SATELLITE MEASUREMENTS OF MIDDLE ATMOSPHERIC IMPACTS BY SOLAR PROTON EVENTS IN SOLAR CYCLE 23

C. H. JACKMAN[1,*], M. T. DELAND[1,2], G. J. LABOW[1,2], E. L. FLEMING[1,2] and M. LÓPEZ-PUERTAS[3]
[1]*NASA Goddard Space Flight Center, Code 613.3, Greenbelt, MD 20771, USA*
[2]*Science Systems and Applications, Inc., Lanham, MD, USA*
[3]*Instituto de Astrofisica de Andalucia, CSIC, Granada, SPAIN*
*(*Author for correspondence: E-mail: charles.h.jackman@nasa.gov)*

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Abstract. Solar cycle 23 was extremely active with seven of the largest twelve solar proton events (SPEs) in the past forty years recorded. These events caused significant polar middle atmospheric changes that were observed by a number of satellites. The highly energetic protons produced ionizations, excitations, dissociations, and dissociative ionizations of the background constituents in the polar cap regions (> 60 degrees geomagnetic latitude), which led to the production of HO_x (H, OH, HO_2) and NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $BrONO_2$, $ClONO_2$). The HO_x increases led to short-lived ozone decreases in the polar mesosphere and upper stratosphere due to the short lifetimes of the HO_x constituents. Polar middle mesospheric ozone decreases greater than 50% were observed and computed to last for hours to days due to the enhanced HO_x. The NO_y increases led to long-lived polar stratospheric ozone changes because of the long lifetime of the NO_y family in this region. Upper stratospheric ozone decreases of >10% were computed to last for several months past the solar events in the winter polar regions because of the enhanced NO_y.

Keywords: ozone, NO_y, solar proton event, middle atmosphere, stratosphere, mesosphere

1. Introduction

Solar eruptive events sometimes result in large fluxes of high-energy solar protons at the Earth. This period of time, wherein the solar proton flux is generally elevated for a few days, is known as a solar proton event (SPE) and primarily occurs near solar maximum. Solar cycle 23 experienced several very large SPEs, which occurred in July and November 2000, September and November 2001, October/November 2003, and January 2005. The twelve largest SPEs in the past 40 years are given in Table I and over half of them (seven) occurred in the past solar maximum period.

The Earth's magnetic field guides the solar protons into the northern and southern polar cap regions (>60° geomagnetic latitude), e.g., see Jackman and McPeters (2004). The protons interact with the neutral middle atmosphere (stratosphere and mesosphere) and produce ionizations, dissociations, dissociative ionizations, and excitations.

Both HO_x (H, OH, HO_2) and NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $BrONO_2$, $ClONO_2$) can be enhanced either directly by the protons and their

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TABLE I
Largest twelve solar proton events in the past forty years.

Date of SPEs	Rank in size	NO_y production in the middle atmosphere (# of molecules)
October 19–27, 1989	1	6.7×10^{33}
August 2–10, 1972	2	3.6×10^{33}
July 14–16, 2000	3	3.5×10^{33}
October 28–31, 2003	4	3.4×10^{33}
November 5–7, 2001	5	3.2×10^{33}
November 9–11, 2000	6	2.3×10^{33}
September 24–30, 2001	7	2.0×10^{33}
August 13–26, 1989	8	1.8×10^{33}
November 23–25, 2001	9	1.7×10^{33}
September 2–7, 1966	10	1.2×10^{33}
January 15–23, 2005	11	1.1×10^{33}
Sep. 29–Oct. 3, 1989	12	1.0×10^{33}

associated secondary electrons or through a photochemical sequence initiated by the protons impacting the atmosphere (e.g., Warneck, 1972; Swider and Keneshea, 1973; Crutzen *et al.*, 1975; Porter *et al.*, 1976; Frederick, 1976; Jackman *et al.*, 1980, 1995, 2000, 2001; Solomon *et al.*, 1981; Rusch *et al.*, 1981; McPeters, 1986; Zadorozhny *et al.*, 1992; Randall *et al.*, 2001). Ozone can be influenced by the solar protons through photochemical depletion processes caused by the enhanced HO_x and NO_y (e.g., Weeks *et al.*, 1972; Heath *et al.*, 1977; McPeters *et al.*, 1981; Solomon and Crutzen, 1981; Thomas *et al.*, 1983; Solomon *et al.*, 1983; McPeters and Jackman, 1985; Jackman and McPeters, 1985, 1987; Jackman *et al.*, 1995, 2000, 2001; Reid *et al.*, 1991; Seppala *et al.*, 2004; Degenstein *et al.*, 2005).

