

Effects of energetic solar proton events on the cyclone development in the North Atlantic

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Received 8 April 2003; received in revised form 3 November 2003; accepted 20 November 2003

Abstract

Short-term effects of the energetic solar proton events (SPE) on the different characteristics of the lower atmosphere were studied in the North Atlantic region, which is an area of intensive cyclone genesis and development. The data of aerological soundings over the set of Danish stations (Greenland, Faeroe Islands and Denmark), the vorticity data at the different pressure levels and weather charts at the Earth's surface were used. It was shown that the SPE under study are accompanied by noticeable pressure and temperature decreases at the high-latitude stations in the cold (October–March) half of year as well as by relative vorticity increases in the troposphere. The most pronounced effects were found in the region of the arctic front near the south-eastern Greenland coasts and Iceland. The weather chart analysis showed that the effects discovered seem to be related to the intensification of the deepening of well developed cold cyclones in this region. The results obtained suggest that the SPE with particle energies sufficient to penetrate the stratospheric heights may influence the cyclone evolution over the northern part of the Atlantic Ocean, a possible physical mechanism involving the radiative forcing of the cloudiness changes which may be associated with cosmic ray variations.

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Keywords: Solar activity; Cosmic rays; Weather; Climate

1. Introduction

It is well known that the weather in middle latitudes strongly depends on extratropical cyclones forming and developing over the North Atlantic and North Pacific regions. Therefore, the influence of solar activity and related phenomena on the cyclone genesis and intensification in these regions is of substantial interest for the investigators of solar-climate relationships. Macdonald and Roberts (1960) and Roberts and Olson (1973) showed that the wintertime low-pressure troughs at the 300 mb isobaric level in the North Pacific region tend to deepen more strongly if preceded by geomagnetic or auroral activity. Schuurmans and Oort (1969) considered the variations of the 500 mb level heights after strong solar flares and found the pressure

decrease predominating at polar and subpolar latitudes (mainly over oceans) and the pressure increase at lower latitudes. Wilcox et al. (1974) showed the tropospheric trough area characterized by the vorticity index reaches a minimum 1 day after the passing of the sector boundary of the interplanetary magnetic field. Olson et al. (1975) revealed the increase of the vorticity index at the 500 mb level related to solar flares with its consequent decrease during the geomagnetic disturbances caused by these flares. Tinsley et al. (1989), and Tinsley and Deen (1991) found vorticity decreases, predominating at the latitudes 40–65°N over oceans, associated with Forbush-decreases of the galactic cosmic rays.

However, the physical mechanism of solar activity effects on weather phenomena remains unclear. It is suggested that a significant part in the transfer of the solar variability to the lower atmosphere may be played by charged particles of solar and galactic origin, mainly protons, with energies

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from ~ 100 MeV to several GeV. These particles are able to penetrate the stratosphere/upper troposphere heights and, on the other hand, their variations are closely related to solar activity (see, for example, Tinsley and Deen, 1991, and references therein). The solar energetic particles mostly originate from solar flares, whereas the galactic cosmic rays are modulated by irregularities in the magnetic fields of the solar wind which are enhanced by increasing solar activity. In this work we study the effects of solar proton events (SPE), with energy above 90 MeV, on atmospheric characteristics in the North Atlantic, where the cyclones may originate or undergo the greatest changes in their evolution.

2. Experimental data and their analysis

2.1. Variations of meteorological characteristics at the North Atlantic stations

To study the effects of the SPE on the lower atmosphere characteristics we used aerological soundings carried out at local noon at the set of Danish stations in the North Atlantic region: Tasiilaq (the south-eastern coast of Greenland, geographic coordinates 65.5°N , 38°W), Thorshavn (Faeroe Islands, 62°N , 6.5°W) and Jægersborg (Denmark, 56°N , 12°E), the geomagnetic latitudes of these stations being 74°N , 65°N and 56°N , respectively. The analyzed values were the geopotential heights of the pressure levels 1000, 850, 700, 500, 400, 300, 200, 100 and 50 mb and the temperature at these levels. It is seen that the stations Tasiilaq and Thorshavn are situated in the region which is of particular interest for the studies of solar influences on weather and climate, since it is a region of the North Atlantic part of the arctic front, one of the main atmosphere fronts, separating in this case the cold arctic air over Greenland and the warmer air of the middle latitudes. It is known that most of the extratropical cyclones arise and develop at the main atmosphere fronts, in particular at the arctic fronts, where there are high temperature contrasts, especially in the cold half of year. The region near the Greenland coast is characterized by a high frequency of occurrence of winter cyclones, increasing from the eastern coasts of North America towards Iceland, which indicates the predominance of cyclone genesis in this zone. To the east of Iceland, where the frequency of cyclone occurrence decreases, filling (destruction) of the cyclones often takes place (Vorobjev, 1991).

As was shown (Veretenenko and Pudovkin, 1993), a significant response of the lower atmosphere circulation to solar proton events is related mainly to the energetic (> 90 MeV) particles. For this reason, isolated (separated by at least 3 days from the preceding event) SPEs, with energy > 90 MeV, were selected for the period 1980–1989, the data being taken from the catalogue by Logachev (1990) as well as from the periodical issues Cosmic data (Institute of Terrestrial Magnetism and Radio Wave

