Powerful Solar Proton Events of January 2005 and their impact on intensity of the stratospheric polar vortex

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Abstract. In January 2005, a series of powerful Solar Proton Events (SPEs) associated with an increase of flare activity on the Sun was observed. Increases of solar proton fluxes with energies 165-500 MeV allowing particles to reach stratospheric altitudes (~30 km and below) were registered during the events starting on 15, 16 and 17 January. The strongest event, with particle energies exceeding 500 MeV, took place on 20 January and was accompanied by an increase of the neutron monitor counting rate (Ground Level Enhancement). The events under study resulted in a considerable increase of stratospheric ionization. In this work an impact of these events on intensity of the stratospheric polar vortex playing an important part in the mechanism of solar-atmospheric links is studied. A noticeable intensification of the vortex (increase of western wind velocity) was revealed at all the stratospheric levels in the course of the SPE series under study. It was shown that auroral activity (precipitations of auroral electrons generating bremsstrahlung X-rays) is also a possible factor of the vortex intensification. The obtained results provide evidence that ionization changes associated with powerful SPEs and auroral activity may influence the state of the stratospheric polar vortex on the day-to-day time scale. A possible cause of the vortex intensification seems to be temperature variations associated with changes of chemical composition of the polar stratosphere due to ionisation changes.

1. Introduction

Energetic charged particles, including galactic (GCR) and solar (SCR) cosmic rays, are now considered as an important link between solar activity and weather/climate variability (e.g. [1-2]). Whereas solar extreme ultraviolet radiation and X-rays ionize the upper atmosphere, cosmic rays penetrate to lower altitudes producing ionization in the middle and lower atmosphere. They are the most important ionization source at altitudes from ~3-4 to ~55-60 km [2]. GCRs arrive in the Earth’s environment constantly, but their flux is strongly modulated by solar activity and decreases by a factor of ~2 in maxima of the 11-year cycle. Having energies in a broad range from 1 to 3·10^{14} MeV, they penetrate into the atmosphere rather deeply causing a maximum of secondary particles at altitudes 15-25 km [2]. Solar cosmic rays are charged particles (mostly protons) accelerated during solar flares or by CME-driven shocks in the corona or in the interplanetary space (CMEs are Coronal Mass Ejections often associated with solar flares). An enhancement of solar proton flux in the near-Earth space exceeding 10 cm^{-2}sr^{-1}s^{-1} for protons with energies >10 MeV is referred to as Solar Proton Event (SPE) [3]. These events occur sporadically, more frequently at solar maxima. Though solar proton energies do not exceed several tens of GeV, their fluxes may be huge which results in a considerable increase of atmospheric ionization [4].
In contrast to GCRs, the intrusion of less-energetic solar protons in the atmosphere is limited by polar latitudes due to geomagnetic cutoff. However, they produce a large number of geophysical effects, including changes of chemical composition of the atmosphere (i.e. ozone depletion caused by enhanced production of nitrogen and hydrogen oxides), perturbations in the global electric circuit, changes in atmospheric transparency etc. [5]. Changes of ozone content, in turn, may influence significantly temperature regime of the polar atmosphere (e.g. [6]) and, then, the atmosphere dynamics. Thus, solar cosmic rays are of significant importance for solar-atmospheric links. In this connection, the aim of this work is to study effects of powerful Solar Proton Events of January 2005 on the middle atmosphere and, in particular, on intensity of the stratospheric polar vortex which plays an important part in the physical mechanism of solar influence on weather and climate [7].

2. Solar Proton Events of January 2005
A series of Solar Proton Events of January 2005 occurred at the deep descending phase of the 23rd solar cycle [8]. In the course of SPEs starting on 15, 16 and 17 January, increases of solar proton fluxes with energies 165-500 MeV were registered. Protons with these energies reach stratospheric altitudes (∼30 km and below) and lose their energy to ionization. The strongest event started on 20 January. It was characterized by an increase of proton flux with energies >500 MeV which participate in nuclear interactions producing a rise of the neutron monitor (NM) counting rate (Ground Level Enhancement). Variations of integral proton fluxes at different threshold energies and the NM counting rate in Calgary are shown in figures 1a and 1b. The studied SPEs were associated with enhancement of solar flare activity on 13-23 January (figure 1c). They resulted in the increase of ionization rate in the upper stratosphere up to several hundred cm$^{-3}$s$^{-1}$ (figure 1d).

Figure 1. a) Solar proton fluxes with energies >5, >50 and >100 MeV according to the GOES-11 data [9]; b) NM counting rate in Calgary (geomagnetic cutoff rigidity $R_c = 1.09$ GV) [10]; c) X-ray solar flares of different classes [11]; d) daily mean ionization rate at geomagnetic latitudes 60-90º [12].
3. Response of the middle atmosphere of polar latitudes to SPEs of January 2005

Let us consider the response of the middle polar atmosphere to the studied events. This region is characterized by the formation of the stratospheric polar vortex, which is an important factor of large-scale circulation and climate variability (e.g., [13]). The polar vortex is a cyclonic circulation forming at polar latitudes above the 500 hPa level; it is seen in the stratosphere as a belt of enhanced western winds. So, daily values of the U-component of wind velocity (directed from west to east) were used to estimate the vortex state, the data being taken from the NCEP/NCAR reanalysis archive [14]. In figure 2, temporal variations of maximal values of western wind velocity $U_{\text{max}}$ at different stratospheric levels in winter 2004/2005 are shown. One can see a noticeable strengthening of western winds during the disturbed period 13-23 January in the entire stratosphere. Increases of $U_{\text{max}}$ relative to the linear trends amount to $\sim$20-30 m·s$^{-1}$ in the upper part of the stratosphere (the levels 30-10 hPa, altitudes $\sim$23-30 km) and $\sim$15 m·s$^{-1}$ in its lower part (the levels 100-50 hPa, altitudes $\sim$15-20 km).

