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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 HO_x (H, OH, HO_2) and NO_y (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$, $BrONO_2$). The HO_x increases lead to short-lived ozone decreases in the polar mesosphere and upper stratosphere due to the short lifetimes of the HO_x constituents. Large mesospheric ozone depletions (>70%) due to the HO_x enhancements were observed and modeled as a result of the very large July 2000 SPE. The NO_y increases lead to long-lived stratospheric ozone changes because of the long lifetime of the NO_y 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 NO_y enhancements due to the very large SPEs.

Keywords: Solar particle events; Odd nitrogen; Ozone; Middle atmosphere

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, wherein 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 HO_x (H, OH, HO_2) and NO_y (N, NO, NO_2,

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NO_3, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$, $BrONO_2$) 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 HO_x and NO_y 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 (HO_x) and odd nitrogen (NO_y) 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 (HO_x) and odd nitrogen (NO_y) 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 (HO_x) is formed through complicated ion chemistry (Solomon et al., 1981). Each ion pair is assumed to produce two HO_x constituents up to an altitude of approximately 70 km. Above 70 km, the HO_x production is assumed to be that provided by Solomon et al. (1981, Figure 2). The HO_x constituents have lifetimes of only hours in the middle atmosphere, therefore, any further effects on other constituents from the HO_x 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 N_2. 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 (NO_y) constituents. Odd nitrogen has a relatively short lifetime (~days) in the sunlit middle and upper mesosphere, however, lower mesospheric and stratospheric NO_y 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 NO_y, which can then be transported to lower altitudes via the general downward flowing winds during this time of year. The lifetime of this enhanced NO_y can range from months to years, if transported to the middle and lower stratosphere.

We have quantified middle atmospheric NO_y production before (Jackman et al., 1980, 1990; Vitt and Jackman, 1996) for years 1955 through 1993. We add NO_y 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

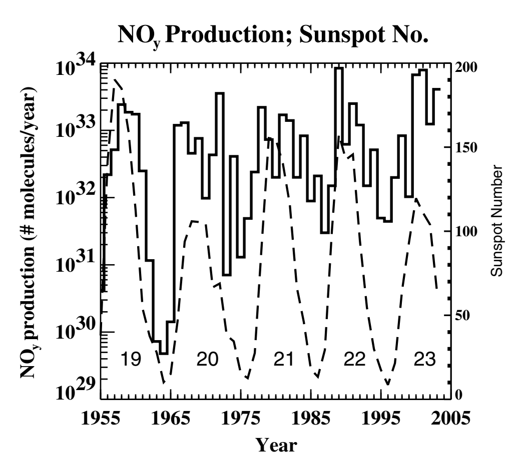

Fig. 1. Total number of NO_y molecules produced per year in the polar stratosphere and mesosphere by SPEs (solid histogram – left ordinate) and annually-averaged sunspot number (dashed line – right ordinate) for years 1955 through 2003.