Influence of energetic Solar Proton Events on the development of cyclonic processes at extratropical latitudes

S Veretenenko¹ and P Thejll²

¹Ioffe Physical-Technical Institute, Russian Academy of Sciences, Politekhknicheskaya 26, 194021 St.-Petersburg, Russia
²Danish Meteorological Institute, Lyngbywei 100, Copenhagen, DK-2100, Denmark
E-mail: s.veretenenko@mail.ioffe.ru

Abstract. Effects of energetic Solar Proton Events (SPEs), with energies above 90 MeV, on the development of cyclonic processes at extratropical latitudes of the Northern and Southern hemispheres were studied, using NCEP/NCAR reanalysis data. The study revealed that these events are accompanied by a noticeable intensification of cyclonic activity at middle latitudes, mainly over oceans. In the Northern hemisphere this effect is observed for the SPEs occurring in October-March, whereas in the Southern hemisphere it is most pronounced for the events in April-September. In the Northern hemisphere the largest cyclone deepening takes place in the North Atlantic near the south-eastern coasts of Greenland, this area being characterized by high temperature contrasts and low geomagnetic cutoff rigidities. In the Southern hemisphere most appreciable cyclone intensification was found over the Southern Ocean near the Antarctic coasts next to the South Magnetic Pole, the region is characterized by low geomagnetic cutoff rigidities and high temperature contrasts, too. The results obtained show an importance of ionization changes produced by cosmic ray variations for the mechanism of solar activity influence on the lower atmosphere circulation.

1. Introduction
It is well known that the weather at middle latitudes strongly depends on cyclonic activity, i.e., on the formation, development and movement of baric systems (cyclones and anticyclones). Changes in intensity and frequency of occurrence of these systems as well as their tracks result in anomalies of temperature, precipitation and other characteristics. Thus, studies of the influence of solar activity and related phenomena on the development of extratropical baric systems are of great importance to forecast weather and climate changes. In the previous works [1-2] we revealed an intensification of cyclonic processes in the North Atlantic on the days following solar proton events (SPEs), with energy particles above 90 MeV. In this work we study variations of cyclonic activity at middle latitudes associated with these events both in the Northern (NH) and Southern (SH) hemispheres.

2. Experimental data and their analysis
As experimental base of this study NCEP/NCAR reanalysis data were used [3]. The sets of isolated (separated by at least 3 days from another similar event) SPEs, with energy > 90 MeV, were selected for the cold (October-March) and warm (April-September) halves of year in 1980-1998. The days of the event onsets were used as the key days for a superposed epoch analysis (SPEA).
extratropical cyclogenesis usually occurs namely at these fronts. The most significant variations of negative and positive changes of pressure located between the climatic Arctic and Polar fronts. Indeed, fronts in the troposphere \cite{4} and geomagnetic cutoff rigidities intensification near Greenland an area of high pressure appears over North America.

By the formation of an anticyclone at the cold front in its rear, simultaneously with cyclone height crest (an area of pressure increase) over Europe. As the cyclone development is accompanied on the next day. Air outflow from cyclones deepening near Greenland results in the formation of a of the SPE onsets pressure starts sharply decreasing near the Greenland coasts, the effect is maximum on the next day. Air outflow from cyclones deepening near Greenland results in the formation of a height crest (an area of pressure increase) over Europe. As the cyclone development is accompanied by the formation of an anticyclone at the cold front in its rear, simultaneously with cyclone intensification near Greenland an area of high pressure appears over North America.

In figure 2 the GPH500 variations on the day +1 after the SPE onsets are compared with climatic fronts in the troposphere \cite{4} and geomagnetic cutoff rigidities $R$ \cite{5}. One can see several large areas of negative and positive changes of pressure located between the climatic Arctic and Polar fronts. Indeed, extratropical cyclogenesis usually occurs namely at these fronts. The most significant variations of

![Figure 1. SPEA charts of GPH500 variations (in gp m) associated with the SPEs in October-March. Number of events $N=48$ (1980-1998). Day 0 corresponds to the day of the event onsets.](image1)

The study revealed that the SPEs occurring in October-March are followed by a noticeable intensification of cyclonic activity at middle latitudes of the Northern hemisphere. Figure 1 shows the variations (departures from the mean charts over the period $\pm 10$ days relative to the key dates) of geopotential (gp) heights of the 500 hPa level (GPH500) obtained by SPEA for 48 events. It is seen that most pronounced pressure variations after the SPEs take place at middle latitudes. Just on the day of the SPE onsets pressure starts sharply decreasing near the Greenland coasts, the effect is maximum on the next day. Air outflow from cyclones deepening near Greenland results in the formation of a height crest (an area of pressure increase) over Europe. As the cyclone development is accompanied by the formation of an anticyclone at the cold front in its rear, simultaneously with cyclone intensification near Greenland an area of high pressure appears over North America.

