

## Influence of Solar Proton Events of January 2005 on the Middle Atmosphere Circulation: Southern Hemisphere

*Veretenenko S.*

Ioffe Institute RAS, St. Petersburg, Russia

E-mail: s.veretenenko@mail.ioffe.ru

### **Abstract.**

Influence of Solar Proton Events (SPEs) of January 2005 on the middle atmosphere circulation in the Southern hemisphere was studied. It was found that circulation disturbances associated with these events reveal a strong dependence both on height and latitude. In the upper stratosphere (30-10 hPa), where eastern transport of air masses dominates in the whole hemisphere in summer months (December-February), a weakening of zonal eastern winds was detected at middle and high latitudes ( $>40^{\circ}\text{S}$ ), whereas at lower latitudes these winds were found to strengthen. Unlike the upper stratosphere, circulation of the undisturbed lower stratosphere (100-50 hPa) in summer is characterized by eastern winds at polar and low latitudes, as well as a strong western zonal flow at middle latitudes ( $30-55^{\circ}\text{S}$ ). In the course of the studied events a weakening of eastern winds was found at polar latitudes ( $>60^{\circ}\text{S}$ ), with a maximum of zonal western winds being shifted about 10 degrees to the south. The detected circulation disturbances seem to be caused by changes in the radiation-thermal balance of the polar middle atmosphere which, in turn, may be associated with changes in its chemical composition due to ionization increase during solar proton intrusions.

### **Introduction**

Solar Proton Events (SPEs) are abrupt enhancements of solar cosmic rays (mostly protons) occurring sporadically in the near-Earth space. Due to a steep energy spectrum and geomagnetic cutoff, intrusions of solar protons into the Earth's atmosphere are usually limited by polar latitudes. However, their fluxes may be huge compared with those of galactic cosmic rays, which results in considerable increases of atmospheric ionization. Ionization changes associated with solar proton intrusions produce a large number of geophysical effects, such as variations of chemical composition of the atmosphere (ozone depletion caused by enhanced production of nitrogen and hydrogen oxides participating in catalytic cycles of ozone destruction), perturbations in the global electric circuit, changes in atmospheric transparency and cloudiness [Miroshnichenko, 2008]. This suggests an important part of solar cosmic rays in Sun-weather relationships. Indeed, a noticeable intensification of extratropical cyclones in the North Atlantic was detected in the course of SPEs, with energies of particles exceeding 90 MeV [Veretenenko and Thejll, 2004, 2005].

In the work [Veretenenko, 2021] an impact of strong Solar Proton Events in January 2005 on the middle atmosphere circulation was investigated. It was found that in the Northern hemisphere the studied events were accompanied by a pronounced enhancement of western winds in the latitudinal belt  $50-80^{\circ}\text{N}$  at all the stratospheric levels. This indicated a strong intensification of the stratospheric polar vortex, which is a characteristic feature of stratosphere circulation in winter. So, the aim of this study is to investigate an impact of Solar Proton Events of January 2005 on stratospheric circulation in the Southern (summer) hemisphere.

### **Solar Proton Events of January 2005**

A series of strong Solar Proton Events, associated with an increase of flare activity on the Sun occurred in January 2005, i.e., at the deep descending phase of the 23<sup>rd</sup> solar cycle. Integral fluxes of solar protons with energies  $>5$ ,  $>50$  and  $>100$  MeV are shown in Fig.1a according to the GOES-11 satellite data. One can see pronounced increases of proton fluxes, with particle

energies  $>100$  MeV, on 15, 16, 17 and 20 January. The estimates according to  $E = a \cdot r^b$ , where  $E$  is proton energy in MeV,  $r$  is the path length in  $\text{g} \cdot \text{cm}^{-2}$ ,  $a = 29.4$ ,  $b = 0.57$  [Bazilevskaya *et al.*, 2003], show that particles with energies  $E \sim 100$  MeV reach stratospheric levels  $\sim 10$  hPa ( $\sim 30$  km) losing their energy to ionization. The strongest event occurred on 20 January and was accompanied by a growth of solar proton fluxes with energies  $>500$  MeV. Particles with such energies reach altitudes of the lower stratosphere ( $\sim 15$  km) and participate in nuclear interactions producing secondary particles (neutrons), which can be registered by ground-based neutron monitor (so called Ground Level Enhancement, GLE). The GLE on 20 January 2005 was the strongest event after the GLE observed on 23 February 1956.