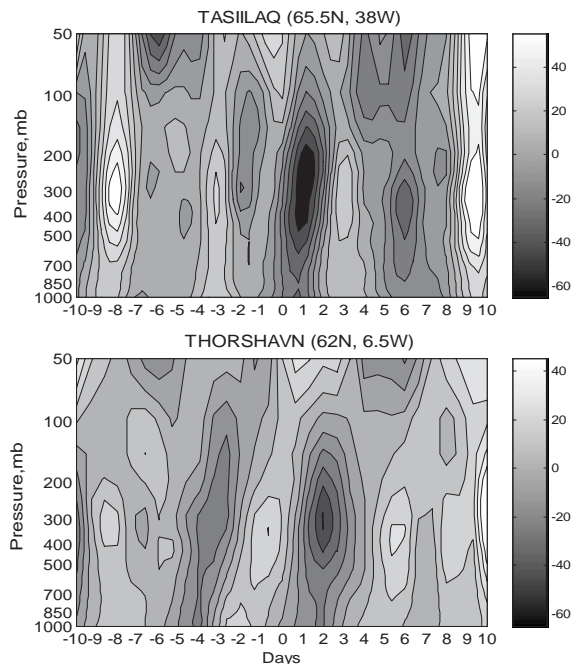


Fig. 1. Mean variations of geopotential heights (in gp m) at the North Atlantic stations associated with the energetic SPE. Day $t=0$ corresponds to the day of the first aerological sounding after the event onset.

Propagation, 1980–1989) which were published in Russia till 1990. Since the Greenland coast is situated at rather high (above 65°N) geomagnetic latitudes, it happens to be in the region of proton intrusion with the energies mentioned above. The events were selected for the cold half of year (October–March), since it is the period of the most intensive cyclogenesis. A list of the selected SPE is presented in the Appendix. The days of the first aerological sounding after the event onsets were used as the key days ($t=0$) for a superposed epoch analysis.

The mean variations in pressure and temperature obtained by subtracting the 10 day running mean values and then averaging over the days surrounding the key dates, are shown in Figs. 1 and 2 for the high-latitude stations. It is seen that the SPEs under study are accompanied by a distinct pressure decrease (i.e. by a decrease of the geopotential heights of the constant pressure levels) at the Greenland station (Tasiilaq) in the whole troposphere and the lower stratosphere (1000–100 mb levels). The minimum of the pressure is reached on the +1 day relative to the event onsets. The most pronounced lowering of pressure levels (by ~ 55 – 65 gp m) is observed in the middle and upper troposphere (500–200 mb levels). The statistical significances of the effects according to the modified Student's t -criterion, taking into account the serial correlation in the time series, amounts to 0.90 in the lower troposphere

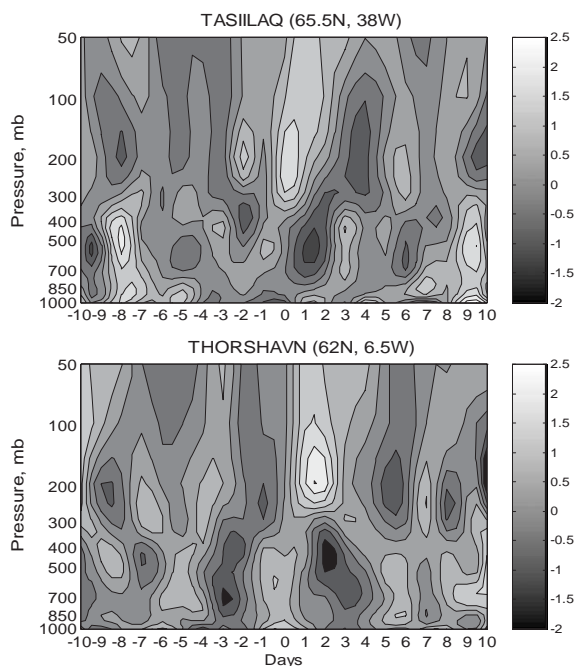


Fig. 2. Mean variations of temperature ($^{\circ}\text{C}$) at the North Atlantic stations associated with the energetic SPE. Day $t = 0$ corresponds to the day of the first aerological sounding after the event onset.

(1000–850 mb levels) and 0.95–0.98 at the higher levels (700–200 mb). At Thorshavn (Faeroe Islands), situated slightly to the south-east of Iceland, there is also a pressure decrease in the whole troposphere, but the amplitude of the effect is less than at Tasiilaq. The greatest decreases of pressure level heights amount to ~ 40 –55 gp m at 500–200 mb levels, the confidence level being 0.98–0.99, on the +2 day after the event onset, i.e. a day later than at Tasiilaq. At Jægersborg, the midlatitudinal station situated in Denmark, we found only a slight increase of the geopotential heights at all the levels. The greatest variations (~ 30 –40 gp m) were observed at 400–200 mb on the 0/+1 day, but their confidence level is rather less than 0.9. We can also note an insignificant decrease of geopotential heights (by ~ 20 –25 gp m) in the middle and upper troposphere (400–200 mb levels) on +3/+4 day after the event onset.

The temperature variations corresponding to the pressure decreases at Tasiilaq and Thorshavn are similar and show a rather complicated pattern (see Fig. 2). The temperature decreases by ~ 1 – 1.5°C below 300 mb (which is the level with the maximum decrease in pressure) and increases by ~ 1.5 – 2°C above this level, the statistical significance of these effects amounts to 0.95–0.98 according to the modified Student's t -test. The maximum of the temperature increases are observed in the upper troposphere and the lower stratosphere (200–100 mb levels). At Jægersborg, where the pressure

tends to increase, the temperature changes are quite opposite: it increases by ~ 1 – 1.5°C at 700–300 mb and decreases by $\sim 2^{\circ}\text{C}$ at 200 mb level.

