Long-term middle atmospheric influence of very large solar proton events of solar cycle 23rd over Sodankyla, Finland

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ABSTRACT

Solar eruptions sometimes produce protons which impact polar middle atmosphere. These solar proton events (SPEs) generally last for few days and produce high energy solar protons that precipitate into the Earth's middle atmosphere. The highly energetic solar protons cause ionizations, dissociations, dissociative ionization of neutral background constituents of atmosphere. Complicated ion chemistry of D region leads to HOx production and dissociation of N_2 leads to NOy production. Both HOx and NOy increases can result in changes to ozone abundance in stratosphere and mesosphere. Life-time of HOx is only on the order of hours in upper stratosphere and mesosphere. Hence any change in ozone cause by HOx species would last for couple of hours past SPE. NOy species have greater lifetime than HOx constituents and hence cause long-term ozone destruction in lower mesosphere and stratosphere. Observations from Global Ozone Monitoring Experiment (GOME) are used to monitor the enhancement in NO_2 and large decrease in O_3 over station Sodankyla (67.4° N, 26.7° E) Finland. A very significant ozone reduction > 11% is computed for July 2000 SPE. Atmospheric impact of two major SPEs namely, SPE occurred in November 2000 and 2001 was quite moderate. Ozone depletion > 5-6% is computed for same SPEs, persisting over period of 1 to 2 month after SPEs.

Key words - ozone, solar proton event, odd nitrogen

INTRODUCTION

Periodically the Sun erupts in a solar flare and associated coronal mass ejection (CME) that results in an intense flux of solar particles in interplanetary space. Such periods of intense solar proton flux are known as solar proton event and tend to be infrequent (Jackman and McPeters, 2004). These SPEs typically last for few days causing significant changes in chemical constituents such as HOx, NOy and ozone. Half an hour after recording a major solar flare, protons and heavier nuclei with energy up to 200MeV are usually observed within polar cap areas of both hemispheres (Krivolutsky *et al,* 2005). Solar protons entering in the Earth's magnetosphere are guided by the Earth's magnetic field and precipitate into Polar Regions. Since the proton can have very high energy, up to tens of MeV, they deposit their energy in mesosphere and stratosphere. Thus they provide the direct connection between the Sun and the Earth middle atmosphere (Seppla *et al.*, 2004). Once high energy solar protons have entered into the Earth's atmosphere, they may collide with neutral air molecules and produces large number of partly ionized atomic and molecular fragments. An ion pair is created when a precipitating proton removes an electron, called a secondary electron from the neutral molecule or atom, leaving behind positive ion. Approximately 35eV energy is expended in production of ion pair (Jackman *et al.*, 2008). The process like ionizations, dissociation and dissociative ionization lead to production of odd hydrogen HOx (H,OH, HO_2) and NOx (N,NO, NO_2) or NOy (N,NO,NO_2, N_2O_5, N_2O, $ClONO_2$) either directly or through photochemical sequences. Both HOx and NOy play a key role in ozone balance at stratospheric and mesospheric height because they destroy ozone abundance through catalytic ozone loss cycles. As a result, chemistry of polar middle atmosphere can be dramatically altered by large SPEs. HOx species can react fairly quickly to destroy each other through reaction

$$OH + HO_2 = H_2O + O_2$$

Therefore, lifetime of HOx is only order of hours in mesosphere and stratosphere. Hence any corresponding change in atmosphere caused by HOx species could last for a couple of hours past any SPEs. SPE-produced HOx constituents are important in controlling ozone in upper stratosphere and mesosphere. Short term ozone destruction via HOx species proceeds through several catalytic ozone loss cycles such as

$$OH + O_3 = HO_2 + O_2$$

$$\text{Followed by} \quad HO_2 + O = OH + O_2$$

$$\text{Net } O_2 + O = 2O_2$$

and

$H + O_3 = OH + O_2$

Followed by $OH + O = H + O_2$

Net $O_2 + O = 2O_2$ (Jackman et al,2005).

SPE-produced NOx or NOy constituents lead to short and longer –term ozone destruction in lower mesosphere and stratosphere through well known NOx- ozone loss cycles.