The first middle atmospheric impact of solar protons was measured with a rocket by Weeks *et al.* (1972). These observations showed a very dramatic reduction in mesospheric ozone caused by the November 1969 SPE, which was explained in Swider and Keneshea (1973) as caused by HO_x enhancements.

Crutzen *et al.* (1975) postulated that stratospheric ozone should be impacted by NO generated through interaction of the protons with the atmosphere. Two years later Heath *et al.* (1977) confirmed with satellite observations that stratospheric ozone was dramatically reduced during the August 1972 SPE.

In this paper we discuss satellite observations of middle atmospheric impacts by protons ejected by the Sun in solar cycle 23. There have been several publications in the past few years on this subject including Jackman *et al.* (2001, 2005a,b), Randall *et al.* (2001), Krivolutsky *et al.* (2003, 2005), Seppala *et al.* (2004), Degenstein *et al.* (2005), Semeniuk *et al.* (2005), Verronen *et al.* (2005), López-Puertas *et al.* (2005a,b, 2006), and Rohen *et al.* (2005). López-Puertas *et al.* (2006) as well as other papers (e.g., Natarajan *et al.*, 2004; Randall *et al.*, 2005; Orsolini *et al.*, 2005; Rinsland *et al.*, 2005) showed certain solar influences on the polar upper stratosphere from effects that may not have been caused by solar protons, but rather by energetic electrons and/or X-rays associated with the solar storms of October–November 2003, and will not be discussed here.

This paper contains seven primary sections, including the Introduction. The solar proton flux and production of HO_x and NO_y are discussed in Section 2. The observations of NO_y constituents, ClO and HOCl constituents, and ozone change as a result of solar protons in solar cycle 23 are given in Sections 3, 4, and 5, respectively. Global model results during certain disturbed time periods are presented in Section 6. Finally, conclusions are given in Section 7.

2. Solar Proton Flux and Production of HO_x and NO_y

The National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) provides a proton flux dataset for the NOAA Geostationary Operational Environmental Satellites (GOES) on their website (see `http://sec.noaa.gov/Data/goes.html`). GOES proton fluxes are provided at this site in several energy intervals (>1 MeV, >5 MeV, >10 MeV, >30 MeV, >50 MeV, and >100 MeV), which are updated every five minutes.

As an example of a very large solar proton flux time period that occurred in solar cycle 23, we present the proton flux measured by GOES-11 for the October 26 through November 7, 2003 time period in Figure 1. The proton fluxes are given for 1 and 100 MeV, which reach to altitudes of about 87 and 33 km, respectively.

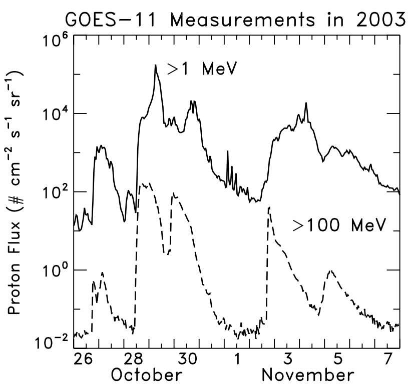

Figure 1. GOES-11 proton flux measurements in 2003 for energies >1 MeV (solid line) and >100 MeV (dashed line). These data are provided by the NOAA SEC at their website (`http://sec.noaa.gov/Data/goes.html`). Taken from Figure 1 of Jackman *et al.* (2005a).

The very fast moving protons with energies >100 MeV arrive at Earth early in the solar event, whereas the slower moving protons with energies >1 MeV mostly arrive later. The most intense time period of proton fluxes occurred during October 28–30.

Using the energy deposition methodology discussed in Vitt and Jackman (1996), the daily average ion pair production can be computed. HO_x is created through ion chemistry (e.g., Solomon *et al.*, 1981) wherein: (1) two (HO_x) constituents are produced per ion pair up to about 70 km; and (2) less than two (HO_x) constituents are produced per ion pair above 70 km.

The solar protons and associated secondary electrons (produced in ionization events) create atomic nitrogen through dissociations, predissociations, or dissociative ionization collisions with N_2. Porter *et al.* (1976) showed that approximately 1.25 N atoms are produced per ion pair. About 45% or 0.55 per ion pair of the N atoms are in the ground state and about 55% or 0.7 per ion pair are in excited states. Although excited state N atoms are more likely to produce other NO_y constituents, both types of N atoms can have an impact on the middle atmosphere.

