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Variations of atmospheric pressure during solar proton events and Forbush decreases for different latitudinal and synoptic zones

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Abstract. Variations of atmospheric pressure during solar proton events (SPE) and Forbush decreases of galactic cosmic ray (GCR) intensity for 223 former USSR (surface pressure) and 10 North-Atlantic (Greenland, Denmark, Iceland, Faeroes, and Jan Mayen – height pressure profiles from balloon measurements) meteorological stations are studied. These stations are divided into a number of latitudinal and synoptic zones. Analysis of the experimental data has shown significant variations in tropospheric pressure caused by the SPEs or Forbush decreases, and the character of the atmosphere's parameter variations caused by the SPEs or Forbush decreases depends on the station's geographical setting and climatic zone. Also, it has been found that patterns of pressure disturbances move latitudinally during SPEs and longitudinally during Forbush decreases. These facts confirm previous results of predominant directions of atmosphere circulation during SPEs or Forbush decreases.

1. Introduction

A number of works have been devoted to the study of solar activity's effect on atmospheric parameters in general and on atmospheric pressure in particular. These studies have shown the effect of long- (11-yr and 22-yr cycles, secular variations) and short-term (solar proton events (SPE), Forbush decreases of galactic cosmic ray (GCR) intensity, crossing of the interplanetary magnetic field (IMF) boundaries, etc.) variations of solar activity on lower atmospheric parameters, weather, and climate.

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In particular, short-term (3–4 day) solar activity variations like SPE or Forbush decrease of GCR have a significant effect on air pressure in the stratosphere and troposphere, and even near the Earth's surface. *Pudovkin and Veretenenko* [1992] found a significant decrease of surface pressure in the middle- and high-latitude atmosphere and a small increase at low latitudes. The magnitude of these variations is about 1–2 hPa. These authors also studied Forbush decrease effects on the lower atmosphere. The results of their investigations have shown that on the third-fourth day after the Forbush decrease of GCR, the surface pressure in the middle- and high-latitude troposphere increases by up to 2 hPa. These results were obtained by analyzing zonal averaged pressure values. Also, there were some investigations dealing with grid data or station data (e.g., [*Stolov and Shapiro*, 1974; *Zerefos*, 1975]). These studies have shown that cells of surface pressure drop and rise are formed after SPEs or Forbush decreases.

If one looks at pressure variations after SPEs or Forbush decreases at other heights, the surface pressure changes are

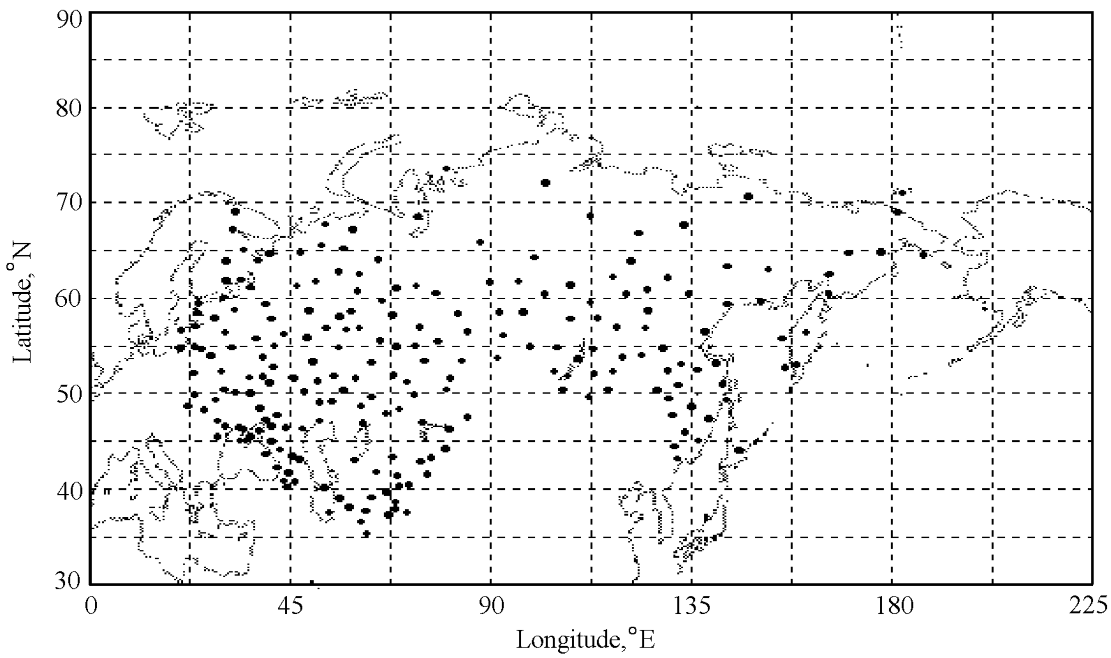

Figure 1. Distribution of 223 meteorological stations from the former USSR.

found to expand upward. In particular, *Pudovkin et al.* [1995] have found a strong decrease in pressure level heights, that is, a pressure decrease (p = 1000, 900, 700, 500, and 300 mbars) in the mid-latitude troposphere associated with bursts of solar cosmic rays (SCR). The magnitude of these variations is about 50–100 gpm. In contrast, Forbush decreases of GCR intensity cause a rise of geopotential surface height, that is, a pressure increase, in the mid-latitude troposphere [*Pudovkin et al.*, 1997] with amplitude of 60–120 gpm.