$NO + O_3 = NO_2 + O_2$

$NO_2 + O = NO + O_2$

Net $O_2 + O = 2O_2$

In this paper we present significant impact of very large SPEs occurred in solar cycle 23 over specific station Sodankyla (67.4° N, 26.7° E), Finland. Satellite instrument observations exist for several constituents during SPEs that occurred in solar cycle 23. Satellite observations for HOx are available after August 2005; therefore we discussed only long- term ozone perturbation caused by long-lived NO_2 species. For the first time, this phenomenon was studied for specific local station in northern region. There have been number of modeling studies focused on understanding and predicting atmospheric influence of SPEs. All of these studies carried out to investigate the more detailed global effects of SPEs. However, SPE-caused long term enhancement of NO_2 and its subsequent effect on ozone over a particular station have not been studied in any literature to our best knowledge.

MATERIALS AND METHODS

Production of Odd hydrogen (HOx) and Odd nitrogen (NOy)

HOx production

Protons and their associated secondary electrons produce odd hydrogen. HOx production takes place after initial formation of ion-pair and is the result of complicated ion chemistry of D region. Atmospheric photochemistry involve in HOx production can be described as follows.

Ionization caused by high energy solar protons results in set of initial ions including O_2^+, leading to formation of its hydrate $O_2^+.(H_2O)$ via O_4^+ (Solomon et al, 1981).

$$O_2^+ + O_2 + M = O_4^+ + M$$

$$O_4^+ + H_2O = O_2^+.(H_2O) + O_2$$

Then, after there are number of reaction pathways with increasing degree of hydration and recombination with electron, by which one water molecule can be converted into two odd hydrogen constituents H and OH.

$O_2^+.(H_2O) + H_2O = H_3O^+.OH + O_2$

$H_3O^+.OH + e^- = H + OH + H_2O$

Net $H_2O = H + OH$

Or by

$O_2^+.(H_2O) + H_2O = H_3O^+.OH + O_2$

$H_3O^+.OH + H_2O = H_3O^+.H_2O + OH$

$H_3O^+.H_2O + nH_2O = H_3O^+.(H_2O)_{n+1}$

$H_3O^+.(H_2O)_{n+1} + e^- = H + (n+2) H_2O$

Net $H_2O = H + OH$

These pathways are effective only at altitude below 80 km, where amount of water vapor is high enough so that water cluster ion can be formed and can be interrupted by the recombination of intermediate ions.

NOx production

Proton bombardment provides a large source of atomic nitrogen in upper stratosphere and mesosphere. Atomic nitrogen is produced by primary protons and associated secondary electrons via dissociation, dissociative ionization processes. In general 1.25 N atoms are produced per ion- pair and divide proton impact of N atom production between ground state N (^4S) and excited state N (^2D). Since atomic nitrogen is highly reactive with atmospheric oxygen, ground state N (^4S) nitrogen atom can produce NOy constituents through (Jackman *et al.*, 2005).

$N(^4S) + O_2 = NO + O$

Mutual destruction of NOy also takes place via

$N(^4S) + NO = N_2 + O$

RESULTS

GOME OBSERVATIONS

GOME is nadir viewing UV/VIS spectrometer which was launched in April 1995 aboard on ERS-2 satellites by European Space agency (ESA) and designed for determination of amount and distribution of atmospheric trace constituents such as O_3 and NO_2 and abundances of aerosol in the atmosphere. ERS-2 flies in retrograde, a Sun-synchronous polar orbit with an inclination of 98° at an altitude of 780 km. This results in an orbital period of about 100 minutes and a speed of the sub satellite point of 7 km/s and 14 orbits per day (www.knmi.nl/gome_fd/doc/gomeintro.html). GOME measures the Earth shine radiance and solar irradiance in UV/VIS spectral range 240-790 nm at moderate spectral resolution 0.2 to 0.4 nm. Spectral features around 330 nm are used to retrieve ozone column.

Trace gas total column amounts are retrieved from primary measurement utilizing their characteristic spectral absorption or emission features. More particular, Differential Optical Absorption Spectroscopy (DOAS) method is used to determine the concentration of trace gases by measuring their specific narrow band absorption structure in UV and visible spectral region.