3. Satellite Measurements of NO_y Constituent Changes from SPEs

3.1. NO_x ($NO + NO_2$) Observations

Substantial changes in NO_y constituents as a result of SPEs have been measured by several satellite instruments during solar cycle 23. Very large fluxes of solar protons in July 2000 produced huge increases (>50 ppbv in the mesosphere) in polar Northern Hemisphere NO_x measured by the Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE) (Jackman *et al.*, 2001). Randall *et al.* (2001) demonstrated that the polar Southern Hemisphere NO_x was also influenced by this very large SPE. Using UARS HALOE and Polar Ozone and Aerosol Measurement (POAM) III data, Randall *et al.* (2001) showed evidence of large NO_x enhancements in September 2000 in the middle stratosphere that were almost certainly caused by the July 2000 SPE.

The large solar storms in late October and early November 2003 also caused very large proton fluxes (see Figure 1) that created NO_x and was measured by UARS HALOE (Jackman *et al.*, 2005a) and Envisat Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (López-Puertas *et al.*, 2005a). Jackman *et al.* (2005a) showed polar Southern Hemisphere NO_x enhancements during the very large SPEs that were nearly as large as those that were measured during the July 2000 SPE. López-Puertas *et al.* (2005a) showed huge NO_x increases in both the polar Northern and Southern Hemispheres, which lasted for at least two weeks after the major SPEs in the Northern polar regions. These measurements by Envisat MIPAS showed polar SPE-driven changes in both the winter (dark) and summer (daylight) hemispheres (López-Puertas *et al.*, 2005a). A plot of this interhemispheric difference is shown in this issue of *Space Science Reviews* in

Figure 1 of Langen (2006), which is similar to that given in Figure 4 of López-Puertas *et al.* (2005a). Seppala *et al.* (2004) showed NO_2 enhancements over several hundred per cent in the middle to upper stratosphere using Envisat Global Ozone Monitoring by Occultation of Stars (GOMOS) data.

3.2. HNO_3, N_2O_5, AND $ClONO_2$ OBSERVATIONS

Other NO_y constituents were also elevated as a result of the huge SPEs that occurred in Oct–Nov 2003. López-Puertas *et al.* (2005b) showed polar HNO_3, N_2O_5, and $ClONO_2$ changes using Envisat MIPAS. Nitric acid (HNO_3) enhancements of 1–2 ppbv (100%) in the middle to upper stratosphere occurred in conjunction with the SPEs in both Hemispheres. Given the sudden nature of this HNO_3 enhancement, it was suggested to be most likely caused by gas phase chemistry (López-Puertas *et al.*, 2005b), in particular, $NO_2 + OH + M \rightarrow HNO_3 + M$. There were measured increases in NO_2 (e.g., Jackman *et al.*, 2005a; López-Puertas *et al.*, 2005b) and predicted increases in OH (Jackman *et al.*, 2005a) as a result of the Oct–Nov 2003 solar events, thus the reaction would likely be accelerated. Orsolini *et al.* (2005) examined the anomalous HNO_3 layer observed by MIPAS over a longer period of time (November 4, 2003 to February 20, 2004). They found that there were two periods of enhanced upper stratospheric HNO_3 in November 2003, one observed November 4–5 (early) and the other observed November 20–30 (late). Only the early enhanced HNO_3 period was thought to be caused directly by solar protons. The late November enhanced HNO_3 period was likely caused by production of NO_x by energetic particle precipitation in the mesosphere followed by descent to the stratosphere (Orsolini *et al.*, 2005).

Dinitrogen pentoxide (N_2O_5) was increased around 40 km by about 0.5 to 1.2 ppbv (20–60%) in the polar Northern middle to upper stratosphere several days after the very large SPEs (López-Puertas *et al.*, 2005b). These enhancements were delayed because the most likely production mechanism $NO_2 + NO_3 + M \rightarrow N_2O_5 + M$ is relatively slow.

Chlorine nitrate ($ClONO_2$) was enhanced because of the previously discussed NO_2 increases speeding up the $ClO + NO_2 + M \rightarrow ClONO_2 + M$ reaction. López-Puertas *et al.* (2005b) showed polar Northern $ClONO_2$ enhancements of a maximum of about 0.4 ppbv (40%) near 32 km.

4. Satellite Measurements of ClO and HOCl Constituents Change from SPEs

Envisat MIPAS measurements showed significant increases of ClO and HOCl in Oct–Nov 2003 (von Clarmann *et al.*, 2005). These observations gave indirect proof of enhanced HO_x abundances as a result of the large SPEs in late October 2003. Northern polar ClO increased by 0.2 to 0.4 ppbv and HOCl increased by 0.3 ppbv at altitudes above 32 km (von Clarmann *et al.*, 2005). These measurements, along with the observed $ClONO_2$ enhancements discussed in Section 3.2, suggest that HCl was destroyed either through reaction with OH or via ion cluster chemistry (von Clarmann *et al.*, 2005).

