The influence of the several very large solar proton events in years 2000–2003 on the neutral middle atmosphere

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Abstract

Solar proton events (SPEs) are known to have caused changes in constituents in the Earth’s polar neutral middle atmosphere. The past four years, 2000–2003, have been replete with SPEs. Huge fluxes of high energy protons entered the Earth’s atmosphere in periods lasting 2–3 days in July and November 2000, September and November 2001 and October 2003. The highly energetic protons produce ionizations, excitations, dissociations and dissociative ionizations of the background constituents, which lead to the production of HOx (H, OH, HO2) and NOy (N, NO, NO2, NO3, N2O5, HNO3, HO2NO2, ClONO2, BrONO2). The HOx increases lead to short-lived ozone decreases in the polar mesosphere and upper stratosphere due to the short lifetimes of the HOx constituents. Large mesospheric ozone depletions (>70%) due to the HOx enhancements were observed and modeled as a result of the very large July 2000 SPE. The NOy increases lead to long-lived stratospheric ozone changes because of the long lifetime of the NOy family in this region. Polar total ozone depletions >1% were simulated in both hemispheres for extended periods of time (several months) as a result of the NOy enhancements due to the very large SPEs.

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1. Introduction

Explosions on the Sun sometimes result in large fluxes of high-energy solar protons at the Earth, especially near Solar Maximum. This period of time, when the solar proton flux is generally elevated for a few days, is known as a solar proton event (SPE). Solar cycle 23 experienced a large number of extremely energetic SPEs in years 2000–2003. Huge fluxes of high-energy protons occurred in July and November 2000, September and November 2001 and October 2003.

Solar protons are guided by the Earth’s magnetic field and impact both the northern and southern polar cap regions (>60° geomagnetic latitude), e.g., see Jackman and McPeters (2004). These protons can impact the neutral middle atmosphere (stratosphere and mesosphere) and produce ionizations, dissociative ionizations and excitations. Both HOx (H, OH, HO2) and NOy (N, NO, NO2,
NO₃, N₂O₅, HNO₃, HO₂NO₂, ClONO₂, BrONO₂) constituents are produced either directly or through a photochemical sequence (e.g., Swider and Keneshea, 1973; Crutzen et al., 1975; Jackman et al., 1980; Solomon et al., 1981; McPeters, 1986; Zadorozhny et al., 1992). Ozone is also impacted by the solar protons through direct photochemical destruction forced by the HOₓ and NOᵧ enhancements (e.g., Weeks et al., 1972; Heath et al., 1977; Solomon et al., 1983; Jackman et al., 1990).

The SPEs that occurred in years 2000-2003 were noteworthy and details of their atmospheric response, including both satellite measurements and model predictions are included in this discussion. The paper is divided into six primary sections, including the introduction. We discuss the very important solar proton measurements and their production of odd hydrogen (HOₓ) and odd nitrogen (NOᵧ) in Section 2. A comparison of the SPEs in solar cycle 23 with some of the largest in past solar cycles is also undertaken in Section 2. The Goddard Space Flight Center (GSFC) two-dimensional (2D) model used to simulate the impact of the SPEs on the atmosphere is discussed in Section 3. The short-term impact of these SPEs on ozone during and for several days after particular events is given in Section 4. Longer term influences of the SPEs on the middle atmosphere are discussed in Section 5. Finally, the conclusions are given in Section 6.

2. Proton fluxes; odd hydrogen (HOₓ) and odd nitrogen (NOᵧ) production

Solar proton fluxes are measured by a few satellites in interplanetary space or in orbit around the Earth. The most accessible and useful proton flux data are available from the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) for the NOAA Geostationary Operational Environmental Satellites (GOES) [see http://sec.noaa.gov/Data/goes.html]. GOES proton fluxes are provided in several energy intervals (>1, >5, >10, >30, >50 and >100 MeV) at this site, updated every five minutes. GOES-8 data are considered most reliable for proton fluxes depositing energy into polar latitudes (private communication, Terry Onsager, NOAA SEC). GOES-8 data are, therefore, used for the periods January 1, 2000 to April 8, 2003; and May 10, 2003 to June 18, 2003. GOES-11 became the primary satellite for protons on June 19, 2003 and was used as the proton flux source through December 31, 2003. GOES-10 data was used to fill in the gap of missing proton flux data from April 9 through May 9, 2003.