Data Collection

The solar protons which caused NOx and ozone changes in polar middle atmosphere were measured by instrument aboard on NOAA's (National Oceanic and atmospheric administration) GOES satellite series. The greater than 10 MeV, 100MeV proton flux measured after every 5 minutes during major SPEs are available on NOAA's web site (www.swpc.noaa.gov.in). Atmospheric data used in this work were recorded by GOME instrument on ERS-2 satellite. GOME is UV- VIS spectrometer designed for global monitoring of atmospheric ozone and trace quantities of other gases. Daily NO_2 and O_3 data were accessed via web www.iup.uni-bremen.de/gome which is maintained by university of Bremen, Germany.

SPE caused long-term atmospheric changes in solar cycle 23

The influence of very large SPEs in solar cycle 23 caused some significant documented changes in atmospheric composition, primarily during and within several months of events. Some of the SPE caused atmospheric perturbations were substantial during and shortly after these SPEs. We focus most of our analysis on SPE-produced NO_2 enhancement and its subsequent effect on ozone abundance. As discussed before, NOy family has a long life-time in polar stratosphere and greatly enhanced by large SPEs. Stratospheric ozone is biologically important for the life on the Earth and its abundance is partly controlled by NOy family.

Year 2000 was particularly active with two large SPEs which occurred in July and November. Satellite measurements showed large atmospheric changes as a result of these extremely intense SPEs. Several solar explosions along with halo CMEs resulted in July 2000 SPE. The most intense SPE period accompanying these solar eruptions was during 15-16 July 2000. GOME measured constituent's changes during and after event is shown in figure 1. GOME observed constituents changes during and after events were calculated by comparing the background constituents before the occurrence of events, define as averages of July 10-13. A very large increase in NO_2 above background amount (4.8×10^{15} molecules /cm^2) is observed in first few days after the event, when major SPE took place. These NO_2 increase were observed during and 1 to 2 months past the event. Maximum increases >10-12% were computed for the SPE- induced NO_2 in first week after the start of event. Long-term ozone impact for July 2000 SPE is well presented in same figure 1. The figure shows very significant deduction in ozone, reaching to its least value 280 DU on 25th July 2000. Long –term computed ozone depletion connected to July 2000 SPE is substantial, reaching level>14% in first few days after the commencement of event. More continuous ozone depletion >11% were calculated over the period of 1-2 month past event for same SPE. Other large SPE in year 2000 was occurred in November; however this event was much smaller than very large SPE in July 2000 and cause smaller NO_2 enhancement along with less ozone perturbation in polar atmosphere. Changes caused by this SPE for NO_2 and ozone was computed and presented in figure 2. We computed modest ozone depletion > 5.40% caused by SPE-produced NO_2 over period of one month. Year 2001 had a very active period with large SPEs in late September and early November. Reduced statistically significant ozone impact was computed for Sept. 2001 SPE. Although not statistically significant, we computed modest ozone increase over station Sodankyla, Finland (maximum 20% increase) as result of this particular SPE. Measured impact of this SPE for NO_2 and O_3 is shown in figure 3. Other large SPE occurred in early November 2001. Largest flare X1/3B was occurred which result in hugeflux peaking at 620000000.00 protons/cm^2-day-sr on 6th November. A very large enhancement in NO_2, reaching to its peak (1.35×10^{15} molecules /cm^2) on 7th November is observed. (Refer figure 4). Computed ozone decreases of 10% in first 7 days are statistically significant over station Sodankyla. The substantial ozone depletion (>7.7%) over period of 1` month was mainly caused by large SPE which produced sufficient NO_2 to cause long-lived ozone loss. Statistically significant ozone impact of this SPE was less intense as compared to July 2000 SPE. It is mainly because of comparatively less proton fluence of this SPE. Late October 2003 the Sun released two powerful solar flares, both associated with CME directed almost straight at the Earth. Consequently flux of the particles entering into the Earth's atmosphere greatly enhanced. Measured impact of Oct. 2003 SPE for NO_2 and O_3 is shown in figure 5.