The data presented above show rather sharp changes in the atmosphere characteristics after the key dates under study, especially at the Greenland station. These changes are distinctly seen at Tasiilaq already at the moment $t = 0$ which corresponds on the average to ~ 9 h after the SPE onset. High-energy solar particles are known to reach the Earth's orbit in a few hours, whereas the high-speed plasma streams resulting in the Forbush-decreases of the galactic cosmic rays which could cause the decrease in the stratosphere ionization and probably the opposite effects in the atmosphere state arrive usually 1–2 days after the solar flares. So we can suggest that the effects observed are related to energetic SPE. Indeed, the analysis of the neutron monitor counting rate in Apatity relative to the selected key dates showed that the Forbush-decreases started on the average on the +2 day after the burst onsets. It should also be noted that the pressure decrease found at the high-latitude stations near the Greenland coast agrees with the data presented by Pudovkin et al. (1996) where the sharp pressure decrease in the lower troposphere was observed already in the first ~ 10 h after the SPE onset, the aerological data from Sodankylä station (Finland, 67°N) being used. A weak decrease of pressure observed at high latitudes before the SPE onset may also imply a possible influence of some additional factors related to the flare activity (in particular, hard X-rays) which was found to increase noticeably on the $-2/-1$ days relative to the key dates.

Thus, the most pronounced variations of meteorological characteristics correlated with energetic SPE were found at the south-eastern coast of Greenland, with the pressure decreasing in the whole troposphere and the temperature decreasing below 300 mb level, on the day after the event onset. The SPE effects are similar at the Faeroe Islands to the south-east of Iceland, though the pressure decreases are less and they are observed a day later than at the Greenland station. A weak pressure decrease was found in the Danish station, situated still farther from the arctic front, on the 3–4 day, whereas on the 0–1 day there is a tendency for a pressure increase.

2.2. Weather chart analysis

To answer the question “what is causing the pressure and temperature changes correlated with the SPE?”, we analyzed the weather charts at the Earth's surface for the days surrounding the selected key dates. The weather charts provide the data on the atmospheric state at the time of observation, i.e. on the distribution and the character of the air masses, the atmospheric fronts, the location of the baric systems (cyclones, anticyclones, troughs and crests). Comparing the weather charts, we can follow the transformation of the air masses and the motion and the evolution of the cyclones and anticyclones etc.

Before presenting the results of the weather chart analysis, let us consider in brief the evolution of extratropical cyclone which involves several stages (e.g. Khromov and Petrociants, 1994; Vorobjev, 1991). First, a wave is formed at the cold front. As the wave develops, the pressure decreases in its center and closed cyclonic circulation appears near the Earth's surface. In the second stage the young cyclone is characterized by a pressure decrease in its center and by the existence of a warm sector (the warm air between the cold and warm fronts of the cyclone which conjugate in its center). Since the cold front of the cyclone moves more rapidly than the warm one, it gradually approaches the warm front and merges with it, the warm air being displaced upward and to the cyclone periphery. This process is called the cyclone occlusion and the formation of the occluded front. At the occlusion the cyclone reaches the stage of its maximal development and the pressure in its center drops to the minimal values. The closed cyclonic circulation extends to higher levels, usually up to 5 km. After the beginning of the occlusion, the pressure does not change significantly, the warm sector disappears at the cyclone periphery and the cold air occupies all the area of the cyclonic circulation. Then the final stage of the cyclone evolution begins: the cyclone cools and slows, and closed circulation is observed in all the troposphere. The pressure in the cyclone center starts increasing and it gradually fills, starting from the surface.

The results of the analysis of the cyclone development after the SPE onset based on weather charts are given in Table 1, the changes of the pressure in the cyclone center before and after the event onset being indicated. It was found that the cases of new cyclone formation are rather rare, whereas the deepening of already existing cyclones (more or less pronounced) traveling near the south-eastern part of Greenland or to the south of it (at latitudes 50–60°N) was observed on the 0/+1 day relative to the key dates in most (~75%) cases. The data in Table 1 show strong cyclone deepening (by 15–35 mb in the center) for 17 events, deepening by 5–10 mb for 8 events and only one case of the net cyclone formation near the Greenland coast correlated with the SPE 23 November 1980. So we can suggest that the pressure decreases observed at the high-latitude stations in the region of Greenland coast and Iceland are related to the deepening of these cyclones correlated with SPE under study. Let us consider some of them.

An example of cyclone deepening correlated with SPE starting on the 7 March 1982 is presented in Fig. 3, the location of the stations being indicated on the bottom chart. One can see that a day before the proton burst (top weather chart) the well developed (with the occluded front in its center and the warm sector displaced to the south periphery) cyclone moves from North America towards the south of Greenland, the pressure in the center is 985 mb. On the day of the burst (middle chart, 7–8 h after the burst onset) it crosses the south of Greenland, with the pressure in the center sharply decreasing to 965 mb and the warm sector disappearing. On the next day (bottom chart) the cyclone slightly

deepens to 960 mb. Another cyclone deepening correlated with SPE on the 3 February 1983 is shown in Fig. 4. In this case, on the day before the burst we can also see the cyclone which moves from North America, as well as the wave to the south-east of it. The cyclone has already started occluding, the pressure being 1000 mb in its center. In 5–6 h after the burst onset (middle chart) the cyclone approached the south of Greenland and merged with the wave, having formed a young cyclone with the pressure being 995 mb in its center. On the next day (bottom chart) this cyclone moved to the north-east, its center being over Iceland, occluded and the pressure in its center decreased sharply to 970 mb.

Let us also consider the interesting events in the cyclone genesis and development correlated with the SPE on the 8 November 1988 (Fig. 5). The top weather chart shows the synoptic situation just before the burst onset: the well developed cyclone (975 mb in the center) is near the east coast of Greenland and the low-pressure area with the partly occluded front is over the ocean. On the next day (23 h after the burst onset, middle chart) this cyclone moved to north-east and the pressure in the center increased to 985 mb. However, at its cold front to the east of Iceland the young cyclone (980 mb) was formed. The low-pressure area (970 mb) appeared also near the south-east coast of Greenland. Over the ocean the cyclone (970 mb) seems to be formed at the cold front of the wave. On the next day (bottom chart) all the cyclones in the region of the Greenland/Iceland merged in one cyclone, the pressure in its center sharply decreasing to 950 mb.