Solar proton intrusions in January 2005 resulted in a considerable increase of ionization rate in the high-latitudinal atmosphere at altitudes above 20 km. Daily mean ionization rates at geomagnetic latitudes  $60\text{--}90^\circ$  are shown in Fig.1b according to the data by the international working group SOLARIS-HEPPA (<https://solarisheppa.geomar.de/>). One can see that the greatest ionization rates (up to  $\sim 1000 \text{ cm}^{-3} \cdot \text{s}^{-1}$ ) took place on 17 and 20 January in the mesosphere ( $\sim 50\text{--}70$  km) and the upper stratosphere ( $\sim 35\text{--}40$  km), respectively.

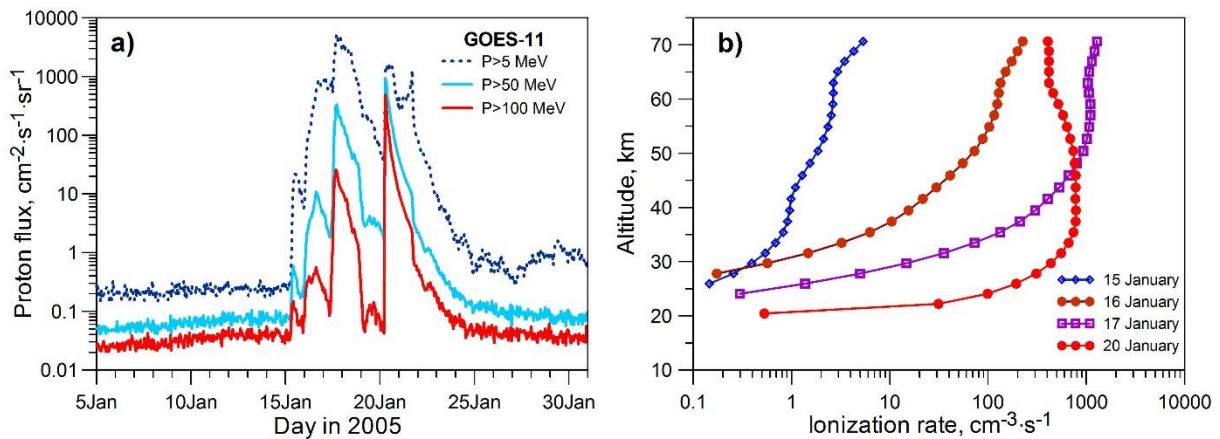


Fig.1. a) Solar proton fluxes with energies  $> 5$ ,  $> 50$  and  $> 100$  MeV according to the GOES-11 data (<https://www.swpc.noaa.gov/products/goes-proton-flux/>); b) daily mean ionization rates at geomagnetic latitudes  $60\text{--}90^\circ$  on the days of Solar Proton Events in January 2005. (<https://solarisheppa.geomar.de/solarprotonfluxes>).

### Peculiarities of stratospheric circulation in the Southern hemisphere in summer period

Unlike the Northern hemisphere in winter, where the polar vortex is observed in the whole stratosphere, stratospheric circulation in the Southern hemisphere in summer reveals strong altitudinal dependence. The data in Fig.2 show distributions of monthly mean values of the  $U$ -component of wind velocity (the positive direction is from west to east) at the levels 50 hPa (the lower stratosphere) and 10 hPa (the upper stratosphere) in January 2005. One can see that in the upper stratosphere strong eastern transport of air mass dominates in the whole hemisphere. This is caused by meridional temperature gradients in the summer stratosphere directed from the pole to the equator (in winter the direction of these temperature gradients is opposite, so strong western winds arise forming the stratospheric polar vortex). In the lower stratosphere, however, we can see eastern winds only at polar and low latitudes, whereas a rather strong western zonal flow takes place at middle latitudes  $30\text{--}55^\circ\text{S}$ . This flow seems to arise due to persistent temperature contrasts between the icy surface of the Antarctic and the warmer ocean surface at middle latitudes, which creates temperature gradients directed to high latitudes both in winter and summer periods and influencing circulation not only in the troposphere, but apparently in the lower stratosphere too.