Fig. 1: SPE- caused changes for NO_2 and O_3 for July 2000 SPE

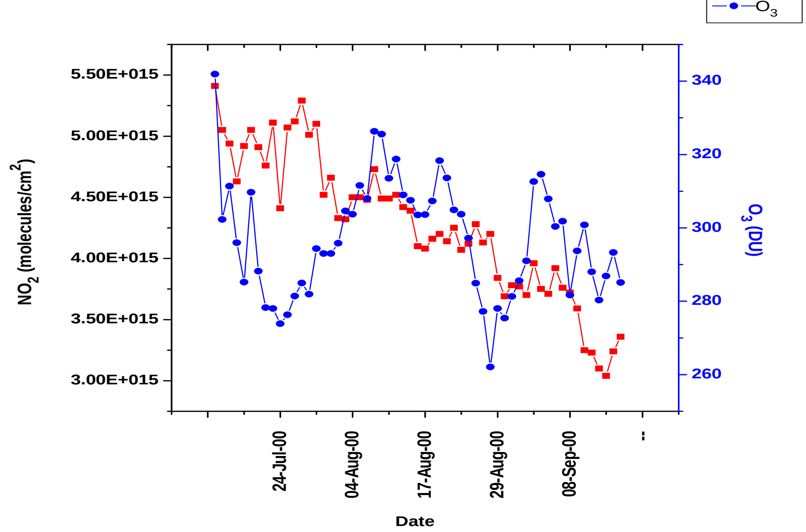

Fig. 2: Anticorrlation between NO_2 and O_3 for Nov. 2000 SPE

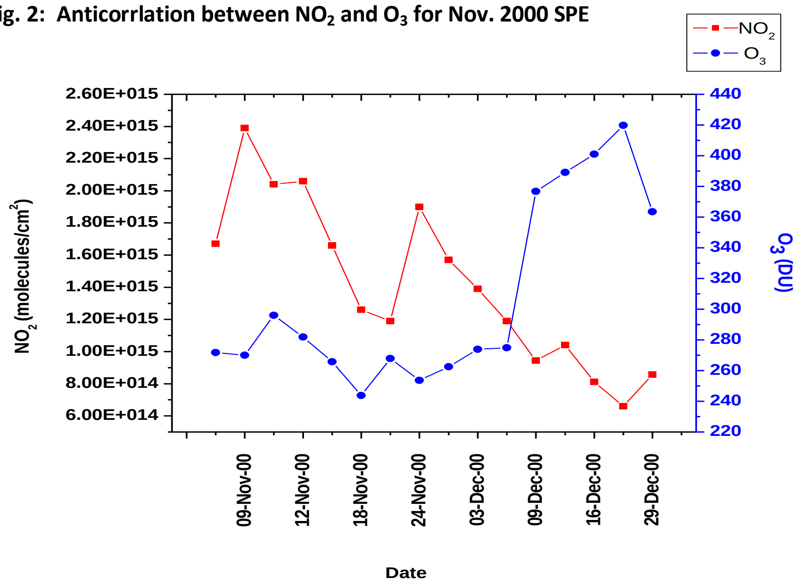

Fig. 3: GOME observed changes in NO_2 and O_3 for Sept. 2001 SPE

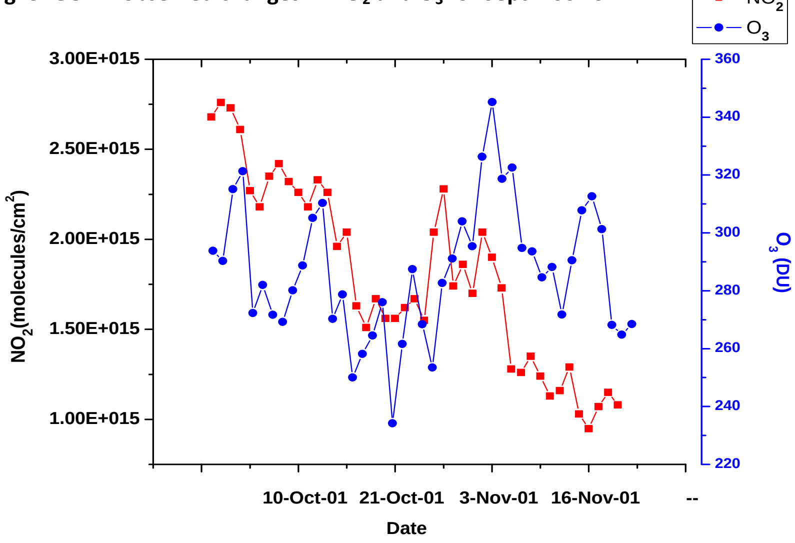

Fig. 4: Negative effect of enhanced NO_2 on O_3 for SPE Nov.