The changes in cyclone evolution found above allow us to explain the pressure and temperature variations at the North Atlantic stations on the days following the SPE. The weather charts showed that, as a rule, Tasiilaq turned out to be in the north (or the north-western) part of the deepening cyclone near its center on the 0/+1 day relative to the event onset that results in the pressure decrease (see Figs. 3–5). Thorshavn, on the Faeroe Islands to the south-east of Greenland coasts and Iceland, was frequently crossed by the southern or the south-eastern periphery of the deepening cyclone (which usually moves to the east or the north-east) on the +1/+2 day. This station was usually rather far from the cyclone center and the observed pressure decrease is less pronounced. Since the deepening cyclones are already well developed (i.e. cold, with no warm sector or with the warm sector displaced to the periphery), we observe the temperature decreases in the troposphere and increases in the stratosphere, which is a characteristic feature of the developed cyclone. Jægersborg was found to be rarely crossed by the cyclone periphery and is still further from its center, so there is only very weak decrease of pressure on the +3/+4 day. As a rule, this station turned out to be in the high-pressure area usually adjoining the cold front of the developed cyclone at its southern periphery. The temperature variations at Jægersborg are typical for the developed anticyclones. The tendency of a pressure increase on the 0/+1 day at this station may be related to some changes in the high

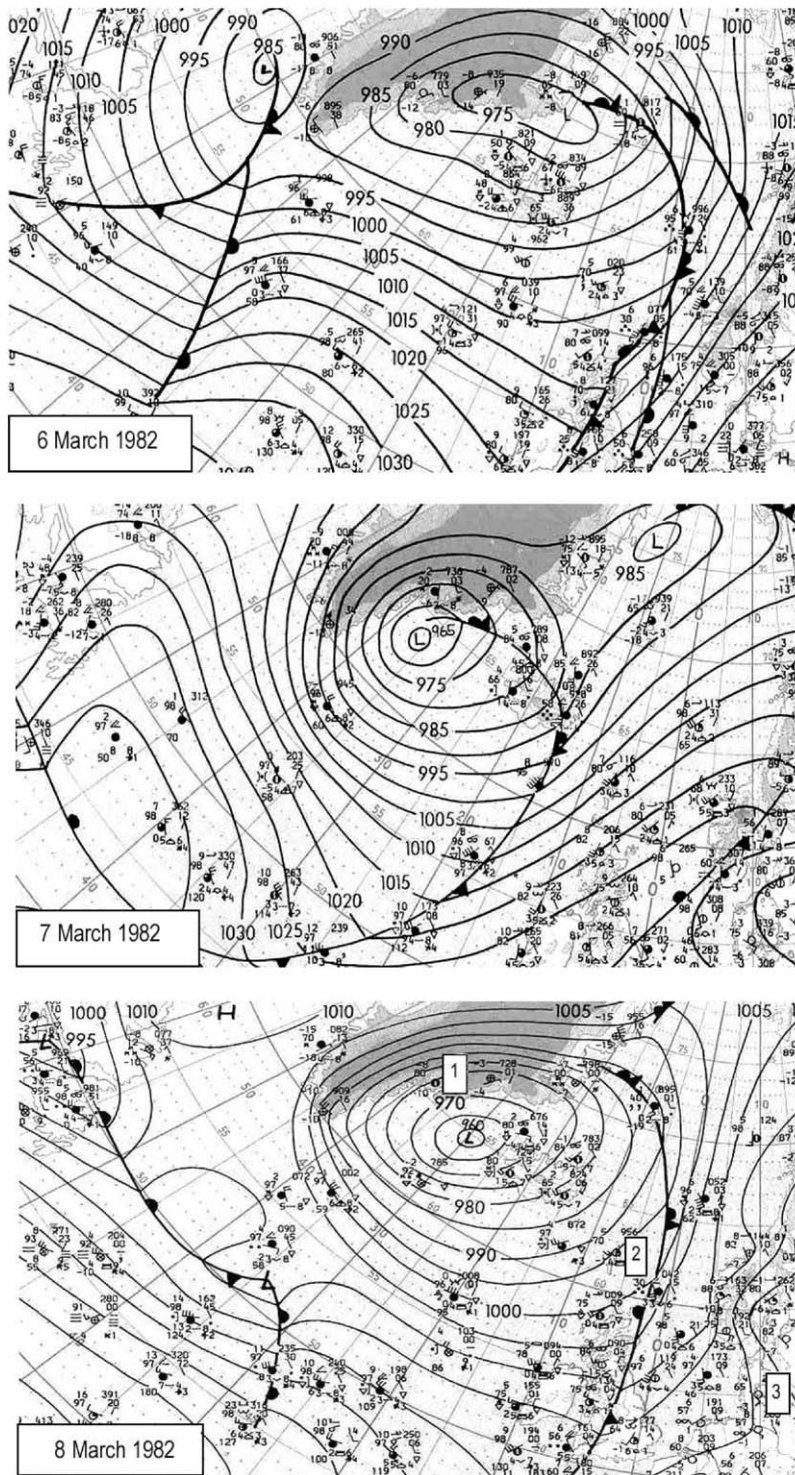


Fig. 3. The deepening of the cyclone correlated with SPE starting on the 7 March 1982. The stations at the bottom chart: 1—Tasiilaq, 2—Thorshavn, 3—Jægersborg.

pressure area taking place simultaneously with the cyclone deepening.