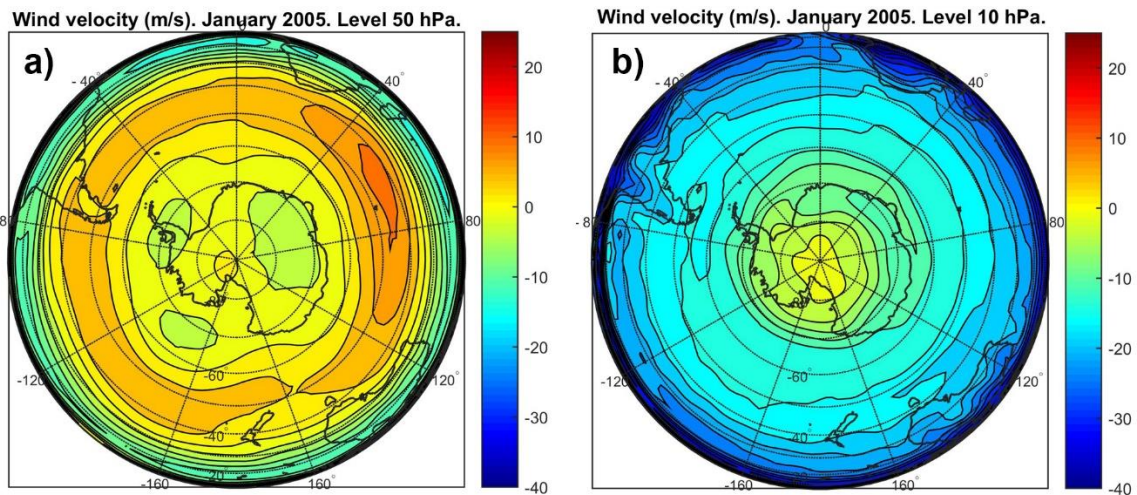


Fig.2. Monthly mean values of the U-component of wind velocity (in  $\text{m}\cdot\text{s}^{-1}$ ) in the lower stratosphere (50 hPa) and the upper stratosphere (10 hPa) in January 2005.

### Effects of Solar Proton Events of January 2005 on wind velocity

Let us consider circulation changes in the course of the SPEs under study. As experimental data for the analysis, daily values of the U-component of wind velocity at different stratospheric levels (100, 70, 50, 30, 20 and 10 hPa) taken from the NCEP-DOE reanalysis-2 archive [Kanamitsu *et al.*, 2002] were used. Fig.3 demonstrates the charts of the U-component of wind velocity before the onset of the SPE series (13 January) and on the 4<sup>th</sup> day after the onset (18 January) in the upper stratosphere (the level 10 hPa). One can see a noticeable intensification of eastern winds (winds with negative U-values) at latitudes below 40°S on the days of the studied SPE series (the area of wind velocities  $U < -20 \text{ m}\cdot\text{s}^{-1}$  (dark blue) increased markedly). At the same time, at middle and high latitudes (40-70°S) a pronounced weakening of eastern winds took place (the area covered by winds with velocities  $-20 < U < -15 \text{ m}\cdot\text{s}^{-1}$  (light blue) reduced, whereas the area of wind velocities  $-15 < U < -10 \text{ m}\cdot\text{s}^{-1}$  (green) increased and stretched to lower latitudes).