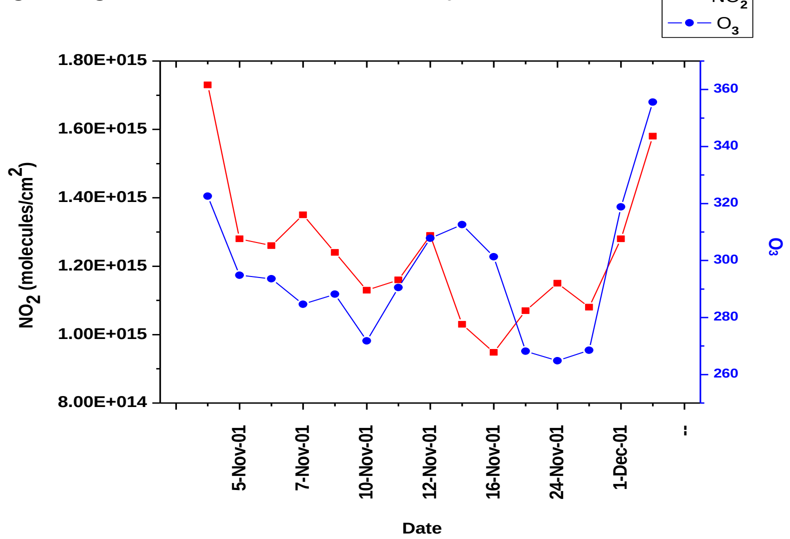

Fig. 5: SPE- caused changes for NO_2 and O_3 for Oct. 2003 SPE

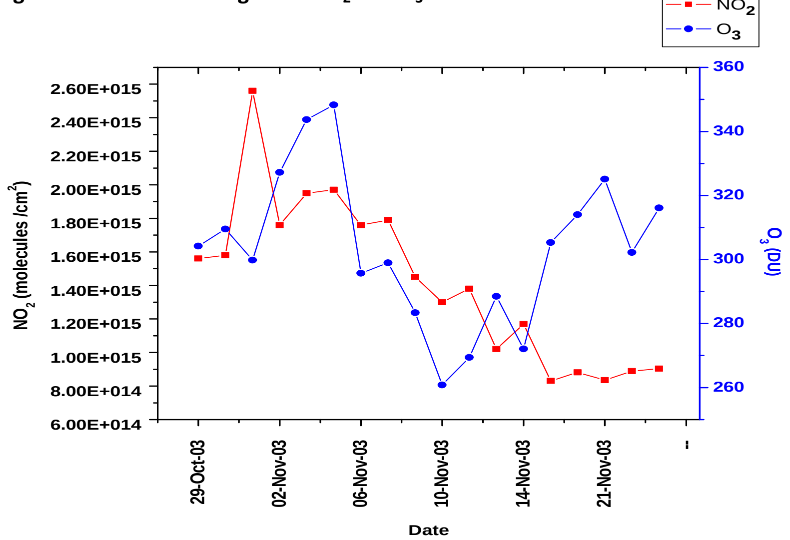

Fig. 6. Plot NO_2 Vs O_3 illustrating impact of NO_2 on ozone

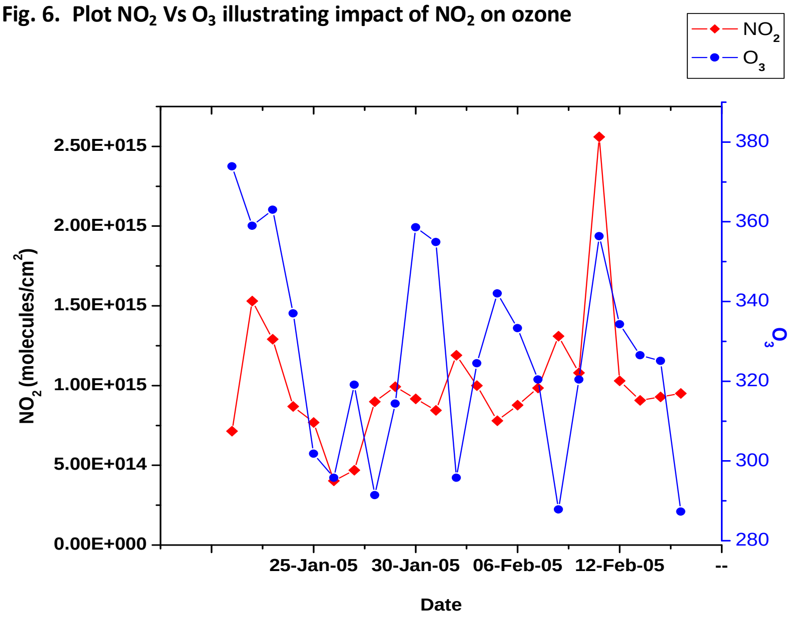

Fig. 7: Ozone variation over complete solar cycle 23

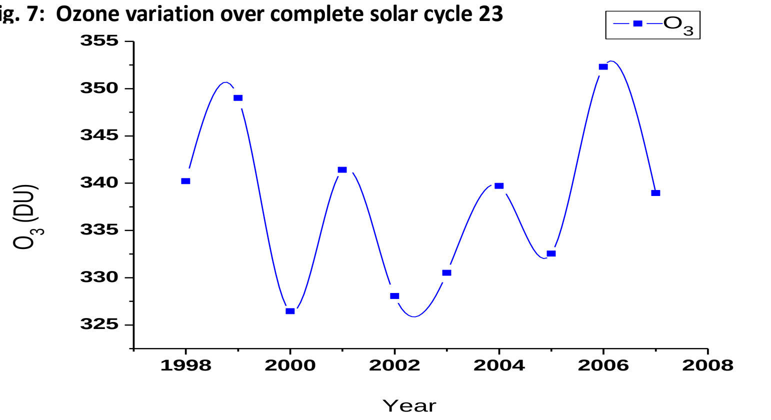

Table 1. Summary of graphical analysis of all proton event >10 MeV

Start date of proton Event >10MeV	Day on which proton event. 10MeV peaked>	Maximum proton (protons/cm^2-day-sr)	Maximum value of NO_2 (molecules/cm^2)	Least value of O_3 (DU)
14th July 2000	15th July 2000	1.00 ×10^9 on 15th July	5.29 ×10^{15} on 27th July	281 on 28th July
8th November 2000	9th November 2000	7.5 ×10^8 on 9th November 2000	2.39 ×10^{15} on 9th November 2000	243.7 on 18th November 2000
24th September 2001	25th September 2001	2.7 ×10^8 on 25th September 2001	2.76 ×10^{15} on 25th September 2001	234 on 20th October 2001
4th November 2001	6th November 2001	6.2 ×10^8 on 6th November 2001	1.35 ×10^{15} on 7th November 2001	271.8 on 10th November 2001
28th October 2003	29th October 2003	7.7 ×10^8 on 29th October 2003	2.56 ×10^{15} 31st October 2003	260 on 10th November 2003
16th January 2005	17th January 2005	1.1 ×10^8 on 17th January 2005	1.53 ×10^{15} 22nd January 2003	291 on 28th January 2005

Table 2. Summary of statistical analysis of all proton event >10 MeV

EVENT / DAYS	After 5 Days	After 6 Days	After 7 Days	After 1 Month
14th July 2000	9.88	10.52	11.39	10.21
8th November 2000	5.33	6.42	8.39	5.40
24th September 2001	-20.47	-22.36	-21.66	-8.5
4th November 2001	9.33	10.9	10.02	7.77
28th October 2003	-6.1	-6.7	-8.5	-3.92

Unexpected ozone peak was observed in first week after the start of event. Afterward, very sharp ozone reduction below 265 DU was measured by GOME. We found that Oct. 2003 SPE which was calculated to produce maximum 2.56 ×10 ^{15} molecules /cm^2 NO_2 molecules caused substantial ozone impact in second week of November. Although statistically not significant, we computed ozone increase (3%) as result of this SPE.

