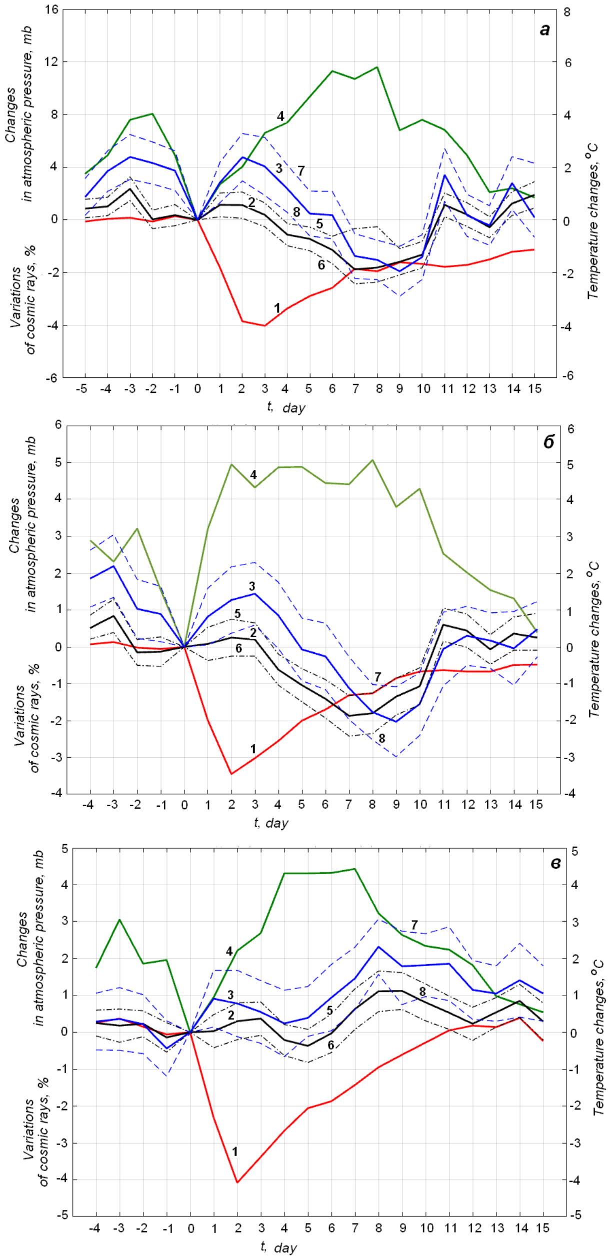

Figure 5. Variations in CR intensity (curve 1), average mass (curve 2) and surface (curve 3) atmospheric temperatures, as well as atmospheric pressure (curve 4) during FDs in winter (*a*), cold (*b*) and warm (*c*) seasons. Curves 5, 6 and 7, 8 indicate boundaries of the ±3σ confidence interval

CR-effect on the ionization rate. With a decrease in the CR intensity during the FD initial phase (Figure 5), the ionization rate in the atmosphere decreases, which leads to an increase in its transparency and a decrease in cloudiness. Consequently, the solar energy influx increases, causing the atmospheric temperature to rise. And vice versa, with an increase in the CR intensity during the FD recovery phase the atmospheric temperature goes down.

CONCLUSION

During an FD at midlatitudes (near Novosibirsk), the atmospheric pressure increases during the decay, minimum, and initial recovery phase of the CR intensity. In terms of duration, this atmospheric response practically coincides with the FD. Atmospheric pressure reaches a maximum on the fifth day after the onset of the FD. A statistically significant effect of increasing pressure during FDs at midlatitudes (near Novosibirsk) occurs during the fall-winter period.

For the mid-latitude region considered, there is also a tendency for pressure to increase after GLE, but only in the cold season.

When the CR intensity decreases and the atmospheric pressure increases, the average mass and surface temperatures rise. At the same time, the average mass temperature goes up by almost a degree; and the surface temperature, by two degrees. At the FD minimum, the temperature stops increasing. With an increase in the CR intensity, the temperature begins to goes down during the FD recovery phase. The average mass temperature reaches its lowest value on the seventh day; the surface temperature, on the ninth day. Statistically significant variations in the average mass and surface temperatures of the atmosphere during FDs are observed in the cold season (October–March).

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