Thus, the weather charts together with the aerological data seem to provide evidence of some noticeable changes in the cyclone evolution associated with the SPE under study. It should be stressed that as a rule we observe the deepening of the cyclones which are already well developed, i.e. started occluding and with no warm sector in its center (see Table 1). As it was mentioned above, at this stage the cyclone reaches its maximum development and must start filling. However, mainly such cyclones were found to deepen, sometimes rather sharply, after the burst onset. Such a secondary deepening of the cyclone which has already started filling, or the sharp increase of the deepening of the cyclone which deepens slowly, is known as “cyclone regeneration” (e.g. Vorobjev, 1991). The main process causing the cyclone regeneration is the advection of cold air in its rear which results in an increase of the temperature contrasts in the cyclone. In particular, the regeneration processes may take place when the occluded cyclone approaches the arctic front where there are conditions for cold advection. The results obtained suggest that the cyclone regeneration near the south-eastern Greenland coast may be intensified due to the energetic SPE.

It should also be noted that the study did not reveal any appreciable dependence between the cyclone deepening and the SPE magnitude. The most significant cyclone deepening (by 35 or more mb in the center) was observed for the events 15 December 1982, 25 December 1982 and 29 October 1989, the maximum fluxes of protons above 90 MeV were not very high (see Appendix). At the same time the effect of the strong event 19 October 1989 was only a 10 mb decrease in the cyclone center. The SPE effects seem to depend rather on the cyclone disposition relative to the Greenland coast, i.e. relative to the region of high temperature gradients. The cyclone seems to deepen more if the Greenland coast lies in its north (north-western) part. The role of cold advection in the cyclone rear in cyclone deepening is rather clear from this. Another factor influencing the SPE effect on the cyclone development seems to be the meteorological situation before the event onset, in particular an existence of a high-pressure area over Iceland and the south-eastern part of Greenland, a so-called “blocking anticyclone” (Vorobjev, 1991), which creates an obstacle for the cyclone movement near the Greenland coast. Such a situation was observed, for example, for the events on the 12 October 1981 and 26 November 1982, when no cyclone deepening took place, though both events were registered by neutron monitor at ground level (Ground Level Enhancements).

2.3. Variations of vorticity

The data presented above seem to provide evidence of significant changes in the cyclone development correlated with SPE under study. In investigations of atmospheric solar–terrestrial effects the evolution of low-pressure systems

has classically been studied using an integrated measure of vorticity called the Vorticity Area Index (e.g. Wilcox et al., 1974). The VAI is typically defined as the area inside which the absolute vorticity—which is the sum of the relative vorticity (the curl or rotation of the horizontal wind field) and the planetary vorticity (the Coriolis effect due to the rotation of Earth) exceeds some arbitrary limit. Since planetary vorticity is positive on the Northern Hemisphere and increases towards the pole while the relative vorticity of a low pressure system is positive on the Northern Hemisphere and increases with the rotation of the system, it is evident that a limit can be set so that just the strongest low-pressure systems contribute to the VAI. On the Southern Hemisphere the argument is reversed. Setting the limits too high will exclude all systems while setting it too low will capture areas that may have no cyclones contributing. The limits for calculating VAI thus have to be set carefully and appropriately for the pressure level considered. There is thus scope for some arbitrariness in the definition of the VAI, which we would like to avoid by working directly with vorticities, such as the mean relative vorticity over an area such as the regions of cyclogenesis.

It seems that mainly one dataset for vorticity and VAI has been used in the past—that originally presented by Olson et al. (in Shapley and Kroehl, 1977; Shapley et al., 1979), and later extended by Kirkland et al. (1996), on the basis of vorticities calculated from the NMC grid, which is a grid with points evenly spaced in the stereographic projection. Most analyses have used the VAI set published in tabular form by Olson et al. (1975).

The calculation of relative vorticity from gridded data can be performed in several ways. One method, used in the Olson et al. (1975) VAI set, is based on the geostrophic approximation and essentially uses the slope of pressure levels, while another method calculates the vorticity directly from the curl of the horizontal wind field. We shall use the later method. We shall use the NCEP/NCAR reanalysis gridded dataset (Kalnay et al., 1996) for horizontal winds to calculate an independent dataset of gridded relative vorticities, and use it for a superposed epoch analysis (SPEA) based on the key dates defined in this paper. Details of calculating and testing the new dataset are given elsewhere (Thejll, 2002). The new dataset captures the same middle and high-frequency variability as the Olson et al. (1975) dataset, but appears smoother and more homogeneous in the low frequencies. A global grid of relative vorticities has been calculated and a region in the North Atlantic is studied for the present work (between 70° and 50° N and between 40° W and 0°). This area includes the southern part of Greenland and the characteristic region of the Iceland depression where we observed the cyclone deepening correlated with SPE under study.

The SPEA is performed by selecting a window in time surrounding the key dates and co-adding area-weighted grid values of the square of the relative vorticity in this window and then looking for large excursions. The squared