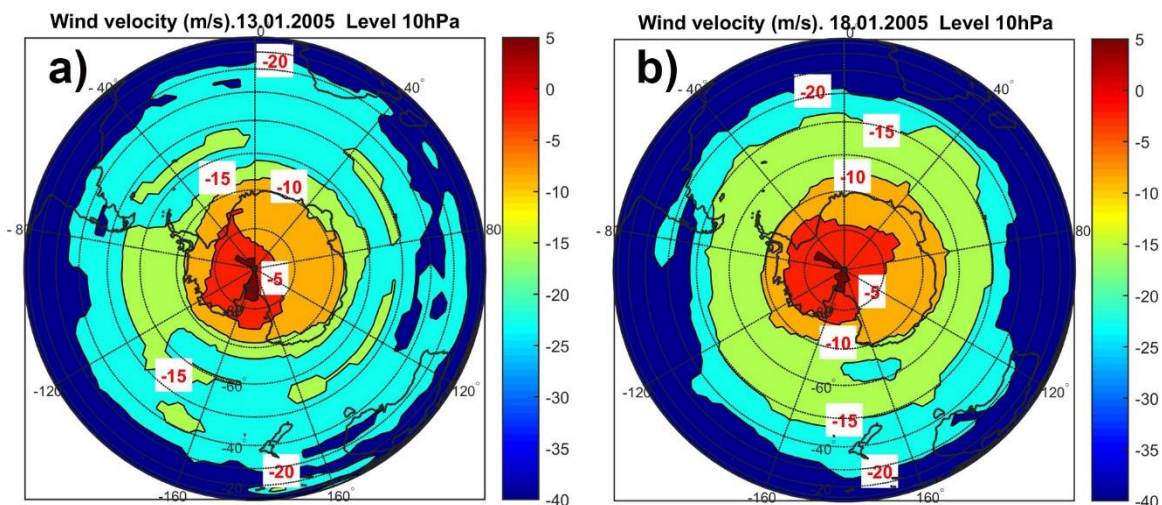


Fig.3. Charts of daily mean values of the U-component of wind velocity (in  $\text{m}\cdot\text{s}^{-1}$ ) in the upper stratosphere (10 hPa): a) before the onset of the SPE series (13 January 2005); b) after the onset of the SPE series (18 January 2005).



Charts of wind velocity before and after the onset of the SPE series in the lower stratosphere (the level 50 hPa) are shown in Fig.4. One can see that in the course of the SPEs under study a weakening of eastern winds took place only at polar latitudes  $>60^{\circ}\text{S}$  (the area of negative values of the  $U$ -component of wind velocity (light blue) reduced noticeably, so did the area of  $U < -5 \text{ m}\cdot\text{s}^{-1}$ ). This results in a shift of western flow (enlargement of the area of positive  $U$ -values) to higher latitudes.

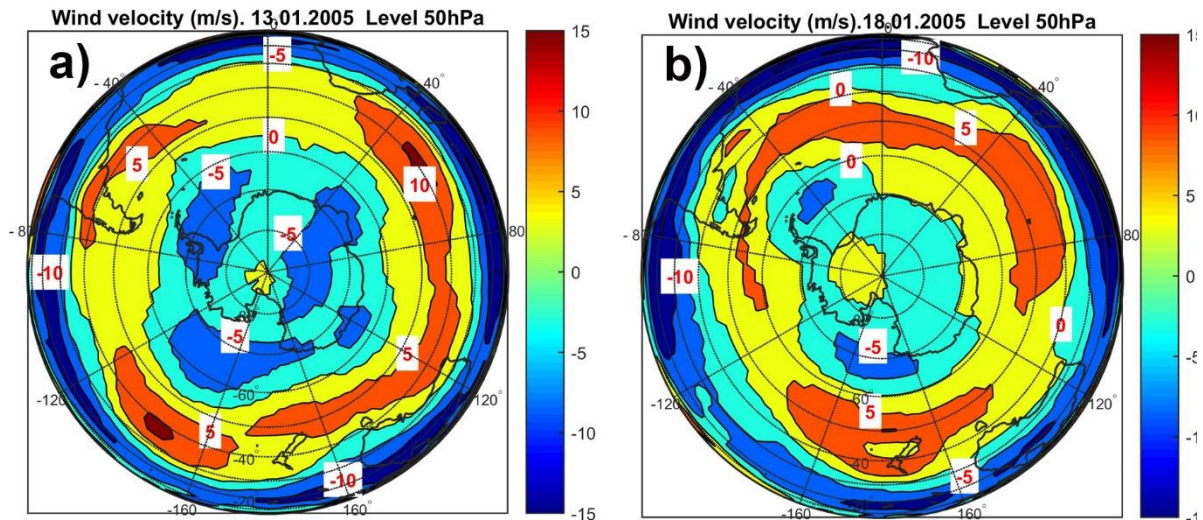


Fig.4. The same as in Fig.3, but for the lower stratosphere (50 hPa).

Fig.5 demonstrates zonal values of wind velocity on 13 and 18 January in the upper (10 hPa) and lower (50 hPa) stratosphere. The presented data confirm that a weakening of eastern winds did really take place at middle and high latitudes ( $>40^{\circ}\text{S}$ ) in the upper stratosphere, whereas in the lower stratosphere this effect was limited by the polar area ( $>60^{\circ}\text{S}$ ). It is seen (Fig.5b) that western zonal flow is displaced to higher latitudes, with a maximum of this flow having a  $\sim 10$ -degree shift to the south (from  $\sim 40^{\circ}\text{S}$  to  $\sim 50^{\circ}\text{S}$ ).