One part of our work is devoted to study of solar activity's effect (SPEs and Forbush decreases) on the height distribution of tropospheric pressure for high-latitude stations in the North-Atlantic region (Greenland, Denmark, Iceland, Faeroes, and Jan Mayen). Pressure variations in this region have been studied by some authors (e.g., *Schuurmans* [1981]; *Stolov and Shapiro* [1974]; and *Thejll* [1997]).

Schuurmans [1981] found a 500-mbar surface cell of drop near the North-Atlantic islands (Iceland, Faeroes) and two cells of 500-mbar surface rise after SPE. One of these rise cells is located above England, Denmark, and southern Sweden, and another is near the southern part of Greenland and the northeastern part of the Arctic Archipelago.

Zerefos [1975] found that on the first day after SPE in northwestern Greenland, heights of 500- and 300-mbar pressure surfaces decrease. In southern Greenland, these pressure surfaces slightly rise.

To continue all previous studies and improve previous results we investigated variations of pressure associated with bursts of SCRs and Forbush decreases of GCR for many meteorological stations at various latitudes and longitudes.

2. Description of Data

2.1. Surface Pressure

The dataset used in this work is a part of CDIAC's NDP-048/R1, "Six- and Three-Hourly Meteorological Observations from 223 USSR stations" database. This database was contributed by the All-Russian Research Institute of Hydrometeorological Information-World Data Centre (Obninsk, Russia) and prepared by the Carbon Dioxide Information Analysis Center in Oak Ridge National Laboratory, Environmental Sciences Division (Oak Ridge, Tennessee), as Publication No. 4771 [*Razuvaev et al.*, 1993; *Vose et al.*, 1992].

The data records contained in this numeric data package include 24 types of meteorological observations from each of the 223 USSR stations. All of these stations are situated in the region with latitude range $\varphi = 35 \ldots 75°$N and longitude range $\lambda = 20 \ldots 190°$E. Figure 1 presents the distribution of 223 station in the former USSR. To study the variations of atmospheric pressure during solar proton events or Forbush decreases of the GCRs we have used the air pressure records (p, expressed in tenths of hPa) at station level measured at local noon. Values of observations considered valid may range from 600.0 to 1100.0 hPa.

The variations of air pressure during SPEs or Forbush decreases have been studied with the superposed epoch analysis for each of the 223 stations. The dates of SCR bursts with $E_p \geq 90$ MeV and Forbush decreases in galactic cos-

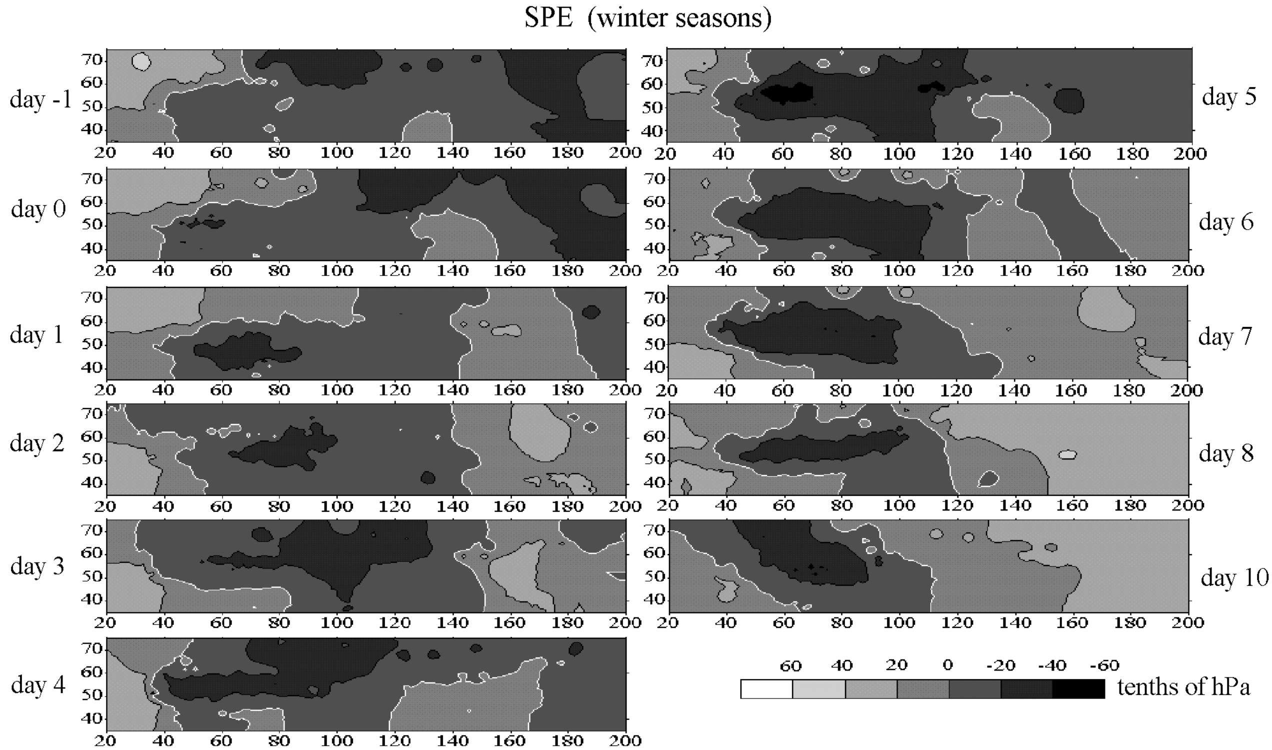

Figure 2. Departures of the surface pressure (in tenths of hPa) from mean value during 1 day before and 10 days after an SPE. White line is $\Delta p = 0$ hPa.

mic ray fluxes larger than 2.5% during winter seasons have been used as "key dates" (see Table 1). Each event under consideration is isolated from other events by at least 4 days.