Table 1
Weather chart analysis of the cyclone evolution after energetic SPE

<i>N</i>	Date of the onset	Cyclone evolution on the 0/ + 1 days	Location of the deepening cyclone	Type of the deepening cyclone
1	6 February 1980	Cyclone deepening from 975 to 960 mb ^a	near the south-eastern coast of Greenland	Well developed
2	23 November 1980	Formation of a new cyclone	over the south-eastern coast of Greenland	
3	7 March 1981	No deepening		
4	25 March 1981	Cyclone deepening 1. from 970 to 965 mb 2. from 985 to 965 mb	1. near the south-eastern coast of Greenland 2. to the south of Greenland	Well developed
5	8 October 1981	Cyclone deepening from 995 to 980 mb	to the south of Iceland and over Great Britain	Well developed
6	12 October 1981	No deepening		
7	31 January 1982	Cyclone deepening from 990 to 980 mb	near the south-eastern coast of Greenland	Well developed
8	8 February 1982	Cyclone deepening from 960 to 935 mb	near the south-eastern coast of Greenland	Well developed
9	7 March 1982	Cyclone deepening from 985 to 960 mb	near the south-eastern coast of Greenland	Well developed
10	22 November 1982	Cyclone deepening from 1000 to 985 mb	to the south of Iceland	Well developed
11	26 November 1982	No deepening		
12	8 December 1982	Cyclone deepening from 975 to 965 mb	to the south of Iceland	Well developed
13	15 December 1982	Cyclone deepening from 980 to 945 mb	over Iceland and then over the Northern Europe	Well developed
14	25 December 1982	Cyclone deepening from 995 to 955 mb	near the south-eastern coast of Greenland, then to the east of Iceland	Young
15	5 January 1983	Cyclone deepening from 960 to 940 mb	near the south-eastern coast of Greenland, then to the east of Iceland	Well developed
16	3 February 1983	Cyclone deepening from 1000 to 970 mb	over Iceland	Well developed /young
17	16 February 1984	Cyclone deepening from 1000 to 980 mb	near the south-eastern coast of Greenland	Young
18	14 March 1984	No deepening		
19	22 January 1985	Cyclone deepening from 975 to 960 mb	to the south of Iceland and over Great Britain	Young
20	6 February 1986	Cyclone deepening from 980 to 965 mb	near the south-western coast of Greenland	Well developed
21	14 February 1986	Cyclone deepening from 975 to 965 mb	to the south of Greenland	Well developed
22	25 March 1988	Cyclone deepening from 1010 to 1005 mb	to the south of Greenland	Well developed
23	12 October 1988	No deepening		
24	8 November 1988	Cyclone formation and deepening from 970 to 950 mb	near the south-eastern coast of Greenland	
25	14 November 1988	Cyclone deepening from 995 to 990 mb	near the eastern coast of Greenland	Well developed
26	14 December 1988	Cyclone deepening from 980 to 975 mb	near the south-eastern coast of Greenland	Young
27	27 December 1988	Cyclone deepening from 970 to 965 mb	near the south-eastern coast of Greenland	Well developed
28	11 March 1989	No deepening		

Table 1 (continued)

<i>N</i>	Date of the onset	Cyclone evolution on the 0/+ 1 days	Location of the deepening cyclone	Type of the deepening cyclone
29	23 March 1989	Cyclone deepening from 990 to 965 mb	near the south-eastern coast of Greenland	Well developed
30	19 October 1989	Cyclone deepening from 965 to 955 mb	near the south-eastern coast of Greenland	Well developed
31	29 October 1989	Cyclone deepening from 975 to 940 mb	near the south-eastern coast of Greenland	Well developed
32	15 November 1989	No deepening		
33	30 November 1989	Cyclone deepening from 975 to 955 mb	near the south-western coast of Greenland	Well developed

^aFirst value is the pressure in the cyclone center before the burst onset and the second one is the minimum value reached on the 0/+1 day.

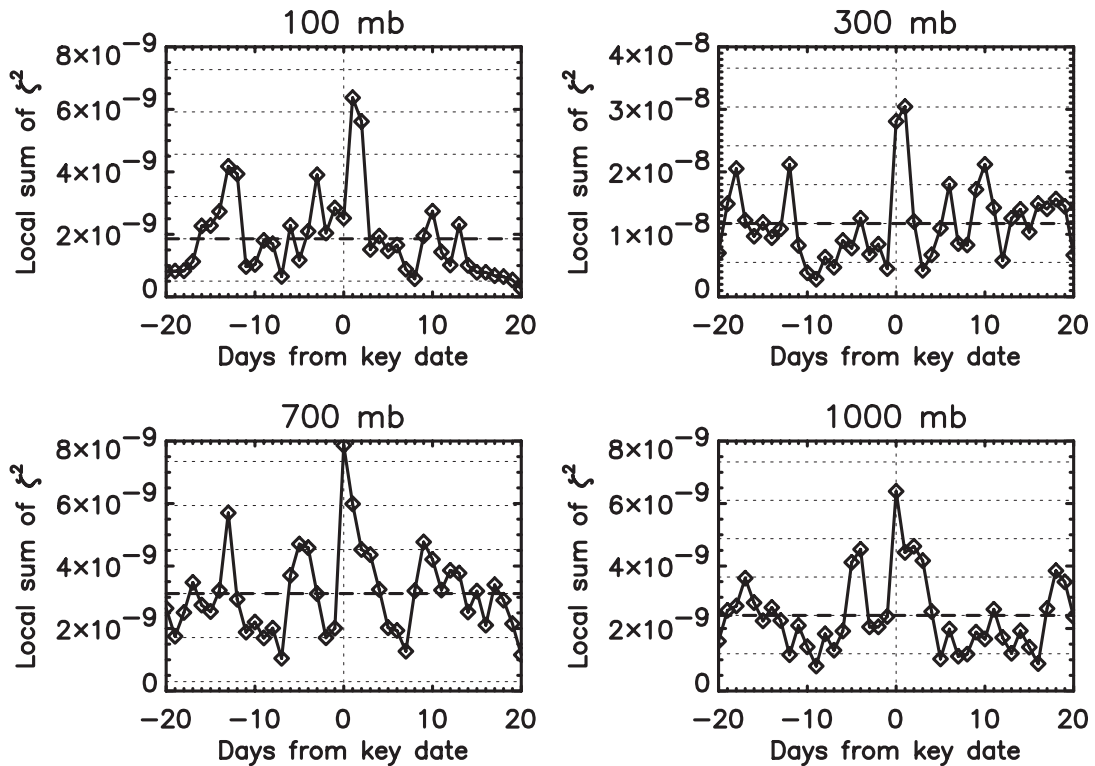


Fig. 6. Mean variations of the squared relative vorticity (in s^{-2}) in the North Atlantic region ($50\text{--}70^\circ\text{N}$, $0\text{--}40^\circ\text{W}$) associated with the energetic SPE. Day $t = 0$ corresponds to the day of the event onset.