![Figure 2. Temporal variations of maximal values of western wind velocity $U_{\text{max}}$ at different stratospheric levels in winter 2004/2005. The disturbed period 13-23 January 2005 is highlighted in gray.](image)

In figure 3 one can see the charts of daily mean values of western wind velocity at the level 50 hPa in the Northern Hemisphere for the period 13-21 January 2005. A region of enhanced wind velocity ($U \geq 40$ m·s$^{-1}$) is shown in black. It is seen that in the course of the studied SPEs this region was growing, with its area and longitudinal extension being increased. One can also see that before the onset of the first event this region was mostly localized over the Arctic coasts of North America, but after the onset it was displaced to the North Atlantic and Scandinavia. An increase of wind velocity also took place in the North Pacific. Similar effects were observed at all the stratospheric levels.

In figure 4, temporal variations of the relative areas (in fractions of the entire Earth’s surface) of the regions with enhanced wind velocity at different levels of the stratosphere are presented. The data in figure 4 show that a noticeable enlargement of the regions with western wind velocity reaching high values did really take place in the entire stratosphere during the period 13-23 January 2005. Thus, the data presented in figures 2, 3 and 4 provide evidence for a pronounced intensification of the stratospheric polar vortex associated with powerful Solar Proton Events of January 2005.
Figure 3. Charts of daily mean velocity of western winds (in m·s⁻¹) at the level 50 hPa for the period 13-21 January 2005. The area with western wind velocity $U \geq 40$ m·s⁻¹ is shown in black.

Figure 4. Areas (in fractions of the entire Earth’s surface) of the regions with enhanced western wind velocity in the upper (a) and lower (b) stratosphere in January 2005 after the linear trend removal. The disturbed period 13-23 January 2005 is highlighted in gray.
Let us consider possible factors of the polar vortex intensification. As it was said above, the vortex is formed in the area of low geomagnetic cutoff rigidities, which allows penetration of charged particles (solar and galactic cosmic rays) in a wide energy range resulting in high ionization rates. On the other hand, maximal values of wind velocity are observed in the belt ∼60-80°N (figure 3) which turns out to be in a region of maximal occurrence of auroras (the auroral zone). Auroras are observed during magnetospheric substorms due to precipitations of auroral electrons, which result in excitation of atmospheric constituents. Though energy of auroral electrons is absorbed in the lower thermosphere (above 90 km), they generate bremsstrahlung X-rays, which may penetrate into the stratosphere producing ionization changes. According to [15], X-rays with energies 30 keV and 10³ keV penetrate to altitudes ∼40 and ∼30 km, respectively.

In figure 5a temporal variations of maximal values of western wind velocity $U_{\text{max}}$ in the upper stratosphere (the 10 hPa level) are compared with those of geomagnetic AE-index values smoothed over 5-day intervals. AE-index characterizes the intensity of auroral electrojet (electric current developing in high-latitude ionosphere during substorms), the development of the current is accompanied by auroral electron precipitations. One can see that temporal variations of the studied values are very similar. The correlation coefficient between $U_{\text{max}}$ and 5-day smoothed AE-indices amounts to ∼0.7.

![Figure 5](image)

**Figure 5.** a) Temporal variations of maximal values of western wind velocity $U_{\text{max}}$ at the level 10 hPa and geomagnetic AE-indices [16] smoothed over 5-day intervals in winter months 2004/2005; b) $U_{\text{max}}$ at the 10 hPa level versus daily mean ionization rate in the upper stratosphere (35 km) at geomagnetic latitudes 60-90° [12] in January 2005.

The data in figure 5b show a relationship between maximal values of western wind velocity $U_{\text{max}}$ and daily mean ionization rate in the upper stratosphere at geomagnetic latitudes 60-90° [12]. One can see that wind velocity starts increasing noticeably (up to ∼120 m·s⁻¹) when SPE-associated ionization rate exceeds ∼1 cm⁻³·s⁻¹. Thus, the data in figure 5b indicate a possible effect of ionization rate on wind velocity in the vortex. The obtained results allow suggesting that the observed intensification of the polar vortex may be related to ionization increase in the stratosphere associated with the intrusion of solar cosmic rays, as well as to auroral activity.

Intensification of the polar vortex associated with SPEs under study indicates an increase of temperature gradients in the high-latitude atmosphere which may be due to changes of its thermal-radiative balance. Indeed, ionization increases caused by SPEs result in changes of chemical composition of the atmosphere, in particular, in enhanced production of nitrogen and hydrogen oxides, which participate in catalytic destruction of ozone (e.g. [6]). Ozone is known to influence significantly radiation fluxes both in shortwave and longwave ranges. Under conditions of polar night, ozone depletion contributes to the polar atmosphere cooling which, in turn, may lead to the polar vortex intensification [17]. Thus, the detected SPE effects on the vortex state seem to be caused by changes of temperature regime of the polar atmosphere due to chemical composition changes.
4. Conclusions

The obtained results showed that the state of the stratospheric polar vortex may be influenced noticeably by solar activity phenomena on the day-to-day time scale. A pronounced intensification of the vortex (increase of western wind velocity) in the entire stratosphere was detected in the course of powerful Solar Proton Events of January 2005, with particle energies being enough to penetrate to stratospheric altitudes. It was shown that ionization changes associated with SPEs and auroral activity (precipitations of auroral electrons generating bremsstrahlung X-rays, which may also penetrate into the stratosphere) may be possible factors of the vortex intensification. The detected SPE effects on the vortex intensity seem to be caused by changes of temperature regime of the polar stratosphere resulting from changes of its chemical composition associated with ionization increase.

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