Less intense NO_2 rise for January 16, 2005 event was observed and confirmed by GOME. Only 1.1×10^{15} molecules /cm^2 NO_2 molecules was found for same event. We are unable to predict the changes during 17 to 21 January due to unavailability of data. Changes in NO_2 and O_3 during intense period of this event are shown in figure in 6. Given the several large SPEs that occurred in years 2000, 2001, 2003, 2005, we have also investigated SPE caused atmospheric changes in year average for complete solar cycle 23. Computed ozone perturbation produced by SPEs is shown in figure 7. Ozone peak was observed in year 1999, 2004, and 2007 when solar activity was quite whereas strong ozone variation was observed during period of SPEs. Summary of graphical and statistical analysis is presented in table one and two.

Discussion and conclusion

Five very large SPEs occurred in solar cycle 23 and caused very significant changes over station Sodankyla, Finland. GOME observations have been used to study the long-term constituent's changes caused by these SPEs. For first time, ozone impact of SPEs is computed over specific local station in northern region though satellite observations for SPE-produced NO_2 and O_3 are global. Most pronounced atmospheric effect were caused by major SPEs and concentrated into polar region like Sodankyla. Substantial enhancement in NO_2 was initiated in year 2000,2001,2003,2005 after very large SPEs and lasted one to two months past event. Huge ozone depletion near about 5-11% was computed over Sodankyla during investigated period.

Ozone is also affected by HOx production. However, these effects are observed only for short duration after SPE, because of the relatively short life-time of HOx. Therefore, long-term ozone destruction observed over Sodankyla is solely due to increase in long-lived NO_2.

GOME observations confirm that without SPE, correlation between NO_2 and O_3 is positive. Correlation becomes strong negative after SPE indicating large increase in NO_2 and resulting ozone depletion.

Concluding remarks of present work can be summarized as follows

a) The atmospheric influence of a SPE is dependent on the energy spectrum of solar protons and absolute flux levels at the particular energies.

b) We found that July 2000 event which was calculated to produce 5.29×10^{15} molecules /cm^2 NO_2 molecules was the third largest SPE in past 40 years.

c) Huge events affected total ozone for several months to years past the events by causing direct ozone decreases from NOy- induced losses.

d) Longer lived NO_2 alter the atmospheric chemistry of stratosphere over period of month, depending on season in which SPE occurred.

e) SPEs may also change temperature and dynamics of polar middle indirectly through associated ozone depletion.

f) Greater the fluence at >10MeV, the more important SPE effects are. SPE with low content of proton fluxes results in smaller perturbation of atmosphere.

g) Seasonal conditions are essential to spread SPE influence on stratosphere.

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LITERATURE CITED

Jackmam CH, Deland MT, Labow GJ, Fleming EL, Weisenstein DK, Malcolm KWKo, Miriam Sinnhuber, James M Russell, 2005. The influence of very large solar proton events in years 2000-2003 on the neutral middle atmosphere. *J. Advances in Space Research*, **35**:445-450.

Jackmam CH, Deland MT, Labow GJ, Fleming EL, Weisenstein DK, Malcolm KW, Sinnhuber M, Russell JM, 2005. Neutral atmospheric influences of the solar proton events in October- November 2003. *J. Geophysical research,* **110**: A09S27

Jackman CH and McPeters RD, 2004. The effect of solar proton events on ozone and other constituents. *J. American Geophysical Union,* **10**: 305-318.

Jackman CH, Marsh DR, Vitt FM, Garcia RR, Fleming EL, Labow GL, Randall CE, Lopez-Puertas M, Funke B , Clarmann GPT von, Stiller, 2008. Short and medium –term atmospheric constituent effect of very large solar proton events. *J.Atmos.chem*, **8**: 765-785.

Krivolutsky A, Kuminov A, Vyushkova T, 2005. Ionization of atmosphere caused by solar protons and its influence on ozonosphere of the earth during 1994-2003. *J. Atmospheric and solar- Terrestrial Physics,* **67**:105-117.

Seppla A , Verronen PT, Kyrola E, Hassinen S, Backman L, Hauchecorne A, Bertaux JL , Fussen, 2004. Solar proton events of October- November 2003: ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat. *J. Geophysical research Letters,* **31**:L19107.

Solomon S, Rusch DW, Gerard JC, Reid GC, Crutzen PJ, 1981. The effect of particle precipitation events on the neutral and ion chemistry of middle atmosphere: II odd Hydrogen**.** *J.Planet Space Science,* **29(**8): 885-892.

http://www.knmi.nl/gome_fd/doc/gomeintro.html