relative vorticity is used as it increases in our case the signal to noise ratio, compared to the use of (un-squared) relative vorticity. The sign of the signal was checked in un-squared vorticity data (i.e. we verified during each individual SPE that a positive excursion corresponding to a deepening of a cyclone occurred in the relative vorticity), and enhanced cyclones do indeed correspond in most cases to larger positive values of relative vorticity, except for a few cases of

very weak deepening, when the signal is apparently lost in the noise. The SPEA has been discussed in detail by Samson and Yeung (1986). We estimate the significance of the detected excursion in the SPEA from the standard deviation (S.D.) of the SPEA in the chosen window—that is, the standard deviation of the superposed result is calculated even including the days when a signal appears to be present in the superposition. Results at levels 100, 300, 700 and 1000 mb

are shown in Fig. 6, where the dashed horizontal line is the mean of the SPEA values of relative local vorticity across all days shown and the dotted horizontal lines are 1, 2, 3, etc. standard deviations from that mean.

We see signals for the days 0 and +1 following the key date at significance levels of 3 S.D., i.e. a consistent rise in squared relative vorticity on these days as the largest signal in the window. As we have 40 days to inspect we should use a significance level adhering to “Thomson’s rule” near $(1-1/40)100\% = 97.5\%$ in order to have the base level information on what to accept as marginally significant. As we are near or surpass the 3 S.D. limit, which corresponds to 99.7% of the area of the two-sided normal distribution, we feel we are comfortably surpassing the Thomson limit and have found statistically significant results.

These results seem to indicate an increase in relative vorticity in the troposphere in the days following the SPE under study, consistent with a picture in which some low pressure systems are enhanced by the action of the SPE or by effects induced by the SPE. The increases of the cyclonic circulation are observed in all the troposphere and the lower stratosphere (1000–100 mb level) which is in good agreement with the pressure decreases detected at the stations near the arctic front which happen to be in the area of the deepening cyclone. Let us note that the effect starts in the very lower part of the troposphere (1000 and 700 mb level) where it is seen on the 0 day (the day of the burst onset) and then it extends to the upper levels where the maximum vorticity is seen on the +1 day. This agrees with the fact that, as the cyclone deepens, the closed circulation first appears near the Earth’s surface and then spreads over all the troposphere. Thus, the vorticity variations found seem to confirm the findings based on synoptic charts and aerological sounding data.

3. Discussion

The results of this study reveals noticeable changes in the evolution of cyclones traveling near the south of Greenland which correlate with proton bursts with sufficient energy to penetrate the lower atmosphere. The deepening of the well developed cold cyclones following these events causes significant pressure and temperature decreases in the troposphere as well as in the increase of the cyclonic circulation near the south-eastern coast of Greenland and over the Iceland depression. It is known that this is the region of the arctic front separating the cold arctic air masses (located over Greenland in winter) and the warm air masses of the middle latitudes (over ocean) which is considered as the cyclogenesis region. As the synoptic practice shows, the atmosphere vortices arise and undergo the most significant changes—namely, in the frontal zones where the horizontal gradients of meteorological values are greater by about an order of magnitude than outside these zones. Indeed, the atmosphere baroclinity is considered as one of the important

factors of the cyclone genesis and deepening and its influence increases significantly in the region of the atmosphere fronts. It was shown (Matveev, 1991) that cold advection contributes to a generation or intensification of the cyclonic vortex, whereas warm advection contributes to a generation or intensification of the anticyclonic one. The deepening of the cyclone is known to continue till there is a cold advection in it. As soon as the cold air spreads over the whole cyclone and the temperature field gets uniform, the cold advection stops and the cyclone starts filling (Matveev, 1991). However, if the input of the colder air takes place in the rear of such a cold filling cyclone, it starts deepening again, that is known as the cyclone regeneration (Vorobjev, 1991). The high temperature contrasts in the frontal zone contributing the cold advection create the favorable conditions for the cyclone strengthening.

The weather chart analysis showed that the deepening of the cyclones correlated with SPE under study may be considered as the cyclone regeneration. Indeed, the majority of these cyclones are formed near the eastern coasts of North America and, when they travel near Greenland, they have already reached their maximum development. However, the observed intensification of their regeneration suggests that energetic SPE seem to create conditions contributing to this process. In particular, there may be an enhancement of the cold advection due to the changes in the temperature contrast in the frontal zone. A possible mechanism may involve the radiative forcing of cloudiness changes (changes in the cloud amount and/or in their radiative properties) associated with the SPE under study. The clouds reduce the input of the short-wave solar radiation as well as the outgoing long-wave radiation ($\geq 4 \mu\text{m}$) emitted by the Earth and the atmosphere. The resulting effect is a warming, when the net radiation of the Earth–atmosphere system (the difference between the solar radiation absorbed by the surface–atmosphere column and the outgoing long-wave radiation) is negative, as it takes place at middle and high latitudes in winter, and a cooling, when the net radiation is positive (in summer). Since in winter the temperature over the ocean is greater than over land, we can suggest that the cloudiness increase in the front region may enhance the temperature contrast near the Greenland coasts if the warming effect of cloudiness is more pronounced over the warmer ocean. Indeed, the mean outgoing radiation fluxes in the cold half of year amount to about 140–150 W/m² over Greenland and about 180–200 W/m² over the ocean near its eastern coasts (Climate Diagnostics Center, <http://www.cdc.noaa.gov>).

