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Effects of Solar Proton Events of January 2005 on Intensity of the Stratospheric Polar Vortex in the Northern Hemisphere

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Abstract.

Influence of Solar Proton Events (SPEs) of January 2005 on the state of the stratospheric polar vortex in the Northern hemisphere was investigated, the NCEP/NCAR reanalysis data being used. It was revealed that the events under study were accompanied by a noticeable increase of western wind velocities in the latitudinal belt 50-80ºN (intensification of the polar vortex) at all the stratospheric levels. The obtained results allow suggesting that ionization changes in the stratosphere associated with powerful SPEs may influence the state of the polar vortex on the day-to-day timescale. A possible reason of the vortex intensification may be changes of the thermal-radiative balance of the polar stratosphere resulting from changes of its chemical composition caused by solar proton intrusion.

Introduction

The polar vortex is a large-scale cyclonic circulation forming in the polar atmosphere, with highest values of wind velocity being observed in the upper stratosphere during the cold half a year. The state of the polar vortex influences significantly the development of dynamic processes in the troposphere [*Baldwin and Dunkerton*, 2001]. The vortex is an important link between solar activity and circulation of the lower atmosphere at extratropical latitudes, since the vortex location, both latitudinal and altitudinal, is favorable for different physical mechanisms of solar-atmospheric relations. First of all, the vortex is formed in the area of low geomagnetic cutoff rigidities allowing energetic charged particles, such as galactic cosmic rays (GCRs) in a broad energy range and solar cosmic rays, to penetrate there producing ionization changes. Precipitations of auroral electrons, as well as high-energy electrons from the radiation belts also take place in this area. Ionization changes associated with variations of these particle fluxes may influence chemical composition and temperature of the polar atmosphere (e.g., [*Krivolutsky and Repnev*, 2009]). On the other hand, the vortex formation area also includes the area of noticeable changes of ionospheric potential caused by interplanetary magnetic field variations; this provides favorable conditions for electric mechanisms of solar activity influence on atmospheric circulation, which involve variations of vertical electric currents and cloud formation [*Tinsley*, 2008, 2012]. It was shown [*Veretenenko and Ogurtsov*, 2019] that variations of the vortex strength play an important part in the formation of GCR effects on the development of extratropical cyclogenesis. So, investigating effects of different helio/geophysical factors on the state of the stratospheric polar vortex is of great importance to clarify the physical mechanisms of solar activity influence on the lower atmosphere circulation, weather and climate. In this connection, the aim of this work is to consider effects of powerful Solar Proton Events of January 2005 on the polar vortex intensity in the stratosphere of the Northern hemisphere.

Solar Proton Events of January 2005

In January 2005, at the deep descending phase of the 23rd solar cycle a series of strong Solar Proton Events took place (Fig.1a). The events starting on 15, 16 and 17 January were accompanied by the enhancements of particle fluxes in the energy range 165-500 MeV, which can reach stratospheric heights (~15-30 km) losing their energy to ionization. The most powerful event occurred 20 January. It was accompanied by the enhancement of solar proton flux with energies >500 MeV, which participate in nuclear interactions resulting in the increase of the neutron monitor (NM) count rate, so called Ground Level Enhancement (Fig.1b). The SPEs under study were associated with the increase of solar flare activity during the period 13-23 January (Fig.1c) and produced significant changes of ionization rate in the stratosphere. Daily mean ionization rates at geomagnetic latitudes 60-90º are presented in Fig.1d according to the SOLARIS-HEPPA data (https://solarisheppa.geomar.de/).