At first, all stations were divided into eight 5° latitude zones. Then the stations for each latitude zone were divided into a number of groups with similar pressure variation characteristics during SPEs or Forbush decreases. The average pressure variations associated with SPEs or Forbush decreases were calculated for each group. The results of these analyses as a departure from mean pressure level are presented in Figures 2, 3, 4, and 5.

2.2. Height Pressure Distribution

To study the solar activity effect on height pressure distribution in the North-Atlantic region, we used a dataset provided by the Danish Meteorological Institute (DMI). This dataset contains selected data from the database of aerological soundings held at the DMI. These data include records of atmospheric pressure (expressed in hPa) height profiles for 10 stations (6 station in Greenland, Iceland, Faeroes, Denmark, and Jan Mayen) measured at local noon.

The geographical distribution of these stations is presented in Table 2 and Figure 6.

To study the variations of air pressure during SPE or Forbush decrease, we have used changes of atmospheric pressure at some height levels. At first, all pressure profiles have been interpolated to a uniform height scale. Then, for each of the stations, we used the superposed epoch method to calculate the average effect of SPE or Forbush decrease on the altitude profiles of atmosphere pressure (see Table 1 for the "key dates"). Because of some numbers of data gaps, the number of analyzed events (both SPEs and Forbush decreases) depends on the station. The results of this analysis are presented in Figures 7 and 8 for three height levels ($h = 3$, 5.5, and 9.5 km) as variations from mean pressure of each height level.

3. Discussion

3.1. Solar Proton Events

3.1.1. Surface pressure. The results of some previous studies (e.g., *Pudovkin and Veretenenko* [1992]) have shown that on the second day after a SPE, the surface pressure at latitudes of 55°–70°N decreases by up to 1 hPa and at latitudes less then 55°N, the surface pressure increases by up to 0.5 hPa. The results presented in this paper make the longitude analysis of this zonal pressure variation possible. Figure 2 shows the averaged variations of surface pressure during SPE as a function of longitude and latitude. As

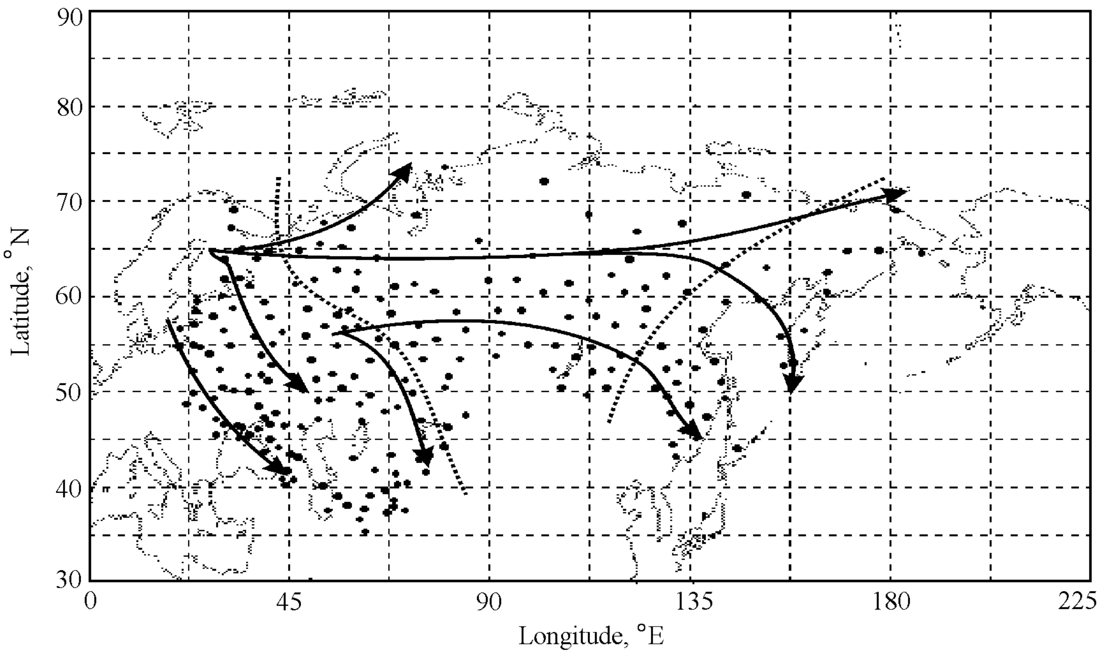

Figure 3. The movement of surface pressure disturbances after an SPE.

one can see, SPE causes an appearance of increased and decreased surface pressure cells. The amplitude of pressure variations is about 5 hPa. The decreased cells are located in the continental part of the former USSR, and increased cells are located in regions with maritime climate.