5. Satellite Measurements of Ozone Changes from SPEs

Several satellite instruments measured ozone decreases during solar cycle 23 as a result of SPEs including the UARS HALOE; NOAA 14 and 16 Solar Backscatter Ultraviolet 2 (SBUV/2) instruments; POAM III; Envisat GOMOS, MIPAS and Scanning Imaging Absorption spectrometer for Atmospheric ChartograpHY (SCIAMACHY); and Odin OSIRIS. Substantial mesospheric and upper stratospheric ozone decreases during and after the July 2000 SPE were measured by UARS HALOE and NOAA 14 SBUV/2 (Jackman *et al.*, 2001). Randall *et al.* (2001) used POAM III observations to show middle stratospheric ozone decreases in September 2000 as a result of the July 2000 SPE.

The most-studied period (to date) of ozone decreases as a result of SPEs occurred in October 26–November 7, 2003. Seppala *et al.* (2004) and Verronen *et al.* (2005) showed long lasting ozone depletions of 20 to 60% in the Northern Hemisphere polar lower mesosphere and upper stratosphere as a result of the events using Envisat GOMOS. Jackman *et al.* (2005a) found short-term ozone depletions of 40% in the Southern Hemisphere polar lower mesosphere with ozone depletions of 5–8% lasting days beyond the events in the upper stratosphere using NOAA 16 SBUV/2. The ozone decreases from a quiescent baseline day (October 25) over the October 28–November 1, 2003 disturbed period are given in Figure 2a.

López-Puertas *et al.* (2005a) showed significant polar lower mesosphere and upper stratosphere ozone decreases (10–70%) during the events using Envisat MIPAS. They also showed large differences between the two Hemispheres, with substantially more polar ozone depletion in the Northern (>20%) than in the Southern Hemisphere (5–10%). This interhemispheric difference is shown in this issue of *Space Science Review* in Figure 1 of Langen (2006), which is similar to that given in Figure 4 of López-Puertas *et al.* (2005a). Envisat SCIAMACHY measurements generally agreed with these Envisat MIPAS observations of ozone depletion (Rohen *et al.*, 2005).

6. Model Predictions of SPE Influences

Models have also been used to help interpret the influence of SPEs on the atmosphere during solar cycle 23. Jackman *et al.* (2001) model predictions showed reasonable agreement with measured NO_x enhancements and ozone depletions caused by the July 2000 SPE. Verronen *et al.* (2005) studied the diurnal variation of ozone de-

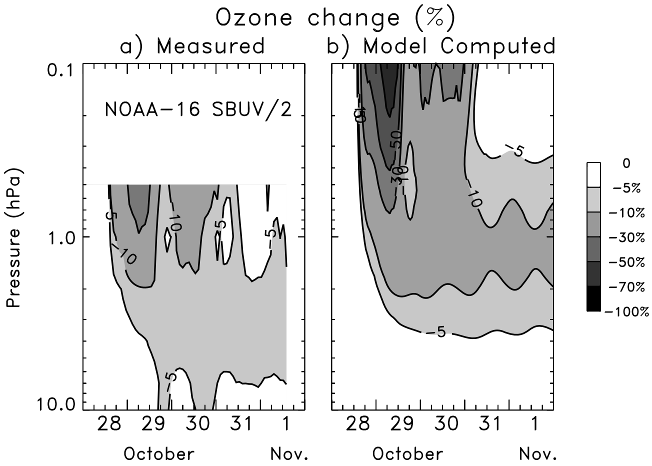

Figure 2. Percentage ozone change from October 25, 2003 values for the polar Southern Hemisphere from (a) NOAA 16 SBUV/2 measurements (top level of 0.5 hPa) and (b) the GSFC 2D model over the October 28–November 1, 2003 period. These plots show the influence of the Oct–Nov 2003 SPEs. Contour levels plotted are −5%, −10%, −30%, −50%, and −70%.

pletion during the Oct–Nov 2003 SPEs and found that maximum ozone depletions were predicted at the maximum solar zenith angles during sunrise and sunset, similar to the results that Solomon *et al.* (1983) obtained in predicting the July 1982 SPE atmospheric impact. Krivolutsky *et al.* (2003) calculated significant ozone depletion due to SPEs in July 2000, November 2000, September 2001, and November 2001. Krivolutsky *et al.* (2005) showed computations of ozone depletion for the three very large SPE periods in July 2000, November 2001, and Oct–Nov 2003.