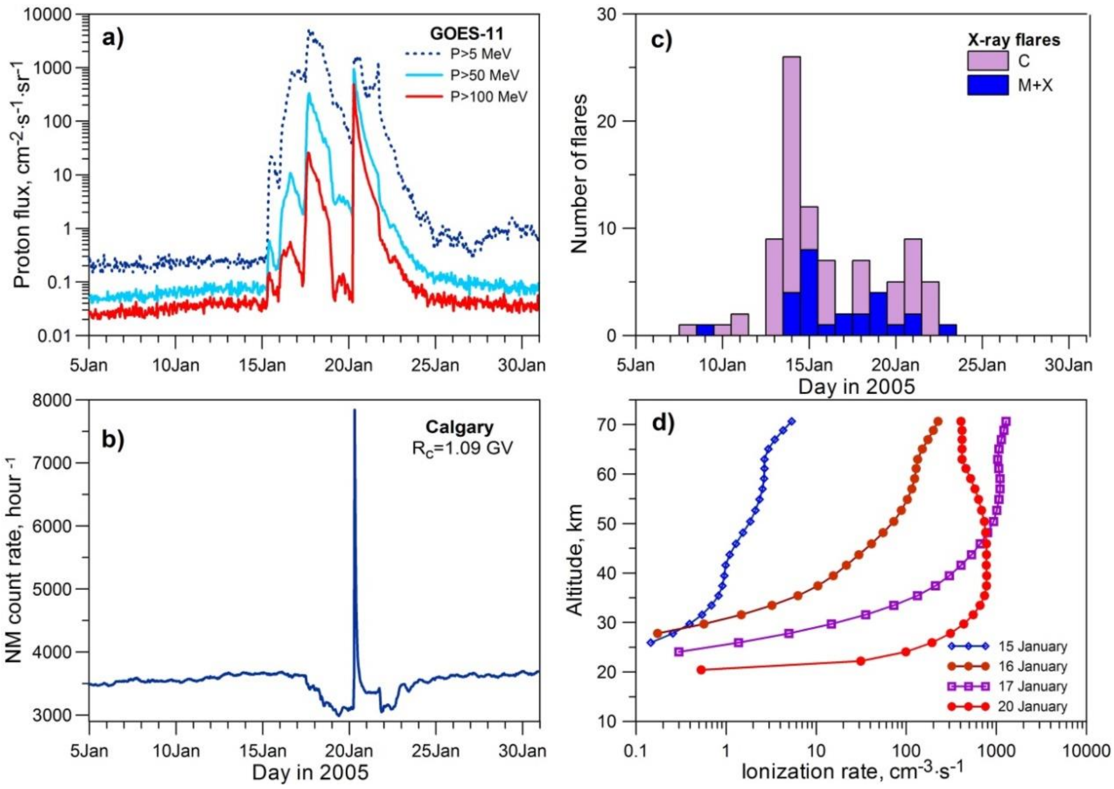

Fig.1. a) Integral solar proton fluxes at different threshold energies (>5, >50 and >100 MeV) according to the GOES-11 data (https://www.swpc.noaa.gov/products/goes-proton-flux/); b) neutron monitor count rate in Calgary ($\Phi \sim 58^o$, geomagnetic cutoff rigidity R_c= 1.09 GV) (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/STATION_DATA/Calgary); c) daily number of X-ray solar flares (https://www.ngdc.noaa.gov/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/); d) daily mean ionization rate at geomagnetic latitudes 60-90º (https://solarisheppa.geomar.de/solarprotonfluxes).

Variations of the polar vortex intensity during SPEs of January 2005

As the polar vortex is seen in the stratosphere as a belt of enhanced western winds, let us use daily mean values of the U-component of wind velocity (directed from west to east) to characterize the vortex intensity. Fig.2 demonstrates temporal variations of maximal values of wind velocity U_{max} observed at different stratospheric levels in the region of the vortex formation in winter months 2004/2005 (the linear trends were removed), the data from the NCEP/NCAR reanalysis archive [*Kalnay et al.*, 1996] being taken. One can see a noticeable strengthening of western winds in the course of the SPEs under study. The deviations from the trends amount to ~20-30 m·s^{-1} at the upper stratospheric levels 30-10 hPa (altitudes ~25-35 km) and ~15 m·s^{-1} at the lower levels 100-50 hPa (~15-20 km).