The solar proton fluxes were used to compute daily average ion pair production profiles using the energy deposition methodology discussed in Vitt and Jackman (1996). Odd hydrogen (HOₓ) is formed through complicated ion chemistry (Solomon et al., 1981). Each ion pair is assumed to produce two HOₓ constituents up to an altitude of approximately 70 km. Above 70 km, the HOₓ production is assumed to be that provided by Solomon et al. (1981, Figure 2). The HOₓ constituents have lifetimes of only hours in the middle atmosphere, therefore, any further effects on other constituents from the HOₓ group are apparent only during and shortly after an SPE.

Atomic nitrogen is produced by the primary protons and associated secondary electrons causing dissociations, predissociations, or dissociative ionizations in collisions with N₂. Following Porter et al. (1976) and Jackman et al. (1980), we assume that 1.25 N atoms are produced per ion pair. The N atoms rapidly produce NO and other odd nitrogen (NOᵧ) constituents. Odd nitrogen has a relatively short lifetime (~days) in the sunlit middle and upper mesosphere, however, lower mesospheric and stratospheric NOᵧ can last for weeks past an SPE. A mostly dark middle atmosphere in the late fall and winter conserves a large portion of the SPE-produced NOᵧ, which can then be transported to lower altitudes via the general downward flowing winds during this time of year. The lifetime of this enhanced NOᵧ can range from months to years, if transported to the middle and lower stratosphere.

We have quantified middle atmospheric NOᵧ production before (Jackman et al., 1980, 1990; Vitt and Jackman, 1996) for years 1955 through 1993. We add NOᵧ computations in this study to these earlier calculations for years 1994 through 2003 and present the annual production from SPEs for the 49-year period 1955 through 2003 in Fig. 1. The source of proton flux data for years 2000 through 2003 was explained above. For the years 1994 through 1999 we use two satellites: (1) GOES-7 for the period January 1, 1994 through February 28, 1995; and (2) GOES-8 for the period March 1, 1995 through the end of 1999. The annual-averaged sunspot
number is also shown in Fig. 1 to illustrate the rough correlation between solar maximum periods and frequency of SPEs.

Solar cycle 23 was quite active with several very large SPEs (also, see Krivolutsky et al., 2003), especially in years 2000 (July and November), 2001 (September and two in November) and 2003 (October). Substantial amounts of NO₃ were produced in 2000, 2001 and 2003 with 1989 being the only year showing a larger production. The annual global NO₃ production from solar protons is computed to be 6.7, 7.9, 1.2 and 4.1 x 10³³ molecules for years 2000, 2001, 2002 and 2003, respectively. These annual production rates from SPEs can be compared with the largest global NO₃ source [nitrous oxide oxidation, N₂O + O¹(D)] of about 3.3 x 10³⁴ molecules/year (Vitt and Jackman, 1996). Clearly, the SPE source of NO₃ was significant for the middle atmosphere during solar cycle 23. Since the SPEs typically last only a few days, these impulses of NO₃ from SPEs can impact the polar odd nitrogen amounts substantially over brief periods (also, see Figs. 2 and 3).

The ten largest SPEs in the past 40 years are given in Table 1 with six of them occurring in the past solar maximum period.

### Table 1

<table>
<thead>
<tr>
<th>Date of SPEs</th>
<th>Rank in size</th>
<th>NO₃ production in the middle atmosphere (¹ of molecules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 19-27, 1989</td>
<td>1</td>
<td>6.7 x 10³³</td>
</tr>
<tr>
<td>August 2-10, 1972</td>
<td>2</td>
<td>3.6 x 10³³</td>
</tr>
<tr>
<td>July 14-16, 2000</td>
<td>3</td>
<td>3.5 x 10³³</td>
</tr>
<tr>
<td>October 28-31, 2003</td>
<td>4</td>
<td>3.4 x 10³³</td>
</tr>
<tr>
<td>November 5-7, 2001</td>
<td>5</td>
<td>3.2 x 10³³</td>
</tr>
<tr>
<td>November 9-11, 2000</td>
<td>6</td>
<td>2.3 x 10³³</td>
</tr>
<tr>
<td>September 24-30, 2001</td>
<td>7</td>
<td>2.0 x 10³³</td>
</tr>
<tr>
<td>August 13-26, 1989</td>
<td>8</td>
<td>1.8 x 10³³</td>
</tr>
<tr>
<td>November 23-25, 2001</td>
<td>9</td>
<td>1.7 x 10³³</td>
</tr>
<tr>
<td>September 2-7, 1966</td>
<td>10</td>
<td>1.2 x 10³³</td>
</tr>
</tbody>
</table>

* a The number reported here for the July 2000 SPE is slightly larger than that reported in Jackman et al. (2001). GOES-8 proton fluxes were used in this work, whereas GOES-10 proton fluxes were used in Jackman et al. (2001).