As was shown earlier, there are short-term variations of cloudiness correlated with the galactic cosmic ray variations (Pudovkin and Veretenenko, 1995). The effects were found to be most pronounced in the regions with a little low cloudiness, but with a high frequency of occurrence of high-level (cirrus) clouds. This allowed the suggestion that there is a predominant influence of cosmic rays on this cloud type. Indeed, having the greatest base heights (~ 6 – 7 km) and a vertical range up to several kilometers, these clouds fall into

the field of the main energy losses of the cosmic rays with the energy ~ 1 GeV, so the direct influence of the ionization changes on the formation of cloud condensation nuclei and the growth of the cloud particles seems to be possible (Dickinson, 1975; Tinsley and Deen, 1991). The high-level clouds do not reduce significantly the solar radiation compared with low and middle clouds, however, their influence on the outgoing radiation may be rather considerable. The calculations of the thermal radiation fluxes using the measured parameters of cirrus clouds showed that the warming effect of cirrus may be about 10 W/m^2 for optically thin cirrus clouds and up to $90\text{--}100 \text{ W/m}^2$ for the optically thick ones (Gorchakova, 1989, 1991).

In the case of SPE with energy of particles ~ 0.1 GeV the main energy losses take place at stratospheric heights ($\sim 30\text{--}40$ km), so we can suggest the indirect influence of the cosmic rays on the nucleation processes, the variations of the atmospheric electricity being involved. A possible mechanism of solar–atmosphere influences in which the cosmic ray variations modulate the Earth’s electric field was proposed by Markson and Muir (1980) summarizing the evidences of solar particle effects on the air-earth current density. Tinsley and Heelis (1993) hypothesized that the atmospheric current depending on the ionization changes produced by cosmic rays and of the ionospheric potential affects the rate of charging of the clouds droplets and aerosols acting as the ice nuclei and, as a result, the rate of ice nucleation and the cloud particle growth. The influence of the atmospheric current on the space charge distribution which in turn affects the charge on the evaporation nuclei and then the rate of the “electroscavenging” of such nuclei by the supercooled droplets, a possible effect being the enhanced ice formation, was discussed by Tinsley (2000) and Tinsley and Yu (2003). However, the mechanism of the cosmic particle variations on the microphysical processes in clouds, as well as on the cyclone evolution, needs further studies.

In this connection an investigation of the effects of solar particles producing Ground Level Enhancements would clarify some features of the suggested mechanisms. According to Tinsley and Yu (2003) the correlations of the cloudiness with cosmic ray fluxes may be considered in terms of two microphysical processes: the ion-mediated nucleation (IMN) suggesting a condensation on the charged clusters of water and sulfuric acid molecules and “electroscavenging”. The results obtained for the particles ~ 100 MeV suggest that changes of the atmospheric current are involved in influencing the cloud processes. However, the GLE particles with higher energies (above several hundred MeV) provide ionization just at the heights of the cloud formation and the IMN processes would contribute to the cloudiness changes.

4. Conclusions

The results of this study show noticeable changes in the lower atmosphere characteristics in the North

Atlantic region correlated with energetic solar proton events (SPE). The most pronounced effects were observed near the south-eastern Greenland coast which is the North Atlantic part of the arctic front and a cyclogenetic area. The combined analysis of the aerological sounding and relative vorticity data as well as of the weather charts on the Earth’s surface showed that the energetic SPE are accompanied by the intensification of re-deepening (regeneration) of well-developed cold cyclones in this region. This process is manifested in the significant pressure and temperature decreases in the troposphere at high-latitude stations near the arctic front and in the relative vorticity increase in this region, while the weather charts showed the predominant deepening of cyclones having already reached their maximum development. The results obtained suggest that the SPE seem to provide favorable conditions for the regeneration of these cyclones. A possible mechanism of the effects found may involve changes in the temperature contrasts in the frontal region due to the radiative forcing of the cloudiness changes associated with the events under study.

Acknowledgements

Authors thank Prof. Vorobjev and Dr. Golovina (Russian Hydrometeorological University, St.Petersburg) for the discussion, as well as the referees for helpful remarks. This work was supported by the Danish Climate Centre.

Appendix

List of the SPE selected for the analysis

<i>N</i>	Date of onset	Pr > 90 MeV pr $\text{cm}^{-2} \text{c}^{-1} \text{ster}^{-1}$
1	6 February 1980	0.02
2	23 November 1980	0.03
3	7 March 1981	0.009
4.	25 March 1981	0.02
5	8 October 1981	> 0.06
6	12 October 1981	> 13
7	31 January 1982	0.51
8	8 February 1982	0.03
9	7 March 1982	0.13
10	22 November 1982	0.27
11	26 November 1982	2.9
12	8 December 1982	24
13	15 December 1982	0.08
14	25 December 1982	0.14
15	5 January 1983	6.6
16	3 February 1983	0.05
17	16 February 1984	> 4
18	14 March 1984	> 0.24
19	22 January 1985	0.28
20	6 February 1986	1.7

21	14 February 1986	1.4
22	25 March 1988	0.29
23	12 October 1988	0.06
24	8 November 1988	0.49
25	14 November 1988	0.06
26	14 December 1988	0.64
27	27 December 1988	0.09
28	11 March 1989	0.30
29	23 March 1989	0.06
30	19 October 1989	170.30
31	29 October 1989	2.23
32	15 November 1989	4.30
33	30 November 1989	0.48

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