In Fig.3 the charts of daily values of western wind velocity in the Northern hemisphere at the 50 hPa level are presented for the period 13-21 January 2005. The polar vortex is seen as the belt of sharp enhancement of wind velocities at latitudes 50-80ºN. The area covered by western winds of high velocity (U ≥ 40 m·s^{-1}) is shown in black. One can see that in the course of the studied SPEs this area was enlarging noticeably, with its longitudinal extension increasing. It should be also noted that before the event onset, this area was localized mostly over the Arctic coasts of North America, but in the course of the SPEs it extended to the North Atlantic and Scandinavia, with U_{max} values in it increasing from 55 to 65-67 m·s^{-1}.

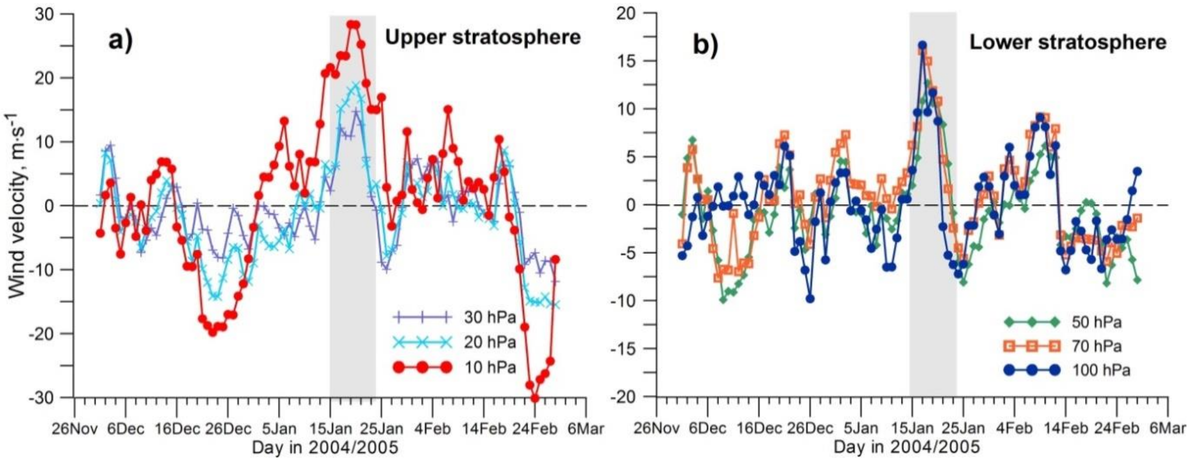

Fig.2. Temporal variations of maximal values (detrended) of western wind velocity U_{max} in the upper (a) and lower (b) stratosphere. The period 15-23 January is shown with a gray background.