3. Goddard Space Flight Center two-dimensional model

The latest version of the GSFC 2D atmospheric model was used to predict atmospheric changes caused by the solar protons. The model has been in use since the late 1980s and has undergone extensive improvements over the years (Douglass et al., 1989; Jackman et al., 1990). Fleming et al. (2002) describes the methodology to compute the transport for the GSFC 2D model. This technique uses the global winds and temperatures from the United Kingdom Meteorological Office (UKMO) data assimilation system for the years 1992–2000. The photochemical reaction rates have been recently updated to Sander et al. (2003). The GSFC 2D chemistry solver has been improved and now uses the Atmospheric Environmental Research (AER) 2D model scheme (Weisenstein et al., 1991, 2004; Rinsland et al., 2003). The new chemistry solver computes a diurnal cycle every day and provides for a more accurate simulation of atmospheric constituents.

4. Short-term atmospheric influences from solar proton events

We used the GSFC 2D model to compute two primary simulations, “base” and “perturbed,” for the...
years 1998 through 2005. The transport for years 1998–2000 is driven by the UKMO products for those particular years, whereas the transport for the individual years 2001–2005 is a repeat of that derived for 2000. The “base” simulation includes no SPEs, whereas the “perturbed” simulation includes all SPEs from January 1, 2000 through December 31, 2003. The perturbation to the atmosphere was caused by the SPE-produced HOx and NOy enhancements.

We show the HOx production (in # cm⁻³ s⁻¹), ozone depletion (in percent) and NOx (NO + NO₂) enhancement (in ppbv) in Fig. 2 as a result of the extremely large solar proton event that started on July 14 (Bastille Day) in 2000. The model computations are compared with Upper Atmosphere Research Satellite (UARS) HALo- gen Occultation Experiment (HALOE) ozone and NOx measurements. The HALOE observed constituent changes during July 14–18 were calculated by comparing to the background atmospheric amounts before the SPE, defined as the average of the July 12–13 measurements. The produced HOx constituents drive practically all the ozone depletion in the mesosphere and the upper stratosphere during the event. There are several HOx catalytic destruction cycles for ozone. An example of one that is important in the middle and upper mesosphere is

$$\text{H} + \text{O}_3 \rightarrow \text{OH} + \text{O}_2$$

$$\text{OH} + \text{O} \rightarrow \text{H} + \text{O}_2$$

Net : $$\text{O}_3 + \text{O} \rightarrow \text{O}_2 + \text{O}_2$$

Other HOx catalytic cycles are important in the lower mesosphere and upper stratosphere including

$$\text{OH} + \text{O}_3 \rightarrow \text{HO}_2 + \text{O}_2$$

$$\text{HO}_2 + \text{O} \rightarrow \text{OH} + \text{O}_2$$

Net : $$\text{O}_3 + \text{O} \rightarrow \text{O}_2 + \text{O}_2$$

as well as others. HOx constituents have a relatively short atmospheric lifetime and the constituents react with one another through several reactions, resulting in mutual destruction. One of the largest HOx loss reactions is

$$\text{OH} + \text{HO}_2 \rightarrow \text{H}_2\text{O} + \text{O}_2$$

The HOx constituents produced by the SPEs are destroyed within hours of formation. The ozone loss associated with the proton-produced HOx proceeds during and for several hours after an event (Figs. 2(a)–(c)).

The NOx enhancement can cause some of the depletion in the upper stratosphere and lower mesosphere during the event, but forces all of the ozone depletion after July 16 (Figs. 2(c)–(e)). Ozone is reduced by the NOx constituents through the following primary catalytic destruction cycle:

$$\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2$$

$$\text{NO}_2 + \text{O} \rightarrow \text{NO} + \text{O}_2$$

Net : $$\text{O}_3 + \text{O} \rightarrow \text{O}_2 + \text{O}_2$$

NOx constituents typically have longer lifetimes than HOx constituents. The primary loss mechanism for NOx in the upper stratosphere and lower mesosphere is

$$\text{NO} + \text{hv} (< 191 \text{ nm}) \rightarrow \text{N} + \text{O}$$

followed by

$$\text{N} + \text{NO} \rightarrow \text{N}_2 + \text{O}$$

This two-step loss mechanism can be fairly fast in the Summer upper mesosphere, but can be significantly slower during other seasons or at lower altitudes where the ultraviolet flux is reduced. For example, the lifetime of Summer polar NOx constituents can range from days in the upper mesosphere to weeks in the upper stratosphere.