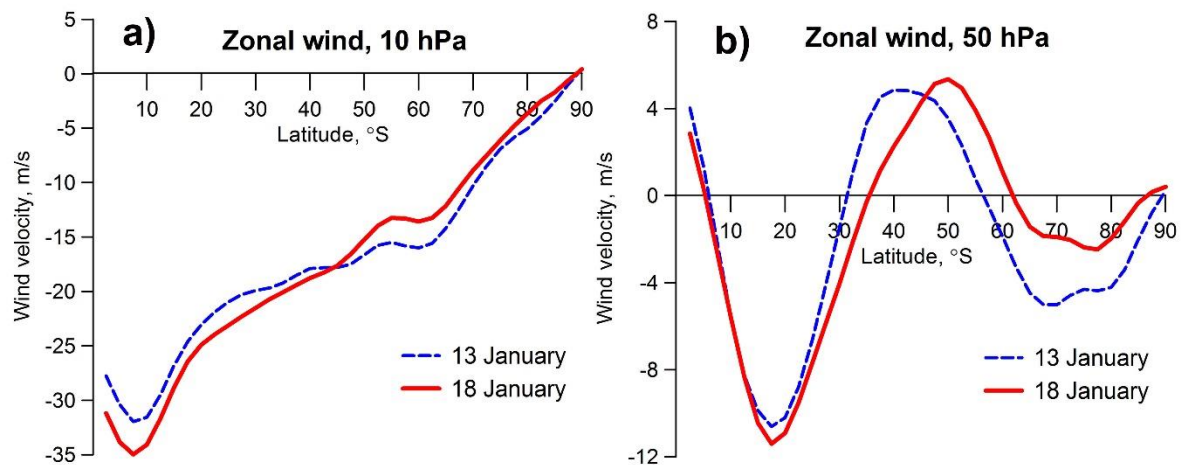


Fig.5. Zonal wind velocity before (13 January) and after (18 January) the onset of the SPEs series in the upper (a) and lower (b) stratosphere.

### A possible mechanism of SPE effects on stratospheric circulation in summer period

The data presented above indicate that the SPEs of January 2005 were accompanied by noticeable disturbances of stratospheric circulation not only in the Northern (winter)



hemisphere, as it was shown earlier, but also in the Southern (summer) hemisphere. In the Northern hemisphere, where the stratospheric polar vortex is formed in the cold half of the year, the events under study contributed to a pronounced intensification of the vortex (enhancement of western winds at all stratospheric levels) [Veretenenko, 2021]. In the Southern hemisphere the regime of stratospheric circulation in summer is quite different, with eastern winds dominating at all latitudes in the upper stratosphere. In the lower stratosphere eastern winds are observed only at polar and low latitudes, with a rather intensive western flow taking place at middle ones. So, the SPEs effects in the Southern (summer) hemisphere revealed a strong dependence both on altitude and latitude. Weakening of eastern winds was detected at middle and high latitudes in the upper stratosphere, whereas in the lower stratosphere this effect was observed only at polar latitudes, being accompanied by a shift of zonal western flow to the south.

Weakening of eastern winds observed in the Southern hemisphere during January 2005 SPEs provides evidence of a decrease of meridional gradients of temperature which are directed to the equator in summer stratosphere. This is possibly due to changes of the temperature regime of the polar stratosphere caused by changes of its chemical composition associated with SPEs (ozone depletion). As it was shown in a number of studies (e.g., [Verronen *et al.*, 2006; Damiani *et al.*, 2008]), increases of ionization rate during solar proton intrusions contribute to more intensive production of nitrogen ( $\text{NO}_x$ ) and hydrogen ( $\text{HO}_x$ ) oxides participating in catalytic cycles of ozone destruction. Ozone is known to be a radiatively active gas significantly influencing radiation fluxes both in shortwave and longwave ranges [Brasseur and Solomon, 2005]. Under summer (sunlight) conditions ozone absorbs solar UV radiation contributing to the stratosphere warming. So, ozone depletion associated with SPEs in summer may result in a cooling of the polar stratosphere and a reduction of meridional temperature gradients. Weakening of eastern winds in the Northern (summer) hemisphere associated with the SPE on 14 July 2000 was revealed by model simulations [Krivolutsky *et al.*, 2006]. Thus, a sequence of processes resulting in the detected weakening of eastern winds may be as shown in Fig.6. Reasons for the enhancement of eastern winds at low latitudes are not clear at the moment and need further investigations.