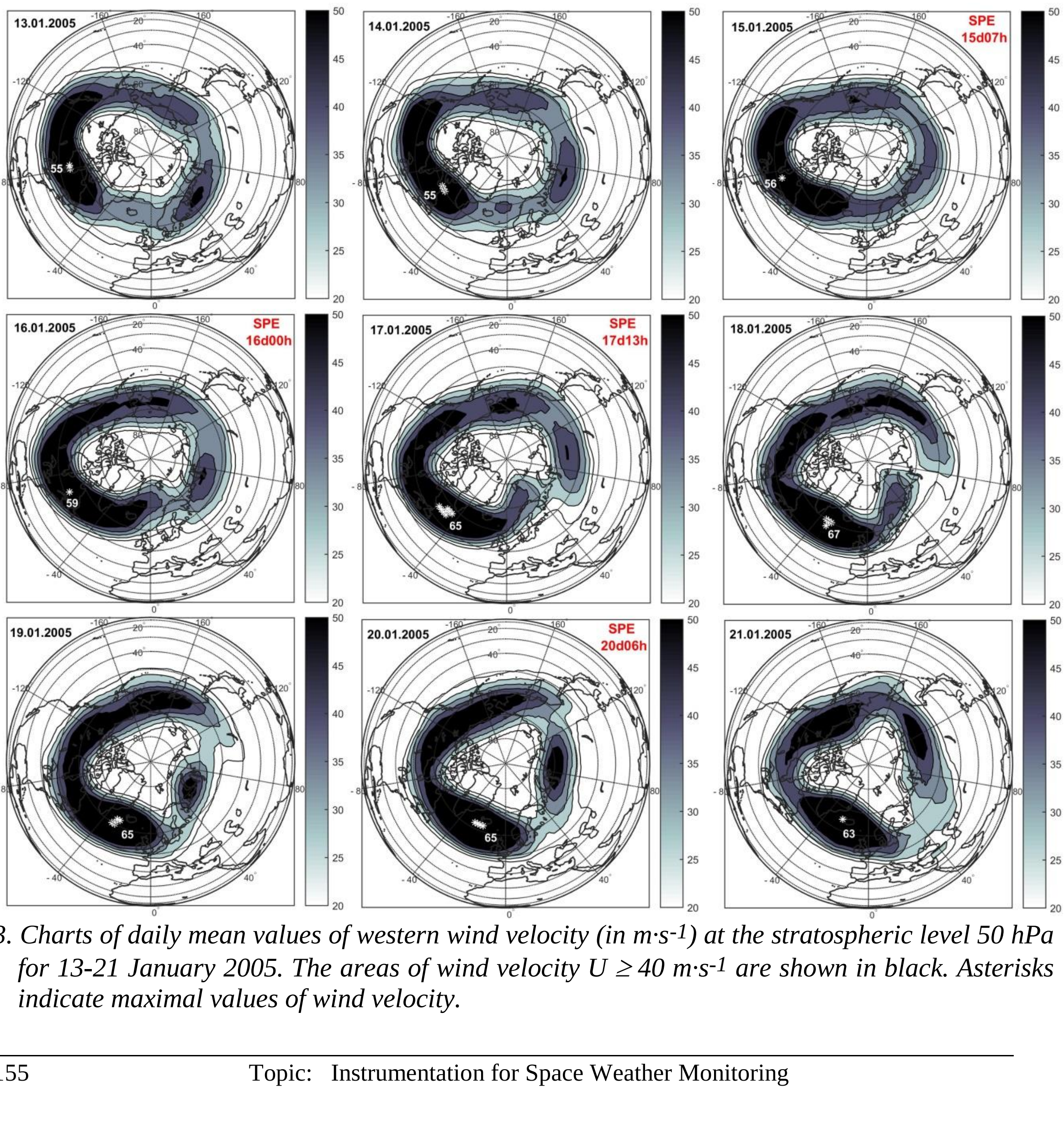

Fig.3. Charts of daily mean values of western wind velocity (in m·s^{-1}) at the stratospheric level 50 hPa for 13-21 January 2005. The areas of wind velocity $U \geq 40$ m·s^{-1} are shown in black. Asterisks indicate maximal values of wind velocity.

The enlargement of the areas of enhanced wind velocity was observed at all the stratospheric levels during the period 15-21 January 2005. Fig.4 demonstrates temporal variations of the areas (in fraction of the entire Earth's surface area) covered by western winds of high velocity (equal or exceeding some threshold value for each stratospheric level). One can see a noticeable enlargement of these areas associated with the SPEs under study (Fig.4a, b). Moreover, new areas of wind velocities which were not observed before the event onset appeared, e.g., the areas with $U \geq 100$ m·s^{-1} at the 10 hPa level and $U \geq 60$ m·s^{-1} at the 50 hPa level (Fig.4c). Thus, the data presented in Figs.2, 3 and 4 provide evidence of a strong intensification of the stratospheric polar vortex during a series of SPEs of January 2005.