Table 1. List of SPE and Forbush Decreases "Key Dates"

No.	Solar Proton Events			Forbush Decreases		
	Year	Month	Day	Year	Month	Day
1	1967	01	28	1969	11	09
2	1969	03	30	1970	11	07
3	1977	11	22	1971	01	27
4	1981	03	07	1978	01	03
5	1982	01	31	1978	02	15
6	1982	02	08	1978	11	12
7	1982	03	07	1979	02	18
8	1982	12	15	1980	03	06
9	1983	01	05	1980	10	31
10	1984	02	16	1980	11	10
11	1984	03	14	1980	12	11
12	1986	02	06	1981	01	30
13	1988	03	25	1981	10	03
14	1988	10	12	1981	11	12
15	1988	11	08	1981	12	29
16	1988	12	14	1982	03	01
17	1988	12	27	1982	12	10
18	1989	03	11	1983	01	10
19	1989	03	23	1986	03	08
20	1989	10	19	1986	11	04
21	1989	10	29	1988	01	05
22	1989	11	15	1988	01	13
23	1989	12	01	1988	02	21

Another interesting result of our investigation is the movement of surface pressure disturbances and their patterns from one station (or group of stations) to another. The directions of these movements are presented by the arrows in Figure 3. For all stations situated northerly than $\varphi = 60°$N, the pressure disturbances move eastward. The pressure disturbances associated with SPEs move in a southeastern direction for southern stations located west of $\lambda \approx 50°$E and in southerly and southeasterly directions for stations located east of $\lambda \approx 50°$E.

We can compare our data with results of other investigations. *Zerefos* [1975] studied variations of air pressure for different geopotential heights in North America. He found a serious drop of isobaric surfaces in the polar and subpolar atmosphere ($\varphi \geq 50°$N) and a rise of more southern stations. These data have been confirmed by *Schuurmans* [1981]. He also found longitudinal cells of drops and rises of the 500-mbar isobaric surface.

In our study, we found that in the east ($20°\text{E} \leq \lambda \leq 50°\text{E}$) and the west ($140°\text{E} \leq \lambda \leq 190°\text{E}$) regions of the former USSR, surface pressure increases for all latitudes. In the middle region ($50°\text{E} \leq \lambda \leq 140°\text{E}$), there is a pressure decrease in the 50°–65°N latitude belt. These data allow us to conclude that for the continental part of Russian Eurasia, our results are in good agreement with previous results. For the eastern and western parts of Russian Eurasia, our results contradict Zerefos's data. This contradiction can be associated with ocean and oceanic cyclone effects. Concerning the appearance of longitude cells of pressure's decrease or increase, our results roughly agree with Schuurmans's data, which can be associated with the difference between pressure levels under consideration (500 mbar in Schuurmans's work and $\simeq$1000 mbar in our case).