The Jackman *et al.* (2005a) simulations using the Goddard Space Flight Center (GSFC) two-dimensional (2D) model for ozone decreases during and after the Oct–Nov 2003 very large SPEs are presented in Figure 2b. Huge ozone depletions (>70%) are calculated near 0.1 hPa on October 29 during the period of maximum proton flux intensity (see Figure 1). The short-lived depletion is caused by the enhanced HO_x constituents, which last only during and for a few hours after the events. The longer-lived ozone depletion between about 0.3 and 3 hPa is caused by the NO_y family. The modeled ozone change is in reasonable agreement during the SPEs. After the SPEs, the computed ozone change is slightly higher (lower) than that measured for the 0.3 to 2 hPa (2 to 7 hPa) altitude region. Ozone is also undergoing other changes at this time of year not connected with the SPEs, thus the apparent model/measurement disagreement does require further analysis.

It is important to note that the UARS HALOE measured and GSFC 2D model computed NO_x changes are in fairly good agreement in the lower mesosphere and upper mesosphere over the October 30 to November 7 period (Jackman *et al.*, 2005a). The long-lived NO_x enhancements drive the ozone changes over the months after the very large SPEs.

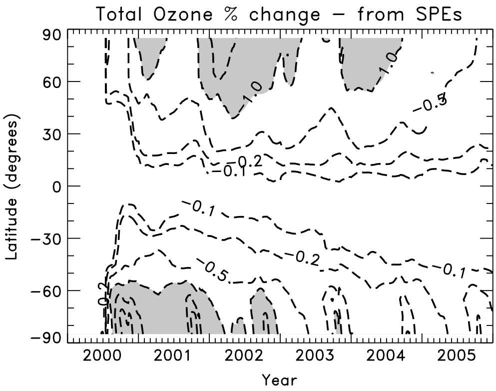

Figure 3. Model computed percentage total ozone changes from 2000–2005 resulting from SPEs in 2000–2003. Contour intervals are −3%, −2%, −1%, −0.5%, −0.2%, and −0.1%. The gray highlighted areas indicate total ozone decreases greater than 1%. Taken from Figure 4 of Jackman *et al.* (2005b).

Jackman *et al.* (2005a) and Rohen *et al.* (2005) both show model results confirming the very large interhemispheric differences observed in the Oct–Nov 2003 SPEs impacts on the middle atmosphere. These studies showed a much larger impact from these SPEs in the Northern than in the Southern Hemisphere. The NO_y family has a much longer lifetime in the late Fall/Winter than in the late Spring/Summer for two reasons:

1. the NO_y is lost through the mechanism $NO + h\nu$ (<191 nm) $\rightarrow N + O$ followed by $N + NO \rightarrow N_2 + O$, thus when the sunlight is intense (e.g., Summer and late Spring) the loss is greater;
2. the NO_y is transported to lower levels in the atmosphere where it is more effectively shielded from loss by sunlight.

Jackman *et al.* (2005b) simulated all the SPEs in the 2000–2003 period with the GSFC 2D model. The computed impact on total ozone in this simulation is shown in Figure 3 for the 2000–2005 time period. Total ozone is reduced by a maximum of about 3% in the polar Southern latitudes in late 2001 and 2002 that is primarily driven by the July 2000 SPE, a Winter SPE in this hemisphere. Both polar regions had extended periods of depleted ozone greater than 1% as a result of SPEs. Although the SPE-driven total ozone change is significant at polar latitudes, the computed annually-averaged global ozone change is fairly small (<0.5%).

7. Conclusions

Solar cycle 23 was extremely active with seven of the largest twelve SPEs in the past forty years recorded, especially in the years 2000, 2001, 2003, and 2005.

These events caused significant polar middle atmospheric changes that were observed by a number of satellites. The atmospheric impacts from the July 2000 and Oct–Nov 2003 SPEs were discussed in several papers published between 2001 and 2005. These SPEs produced both HO_x and NO_y constituents. Most of the substantial polar ozone decreases caused by the SPEs were short-lived and driven by the HO_x enhancements, however, the longer-lived ozone depletions caused by NO_y increases were observed to last for months past the events in the late Fall and Winter seasons. These longer term impacts from SPEs should be considered when quantifying other natural as well as anthropogenic influences on the middle atmosphere, especially near solar maximum in the polar regions.

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