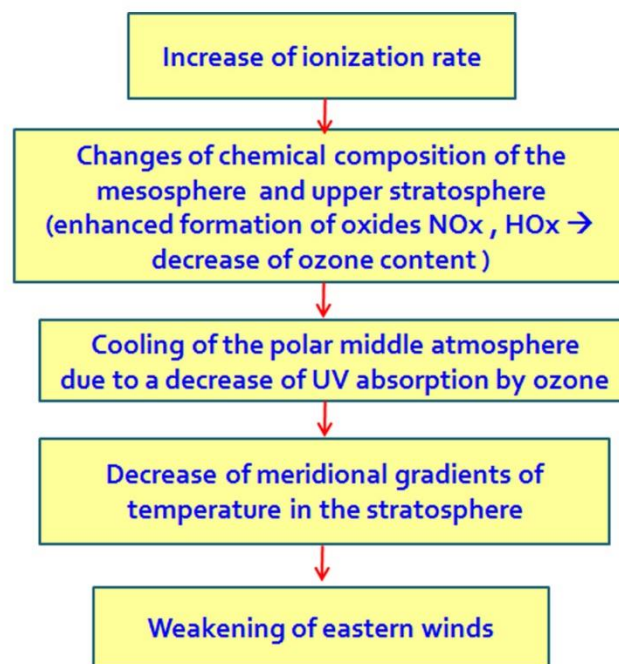


Fig.6. A possible scheme of SPE influence on stratospheric circulation in summer period.

## Conclusions

1. Solar Proton Events of January 2005 were accompanied by noticeable disturbances of stratospheric circulation both in the Northern (winter) and Southern (summer) hemispheres, with the SPE effects in the winter and summer stratosphere differing significantly.
2. SPE effects on stratospheric circulation in the Southern hemisphere in summer revealed a strong dependence on altitude and latitude.
3. In the upper stratosphere a pronounced weakening of eastern winds associated with the studied SPEs was detected at middle and high latitudes ( $>40^{\circ}\text{S}$ ). At lower latitudes eastern winds were found to enhance.
4. In the lower stratosphere weakening of eastern winds was limited by the polar area ( $>60^{\circ}\text{S}$ ). Zonal western flow of middle latitudes was found to displace  $\sim 10$  degrees to the south.
5. A possible mechanism of the detected effects seems to involve changes in the radiation-thermal balance of the polar middle atmosphere caused by changes in its chemical composition associated with ionization increase during SPEs.

## References

- Bazilevskaya, G.A., Krainev, M.B., et al. (2003). Solar proton events observed in the FIAN stratospheric experiment. *Geomagn. Aeron.* 43, no 4, 412-421.
- Brasseur, G.P., Solomon, S. (2005). *Aeronomy of the middle atmosphere*. Springer, The Netherlands.
- Damiani, A., Storini, M., et al. (2008). Solar particle effects on minor components of the Polar atmosphere. *Ann. Geophys.* 26, no 2, 361-370.
- Kanamitsu, M., Ebisuzaki, W., et al. (2002). NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteorol. Soc.* 83, no 11, 1631-1644.
- Krivolutsky, A.A., Klyuchnikova, A.V., et al. (2006). Dynamical response of the middle atmosphere to solar proton event of July 2000: Three-dimensional model simulations. *Adv. Space Res.* 37, no 8, 1602-1613.
- Miroshnichenko, L.I. (2008). Solar cosmic rays in the system of solar-terrestrial relations. *J. Atmos. Sol.-Terr. Phys.* 70, 450-466.
- Veretenenko S. (2021). Effects of Solar Proton Events of January 2005 on the middle atmosphere dynamics in the Northern hemisphere. *Adv. Space Res.* 68, no 4, 1814-1824.
- Veretenenko, S., Thejll, P. (2004). Effects of energetic Solar Proton Events on the cyclone development in the North Atlantic. *J. Atmos. Sol.-Terr. Phys.* 66, no 5, 393-405.
- Veretenenko, S.V., Thejll, P. (2005). Cyclone regeneration in the North Atlantic intensified by energetic solar proton events. *Adv. Space Res.* 25, no 3, 470-475.
- Verronen, P.T., Seppälä, A., et al. (2006). Production of odd hydrogen in the mesosphere during the January 2005 solar proton event. *Geophys. Res. Lett.* 33, L24811.