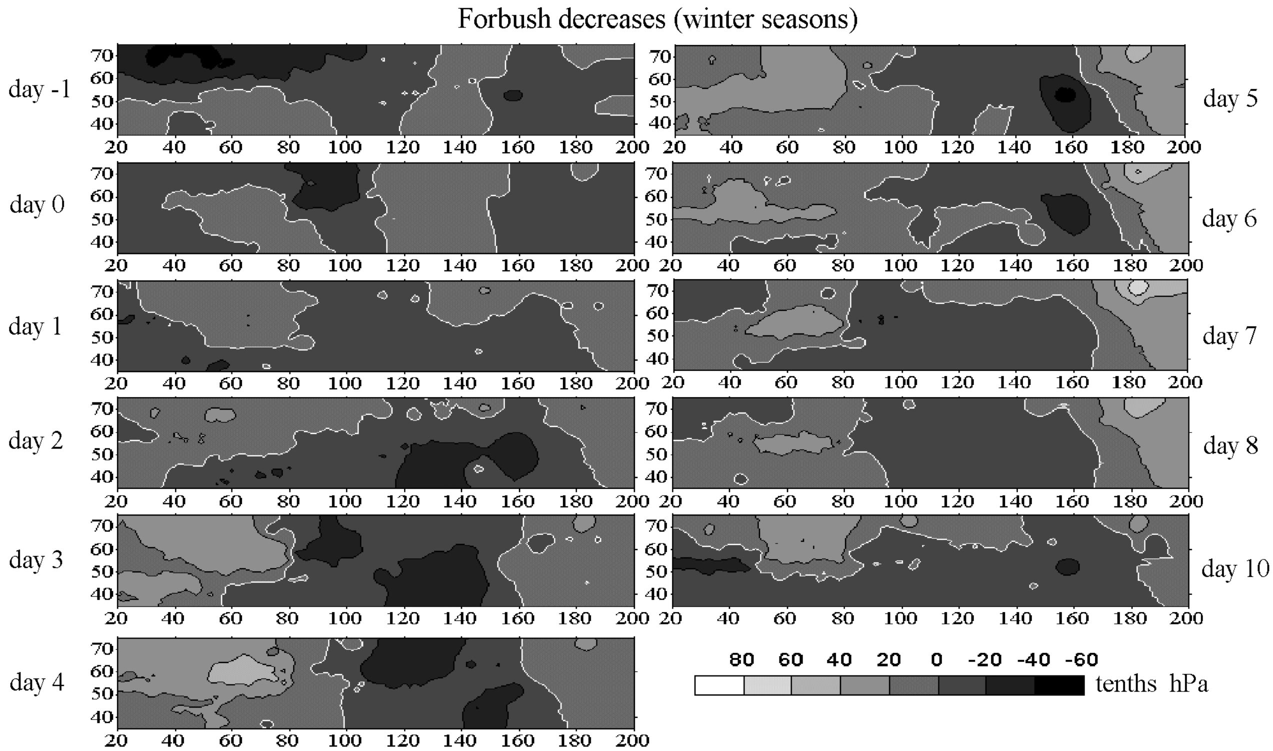

Figure 4. Same as in Figure 2, but for Forbush decrease.

3.2. Height Pressure Distribution

Figure 7 shows pressure variations caused by bursts of energetic protons from SCR at three height levels for the North-Atlantic region. One can see that the effect of the SPE is not uniform in the region under consideration. There are cells of pressure increase and pressure drop. These cells are similar for all three heights.

The main effect of the SPE on pressure in the North-Atlantic region at $h = 3$ km on the zeroth-first days is the production of a pressure drop cell in the oceanic part of this region (east coast of Greenland, Jan Mayen, Faeroes, Iceland). In the west (west coast of Greenland) and east (Denmark) part of the region under consideration there are cells of pressure rise. This pattern is repeated (in main) at height levels $h = 5.5$ and 9.5 km.

On the second day after the SPE, the cell of pressure drop moves westward and becomes smaller. It now covers only the east coast of Greenland. On the other side, the east cell of pressure increase also moves westwardly and expands to the region of the North-Atlantic islands (Jan Mayen, Faeroes, Iceland).

On the third day, the west cell moves north, and during the fourth through fifth days, it expands across the whole region under consideration.

Thus, the SPE's effect on pressure variations in the North-Atlantic region on the zeroth-third day is a pressure

Table 2. List of North-Atlantic Stations Under Consideration

No.	Latitude, deg N	Longitude, deg E (deg W)	Station Number	Station Name
1	56	12	6181	Jaegersborg
2	62	353 (7)	6011	Thorshavn
3	65.5	322 (38)	4360	Tasiilaq
4	70.5	338 (22)	4339	Scoresbysund
5	77	341 (19)	4320	Danmarkshavn
6	61.2	314.6 (45.4)	4270	Narsarsuaq
7	68.6	310 (50)	4220	Aasiaat
8	77.5	290.8 (69.2)	4202	Thule
9	64	337.5 (22.5)	4018	Keflavik
10	71	351 (9)	1001	Jan Mayen

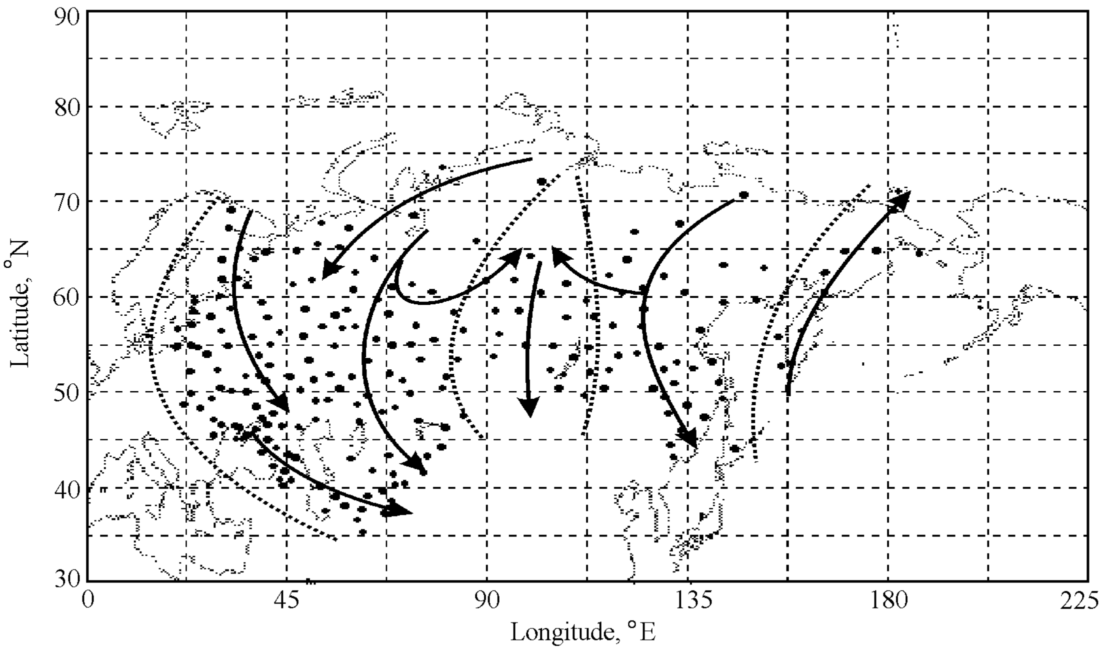

Figure 5. Same as in Figure 3, but for Forbush decreases.

decrease in the oceanic part and an increase in the northwest and southeast part of this region. On the fourth-fifth day after the SPEs, the pressure in the region increases.