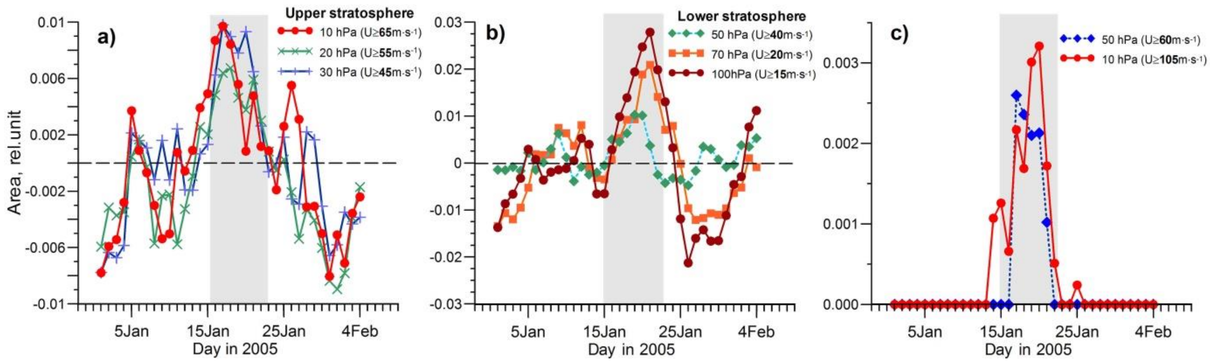

Fig.4. Temporal variations of the areas (in relative units) with enhanced wind velocity (threshold values are indicated in the legend) in the upper (a) and lower (b) stratosphere in January 2005; c) Temporal variations of the areas of extremely high (not observed before the SPE onset) velocities of western wind. The period 15-23 January is shown with a gray background.

Possible factors of the polar vortex intensification

Let us consider possible factors contributing to the vortex intensification. The vortex formation area is characterized by low geomagnetic cutoff rigidities allowing penetration of charged cosmic particles (cosmic rays) in a wide energy range. This provides higher values of ionization rates in this area compared with those at lower latitudes. Besides, the belt of enhanced wind velocities 60-80ºN (Fig.3) turns out to be in a zone of maximal occurrence of auroral phenomena (auroral zone). Auroras are caused by precipitations of auroral electrons which lead to excitation of atmospheric constituents during magnetospheric substorms. Though auroral electron energy is absorbed mainly in the lower thermosphere (above 90 km), they contribute to generation of bremsstrahlung X-rays which are capable to penetrate into the stratosphere. According to [*Jackman*, 1991], X-rays with energies 30 keV and 10^3 keV may reach stratospheric altitudes, respectively, ~40 km and ~30 km producing ionization changes.

Temporal variations of maximal values of western wind velocity U_{max} at the upper stratospheric level 10 hPa are compared with 5-day running averages of geomagnetic AE-index in Fig.5a. AE-index characterizes intensity of electric current (auroral electrojet) which develops in the ionosphere at high latitudes during magnetospheric substorms and is accompanied by precipitation of auroral electrons. One can note that temporal variations of maximal wind velocities U_{max} in the upper stratosphere and those of AE-index are very similar, with the maxima of U_{max} following the maxima of AE-index or coinciding with them. The correlation coefficient between U_{max} and AE-indices in winter months 2004/2005 amounts to ~0.5 and increases up to ~0.7 if AE-indices are smoothed over 5-day intervals.

Fig.5b shows a relationship between U_{max} at the stratospheric level 10 hPa in January 2005 and daily mean ionization rates in the upper stratosphere (35 km) at geomagnetic latitudes 60-90º according to the SOLARIS-HEPPA data. It can be seen that maximal values of wind velocity varies in a wide range (from ~80 to ~110 m·s^{-1}) when ionization rate is less than 1 cm-

$^{3}\cdot s^{-1}$. However, when ionization rate exceeds 1 $cm^{-3}\cdot s^{-1}$, wind velocity starts increasing (up to ~120 $m\cdot s^{-1}$) with ionization increase. Thus, the increase of stratospheric ionization rate seems to contribute to the intensification of the polar vortex on the day-to-day time scale.