In figure 2 the GPH500 variations on the day +1 after the SPE onsets are compared with climatic fronts in the troposphere \cite{4} and geomagnetic cutoff rigidities $R$ \cite{5}. One can see several large areas of negative and positive changes of pressure located between the climatic Arctic and Polar fronts. Indeed, extratropical cyclogenesis usually occurs namely at these fronts. The most significant variations of

![Figure 2. SPEA charts of GPH500 variations in the NH on the next day after the SPE onsets in October-March. Yellow lines (a) show the statistical significance of the variations according to Monte-Carlo tests. Thick black and blue lines (a) show the climatic Arctic and Polar fronts, respectively \cite{4}. Thin white lines (b) show vertical geomagnetic cutoff rigidities (in GV) \cite{5}.](image2)
pressure seem to be associated with the Arctic fronts which bound the Arctic air mass where the polar stratospheric vortex is formed. The Arctic fronts are in the area of low geomagnetic cutoff rigidities, so cosmic ray particles with a broad energy range may precipitate here.

The data above show that the North Atlantic near Greenland is an area of most pronounced cyclone deepening associated with the SPEs under study. Indeed, this region is characterized by a favorable structure of the tropospheric thermo-baric field (figure 3a), i.e., by a divergence of isohypses in the middle troposphere contributing to air outflow and by high temperature contrasts in the Arctic frontal zone near the south-eastern coasts of Greenland. Temperature contrasts create favorable conditions for cold advection contributing to the intensification of cyclonic vortices [6]. At the same time this region turns out to be in the area of precipitation of particles with energies above 90 MeV.

Let us consider SPE effects in the Southern hemisphere. An insignificant enhancement of cyclonic activity at middle latitudes of the SH was observed for the events in October-March (the warm period in the SH). For the events in April-September (figure 4) there is no effect in the NH, but in the SH we can see an intensification of cyclonic activity in the southern parts of the Indian and Pacific Oceans, the effects being most pronounced on the day +1 after the event onsets. Figure 5a shows that most

![Figure 3](image_url)

**Figure 3.** Distribution of temperature gradient magnitude in the layer 1000-500 hPa superimposed by isohypses of the 500 hPa level (a) and by isolines of vertical geomagnetic cutoff rigidities [5] (b) in the North Atlantic. Red line shows the rigidity $R=0.42$ GV corresponding to particle energy 90 MeV.

Let us consider SPE effects in the Southern hemisphere. An insignificant enhancement of cyclonic activity at middle latitudes of the SH was observed for the events in October-March (the warm period in the SH). For the events in April-September (figure 4) there is no effect in the NH, but in the SH we can see an intensification of cyclonic activity in the southern parts of the Indian and Pacific Oceans, the effects being most pronounced on the day +1 after the event onsets. Figure 5a shows that most

![Figure 4](image_url)

**Figure 4.** The same as in figure 1 but for the SPEs in April-September ($N=35$, 1980-1998).
pronounced GPH500 variations in the SH are also associated with the climatic fronts as in the NH. The largest cyclone intensification takes place in the region of the climatic Antarctic front near the Antarctic coasts next to the South Magnetic Pole, i.e., in the area of highest temperature contrasts and lowest geomagnetic cutoff rigidities (figure 5b).

The results obtained suggest that energetic SPEs may intensify cyclonic activity at middle latitudes of both hemispheres. The effects are observed for the events occurring in the cold half of year for the hemisphere under study, i.e., in October-March for the NH and in April-September for the SH. Indeed, the cold half of year is the period of most intensive cyclogenic processes caused by an increase of temperature contrasts in the troposphere. The effects are closely associated with climatic Polar and Arctic/Antarctic fronts which are the areas of enhanced temperature gradients and, then, predominant formation and intensification of extratropical cyclones. The most appreciable cyclone intensification was detected near the Greenland coasts in the NH and near the Antarctic coasts next to the South Magnetic Pole in the SH. Both regions are characterized by low cutoff rigidities and high temperature contrasts between the ice land surface and that of the warmer ocean. Low rigidities in these regions allow precipitation of cosmic particles with a broad energy range. Variations of these particles influence atmospheric conductivity resulting in variations of electric currents which, in turn, may affect processes of cloud and aerosol formation [7]. Changes of radiative budget associated with cloudy and aerosol particle variations may be a possible reason for an enhancement of temperature contrasts in the troposphere and the corresponding changes in cyclogenesis intensity.

3. Conclusions
This study showed that SPEs with energies enough to penetrate the stratosphere heights may influence extratropical cyclonic activity both in the Northern and Southern hemispheres, the effects being most pronounced in the regions characterized by low geomagnetic cutoff rigidities and high temperature contrasts. The results obtained suggest an important contribution of cosmic ray variations in the mechanism of solar activity influence on the lower atmosphere circulation.

References
[1] Veretenenko S and Thejll P 2004 J. Atm. Sol.-Terr. Phys. 66 393
[2] Veretenenko S and Thejll P 2005 Adv. Space Res. 35 470
[3] Kalnay E et al. 1996 Bull. Amer. Meteorol. Soc. 77 437
[4] Khromov S and Petrociants M 1994 Meteorology and Climatology (Moscow: Moscow University Press)
[5] Shea M and Smart D 1983 Proc. 18th Int. Cosmic Ray Conf. (Bangalore) vol 3 (Bombay: Tata Institute of Fundamental Research) p 415
[6] Vorobjev V 1991 Synoptic Meteorology (Leningrad: Hydrometeoizdat)
[7] Tinsley B 2008 Rep. Prog. Phys. 71 66801