Our results are in good agreement with the data of *Schuurmans* [1981]. We also have found that on the first day after the SPE, at the height 5.5 km, pressure rises in the longitude ranges $0 \leq \lambda \leq 15°$E and 290°E (70°W) $\leq \lambda \leq$ 320°E (40°W) and falls in the longitude range 320°E (40°W) $\leq \lambda \leq$ 340°E (20°W). Concerning the meridional pressure variations, we also have found that (in main) the pressure falls in the middle latitude troposphere ($\varphi \leq 65°$N) and slightly rises (in average) at high latitudes ($\varphi \geq 65°$N).

Our data also confirm results shown by *Zerefos* [1975]. On the first day after the SPE on the west coast of Greenland, at heights of 5.5 and 9.5 km, pressure falls down near Thule (4202) station (northwest of Greenland) and rises near the south Greenland stations (Narsarsuaq (4270) and Aasiaat (4220)).

One station used in this study, Thule (4202), is located near the North magnetic pole. During the first days after

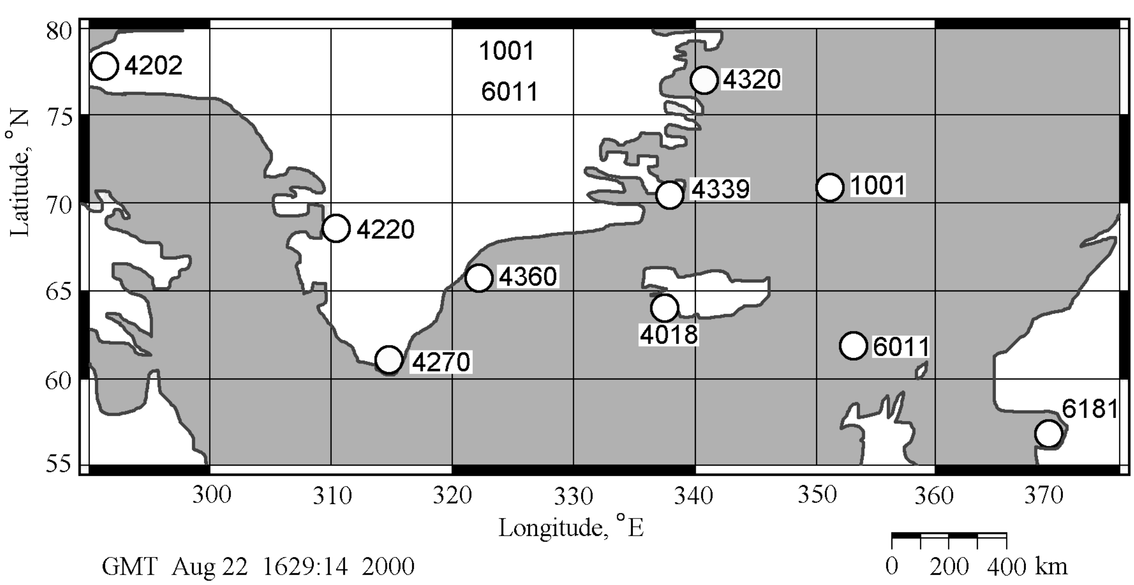

Figure 6. Distribution of 10 meteorological stations in the North-Atlantic region. See Table 2 also.