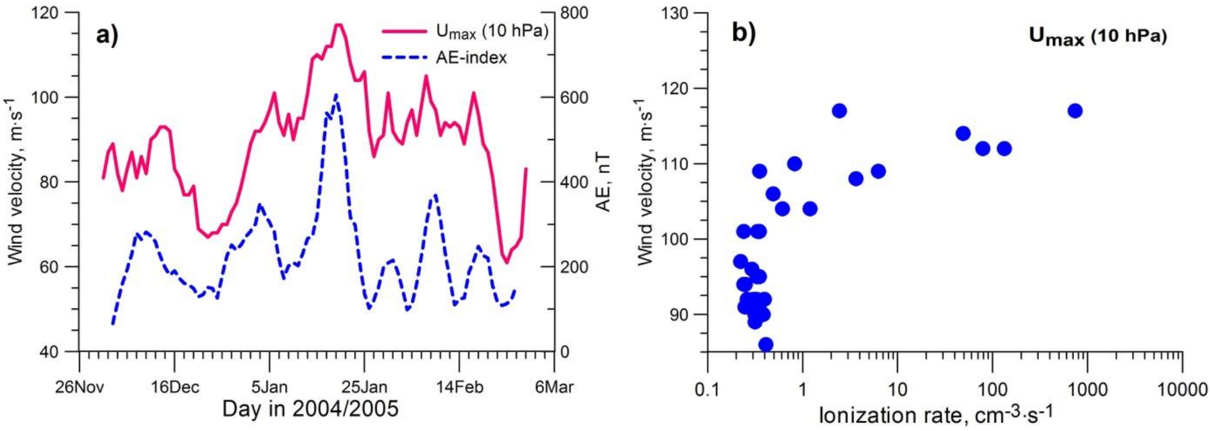

Fig.5. a) Temporal variations of maximal values of western wind velocity U_{max} in the upper stratosphere (the 10 hPa level) and 5-day running averages of geomagnetic AE-indices (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/ INDICES/AURORAL_ELECTROJET/) in winter months 2004/2005; b) maximal values of western wind velocity U_{max} (the 10 hPa level) in January 2005 versus daily mean ionization rates in the upper stratosphere (35 km).

The data above provide evidence for influence of phenomena associated with solar activity on the state of the stratospheric polar vortex on the day-to-day scale. An important part seems to be played by stratospheric ionization changes caused by solar proton events, the energy of particles being enough to penetrate into the stratosphere, as well as auroral activity (bremsstrahlung X-ray with energies above 30 keV). The obtained results suggest that pronounced increases of stratospheric ionization may contribute to the vortex intensification.

As wind velocity in the atmosphere is closely related to temperature gradients, the detected strengthening of the polar vortex indicates that a significant increase of temperature gradients between high and middle latitudes took place during the studied series of SPEs in January 2005. A possible reason for this increase may be changes of thermal-radiative balance of the high-latitudinal stratosphere. Indeed, increases of ionization caused by SPEs lead to noticeable changes of chemical composition of the polar atmosphere, in particular, to enhanced production of nitrogen and hydrogen oxides, which participate in catalytic destruction of ozone (e.g., [*Krivolutsky and Repnev*, 2009]). As ozone can influence significantly fluxes both of shortwave and longwave radiation, a reduction of its content may result in some changes of temperature regime of the polar atmosphere, namely radiative cooling of the atmosphere under polar night conditions, which contribute to an increase of temperature gradients between polar and middle latitudes and, then, a strengthening of the polar vortex. Thus, the detected effects of strong SPEs on the polar vortex intensity may be related to changes of chemical composition of the polar atmosphere caused by SPE-induced ionization changes and, in turn, influencing its temperature regime.

Conclusions

1. Intensity of the stratospheric polar vortex may be affected noticeably by phenomena related to solar/geomagnetic activity on the day-to-day time scale.
2. An appreciable strengthening of the polar vortex (an increase of western wind velocity in the latitudinal belt 60-80°N) was revealed at all the stratospheric levels in the course of Solar Proton Events in January 2005, with energies of particles being enough to reach stratospheric heights.

3. Auroral activity (auroral electron precipitations generating bremsstrahlung X-rays) may be an additional factor contributing to the polar vortex intensification.
4. A possible reason for the polar vortex intensification may be changes of temperature regime of the polar atmosphere resulting from changes of its chemical composition caused by intrusion of energetic solar protons.

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