The ozone changes are similar between HALOE measurements and model computations during the maximum intensity of the July 14–16, 2000 SPE. Both measurements and model calculations show a maximum of about 70% depletion in the middle and upper mesosphere on July 15, which is almost wholly caused by the HOx constituents. The model computed ozone depletions in the lower mesosphere and upper stratosphere are larger than that measured by HALOE on July 16 (late in the day) and on July 17–18 (see Figs. 2(b) and (c)), which are entirely caused by the NOx constituents. The ozone reduction by SPE-enhanced HOx is thus fairly reasonably simulated, whereas the ozone reduction by SPE-enhanced NOx may have difficulties. It is possible that the HALOE measured ozone change is underestimated due to some long-term transport-driven change that occurred over a few days.

Clearly, the HALOE and modeled NOx are enhanced in the mesosphere and upper stratosphere on July 17–18 (Figs. 2(d) and (e)) by the extremely large SPE. These NOx enhancements should lead to a reduced ozone, which is simulated by the model in Fig. 2(c). The computed enhanced NOx is somewhat larger than measured in the middle and upper mesosphere on July 17–18, but is similar to the observed NOx in the lower mesosphere and upper stratosphere during these two days.

5. Long-term atmospheric influences from solar proton events

Over the course of a few days, the enhancements of NO and NO₂ from SPEs elevate the amount of other NOx constituents. As noted above, the NOy family has a lifetime of months to years if transported to the middle and lower stratosphere. Transport to lower altitudes is especially effective in the middle to late Fall and Winter,
when the middle atmospheric winds are directed polewards and downwards.

Four very large SPEs occurred in the northern middle to late Fall time period (see November 2000, November 2001 and October 2003 in Table 1). The SPE-related NOx enhancements were thus produced at an opportune time to be conserved for a very long period of time. We computed the percentage change of NOx and ozone in the northern polar latitudes (50–90°N) for years 2000–2005 and present the results in Fig. 3. NOx enhancements of greater than 100% are noted on several occasions in the upper stratosphere and lower mesosphere, however, the SPE-caused NOx increases in the middle to late Fall periods lead to much larger and longer-lasting middle and lower stratospheric enhancements. Much of the northern polar middle stratosphere has computed NOx enhancements of >10% in 2001, 2002 and 2004 as a result of the middle to late Fall very large SPEs. These periods are highlighted in gray in Fig. 3 (upper plot). The increased NOx led to a northern polar stratospheric ozone depletion for extended periods. SPE-caused depletions in ozone greater than 2% are highlighted in gray in Fig. 3 (lower plot) to show the scope of this effect.

The impact on total ozone is shown in Fig. 4. Total ozone is reduced by a maximum of about 3% in late 2001 and 2002. Much of this depletion was caused by the huge amount of NOx, produced by the July 2000 SPE in the Winter, which was conserved and transported downwards (Randall et al., 2001), where it steadily reduced ozone over a period of a few months. This July 2000 SPE-enhanced stratospheric NOx was slowly reduced over time, however, other large SPEs also added to the NOx reservoir in both the southern and northern hemispheres. Both polar hemispheres had extended periods of depleted ozone greater than 1% (highlighted in gray) as a result of SPEs.

Did the SPEs in solar cycle 23 make a difference in the calculated ozone trends? The latest ozone assessment (WMO, 2003) focused on near-global (60°S–60°N) total ozone trends and found decreases of approximately 3% from a 1964–1980 average to a 1997–2001 average. Our computed annually-averaged near-global total ozone depletion from SPEs was about 0.1% in 2000 and 0.3% in 2001, relatively modest perturbations that probably did not add significantly to the trend given in WMO (2003).

6. Conclusions

Six very large SPEs occurred in solar cycle 23 and caused very significant perturbations in the polar middle atmospheric regions. These SPE-caused influences were quite substantial (e.g., >70% ozone destruction), but also very short-lived (~days) in the middle and upper mesosphere. The SPE-produced HOx likely caused the ozone depletions in this atmospheric region. The NOx enhancements from the SPEs caused some ozone depletion on a short-time scale (days) during the events in the lower mesosphere and upper stratosphere. However, much of the NOx lasted for a longer time period of months past the very large SPEs. Longer-lived ozone destruction was connected to SPE-enhanced NOx. Total
ozone depletions greater than 1% were computed for both northern and southern polar hemispheres.

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References