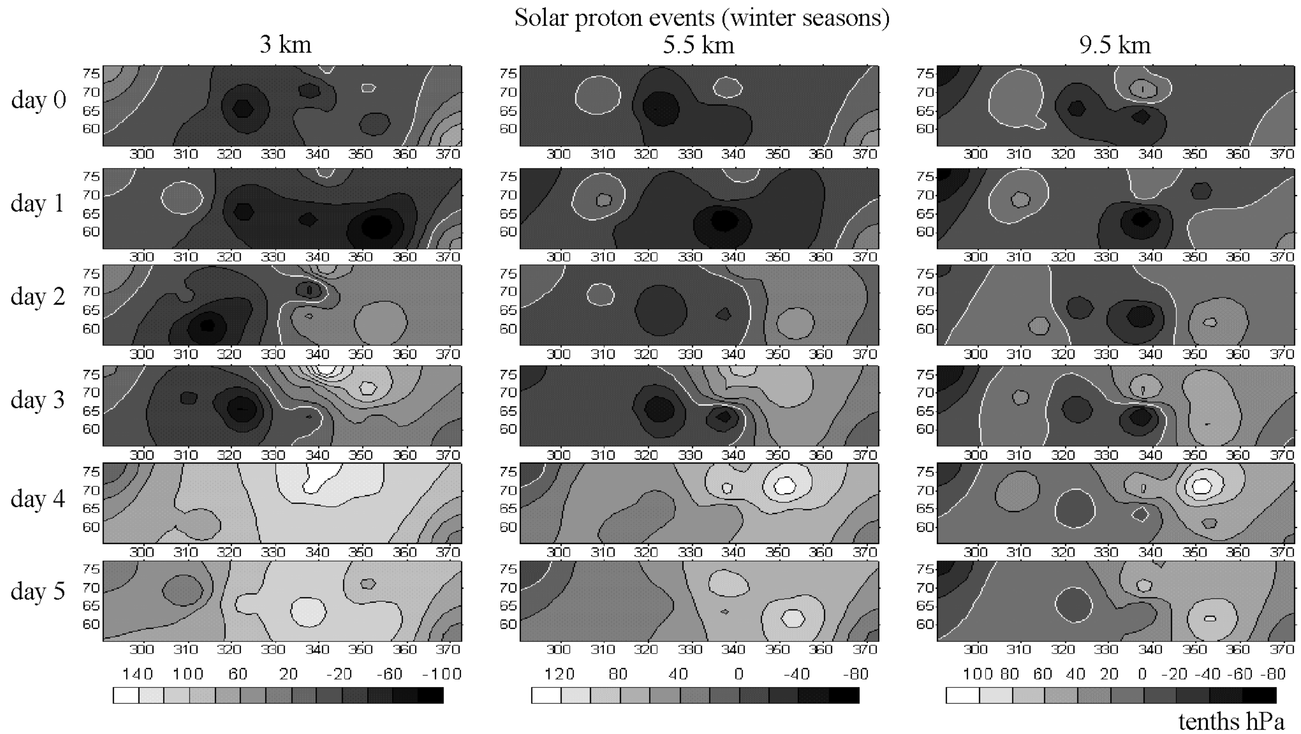

Figure 7. Departures from mean values of the pressure at $h = 3$, 5.5, and 9.5 km (in tenths of hPa) during 0–5 days after an SPE. White line is $\Delta p = 0$ hPa.

the SPE, pressure at Thule increased $h = 3$ and 5.5 km, and the pressure decreased at $h = 9.5$ km. We can compare these results with pressure variations observed after the SPE near the south magnetic pole in the Antarctic. *Vovk et al.* [1997] found that after the proton flares in the region near the south magnetic pole, atmospheric pressure increases near the ground level, is almost constant at $h = 5$ km, and decreases at $h \geq 10$ km. Thus, the pressure variations associated with SPEs are similar for the magnetic poles.

3.3. Forbush Decreases of GCR Intensity

3.3.1. Surface pressure. The results of some previous studies (e.g., *Pudovkin and Veretenenko* [1992]) show that on the third-fourth day after Forbush decreases of GCR, surface pressure in the latitude belt $\varphi = 50 \ldots 70°$N increases by up to 2 hPa. Here we present the longitude analysis of this zonal variation. Figure 4 shows the averaged variations of surface pressure during Forbush decreases as a function of longitude and latitude.

Figure 4 shows that after Forbush decreases of GCR, cells of pressure increases and decreases appear, but they are stretched longitudinally and the pressure variations have an inverse sign. The magnitude of pressure variations $\Delta p = 7 - 8$ hPa.

Figure 5 analyzes the movement of surface pressure disturbance patterns from one of more stations to another. Unlike the SPE effect, the surface pressure disturbances associated with Forbush decreases mainly move from north to south (and from south to north for the Far-East region with $\lambda \geq 150°$E). Theses movements are presented in Figure 5 by the arrows.

We can compare our results with investigations of *Stolov and Shapiro* [1974]. They studied changes of 700-mbar contour heights associated with geomagnetic disturbances and also found cells of isobaric surfaces's rise and drop. Our data do not show significant agreement with Stolov and Shapiro's results. This disagreement could be caused by the different pressure levels under consideration (700-mbar in Stolov and Shapiro's work and $\simeq$1000 mbar in our case).

3.3.2. Height pressure distribution. As with the SPE effect, we have found an increase of pressure in the North-Atlantic region at all three height levels under consideration on the first day after Forbush decrease (Figure 8; There is only one exception – it is a Danish station in the southeastern part of the North-Atlantic region. On the second day, two regions of pressure decrease are formed. One of them is near the east coast of Greenland and another is in the region of Denmark–Faeroes. Also on this day, two regions of pressure rise are formed. One of them is located near the west coast of Greenland and another is near Iceland. On the fifth day after the Forbush decrease, there are only two regions with pressure variations of opposite sign. The first one is the region of pressure rise located near Thule (4202) station. The second one is the cell of pressure drop situated near Jan Mayen (1001) and expanded from one side to Denmark and from the other side to the east coast of Greenland.

The patterns of pressure variation distribution in the

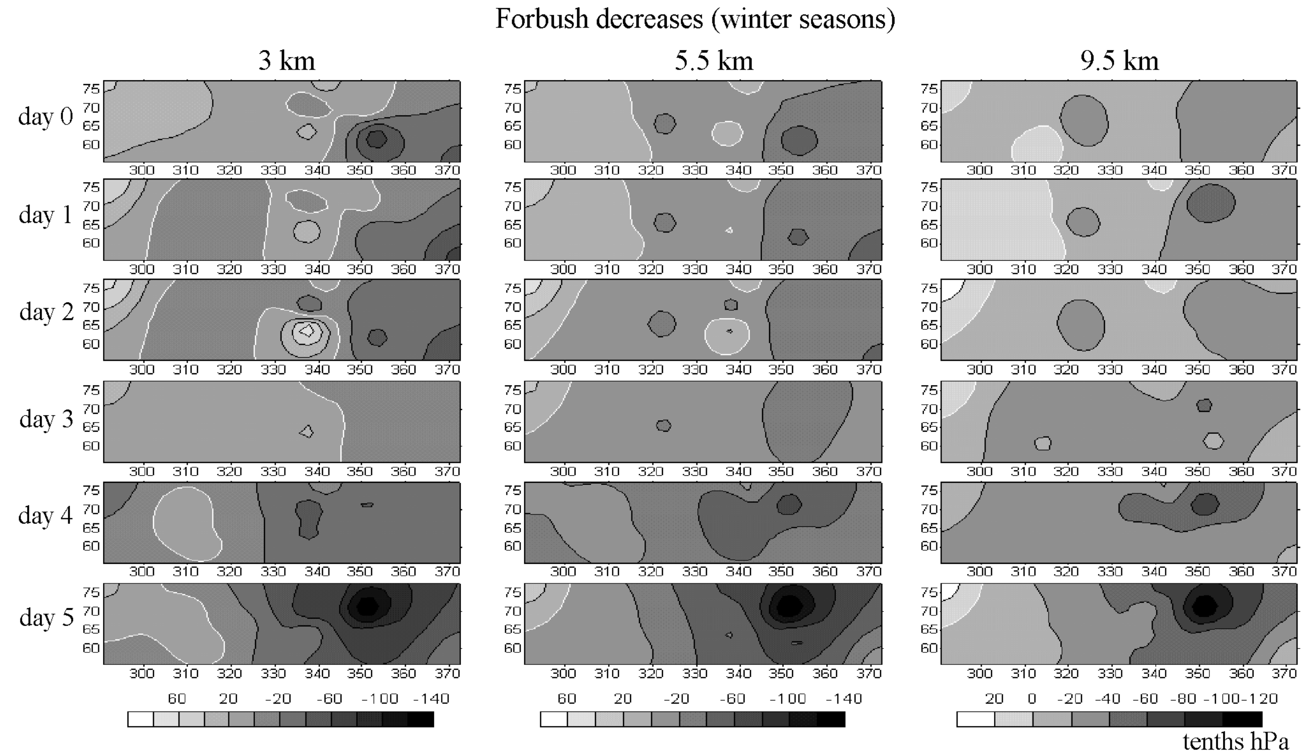

Figure 8. Same as in Figure 7, but for Forbush decrease.

North-Atlantic region are similar for different height levels.

Our results do not confirm data presented by *Stolov and Shapiro* [1974]. On the zeroth day after the Forbush decrease, we also found a cell of pressure rise in the longitude region 330°E (30°W)$\leq \lambda \leq$ 350°E (10°W), but our data did not display a cell of pressure decrease centered at $\lambda \approx 300°$E (60°W), $\varphi \geq 60°$N.

Also, our results concerning the pressure variations associated with Forbush decreases for Thule (4202) station do not agree with *Vovk et al.* [1997] data for the south magnetic pole. We did not find in Thule data any sign of pressure fall associated with Forbush decreases, whereas pressure measured on Antarctic stations near the south magnetic pole fell on the first day after Forbush decreases.

4. Conclusion

1. Analysis of surface pressure variations after SPEs and Forbush decreases for the Eurasian region have shown significant variations of this atmospheric pressure during at least the first five days after the events. These variations differ with regard to latitude and longitude. There are cells of increased and decreased surface pressure. The character of surface pressure variations associated with SPEs differs from those associated with Forbush decreases.

2. The directions of movement of the pressure disturbances for SPEs and Forbush decreases are different. After SPEs, the pressure disturbance patterns move (in main) in zonal direction from west to east and slightly to the south. After Forbush decreases, the disturbance patterns move from north to south (and from south to north in the Far East). These changes of pressure pattern movements can be interpreted as an influence of atmospheric circulation changes associated with SPEs or Forbush decreases. As has been shown in some previous works (e.g., *Pudovkin and Babushkina* [1992]), the bursts of SCRs cause an intensification of zonal flow in the troposphere. On the other side, Forbush decreases of GCRs are associated with a decrease in zonal wind velocity. This can also be interpreted as an intensification of meridional winds. Therefore, the results presented in this work confirm previous conclusions and point out that the SPE-effect is a stimulation of zonal winds. Forbush decreases, on the contrary, damp zonal flow and intensify meridional winds.

3. Analysis of altitude pressure profile variations after SPEs and Forbush decreases for the North-Atlantic region has shown significant variations of this atmospheric parameter during at least the first 5 days after the events. There are cells of rise and drop of surface pressure. After SPEs the one cell of pressure drop (in the oceanic part) and two cells of pressure rise (in the western and eastern part of the region under consideration) are formed. Forbush decreases cause the

appearance of two cells of pressure increase (one is located near the west coast of Greenland and another is located near Iceland) and two cells of the pressure decrease (one is located near the east coast of Greenland and another is located near Denmark and the Faeroes). The character of pressure variations associated with SPE differs from that associated with Forbush decreases, except for pressure changes at Thule (4202) station.

4. The spatial difference in pressure variations may be associated with a difference in synoptic conditions caused by the presence of Canadian anticyclone (above the western part of Greenland) and Icelandic trough. It must be mentioned that a similar spatial difference of solar activity's effect on pressure was found earlier by *Thejll* [1997]. He found that ground-level air pressure in Greenland, Jan Mayen, Iceland, and the Faeroes decreases with cosmic ray flux, while southern Sweden shows an increase in pressure with the drop in the GCR flux.

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