Solar proton events of October–November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat

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Received 19 July 2004; revised 3 September 2004; accepted 21 September 2004; published 13 October 2004.

[1] Observations of O_3 and NO_2 made by the GOMOS instrument on board European Space Agency's Envisat satellite have been used to monitor the increase of NO_2 and depletion of ozone due to the solar proton events of October–November 2003. For the first time this phenomenon was measured in polar winter conditions by a satellite instrument. Results show NO_2 enhancement of several hundred per cent and tens of per cent ozone depletion between 36 and 60 km, an effect which lasts several months after the events. A comparison of the after-event concentrations of NO_2 and ozone reveals a strong negative correlation. INDEX TERMS: 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 2455 Ionosphere: Particle precipitation; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Seppälä, A., P. T. Verronen, E. Kyrölä, S. Hassinen, L. Backman, A. Hauchecorne, J. L. Bertaux, and D. Fussen (2004), Solar proton events of October–November 2003: Ozone depletion in the Northern Hemisphere polar winter as seen by GOMOS/Envisat, Geophys. Res. Lett., 31, L19107, doi:10.1029/2004GL021042.

1. Introduction

[2] Solar proton events (SPE) correspond to solar coronal mass ejections (CME) during which a large amount of protons and heavier ions are emitted, sometimes toward the Earth. Solar protons entering the Earth's magnetosphere are guided by the Earth's magnetic field and precipitate into the polar cap areas. Since the protons can have very high energy, up to tens of MeVs, they deposit their energy in the mesosphere and stratosphere. Thus they provide a direct connection between the Sun and the Earth's middle atmosphere. SPEs are sporadic although more probable during solar maxima. But when occurring they provide extreme forcing on the middle atmosphere.

[3] The precipitating particles produce 1) odd hydrogen HO_x ($H + OH + HO_2$) through chemistry associated with ion pair production, water cluster ion formation, and subsequent neutralization, and 2) odd nitrogen NO_x ($N + NO + NO_2$) through dissociation of molecular nitrogen via charged particle impact [Crutzen et al., 1975; Solomon et al., 1981; Rusch et al., 1981]. HO_x and NO_x play a key role in ozone balance of the middle atmosphere because they destroy odd oxygen through catalytic reactions [see, e.g., Brasseur and Solomon, 1986, pp. 291–299]. The produced HO_x has a relatively short lifetime, but without solar radiation NO_x chemical loss is inefficient. Therefore the NO_x produced during polar night has a long chemical lifetime and is transported to lower altitudes and latitudes [Siskind et al., 1997; Callis and Lambeth, 1998]. Significant depletions of ozone concentrations after large solar proton events have been predicted by atmospheric modelling [Rusch et al., 1981; Solomon et al., 1983; Reid et al., 1991; Jackman et al., 2000] and this phenomenon has been captured in the dayside middle atmosphere using satellite measurements [Thomas et al., 1983; McPeters and Jackman, 1985; Jackman et al., 2001; Randall et al., 2001].

[4] The GOMOS (Global Ozone Monitoring by Occultation of Stars) instrument measures vertical profiles of several middle atmospheric gases, including O_3 and NO_2. GOMOS makes several hundred occultations per day with good global coverage, including the polar areas. It can measure in both day and night conditions because the stellar occultation technique does not require solar radiation. Therefore, GOMOS has a unique capability of observing the effects of SPEs during polar winter. In this paper, we use GOMOS measurements from the northern hemisphere during and after the October–November 2003 SPEs to confirm the increase/persistence of NO_2 and depletion of O_3 due to the events.

2. Solar Storms on October–November 2003

[5] Late October 2003 the Sun released two powerful X-class solar flares both associated with a CME directed almost straight at the Earth. Consequently the flux of particles entering the Earth's atmosphere was greatly enhanced. During October–November 2003 there were four occasions of noticeable increase in the proton flux (NOAA NGDC–Solar Terrestrial Physics, 2004, see http://www.ngdc.noaa.gov/stp/stp.html). First on October 26th and second on the 28th, then again on November 2nd and 4th. The first event was caused by a solar X1-class flare and associated CME. This event lasted only few hours, but only a day later a second flare, this time even larger X17 followed by a halo-type CME led to measured maximum

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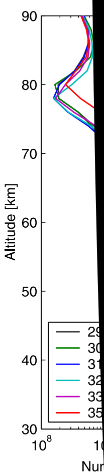

Figure 1. [redacted]
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3. GOMO[redacted]

[6] GOMO[redacted]
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[8] For this study we used nighttim[redacted] measure-ments from the northern hemisphere polar region (GOMOS processing prototype version 6.0a, geographic latitude ≥45°, solar zenith angle ≥107°, and solar zenith angle at satellite location >90° to avoid straylight conditions). In

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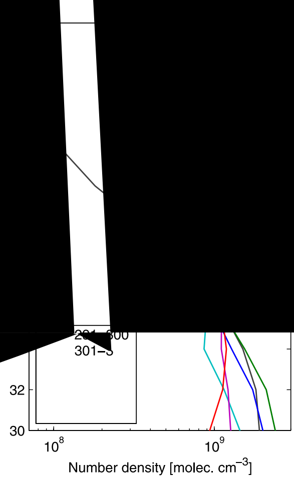


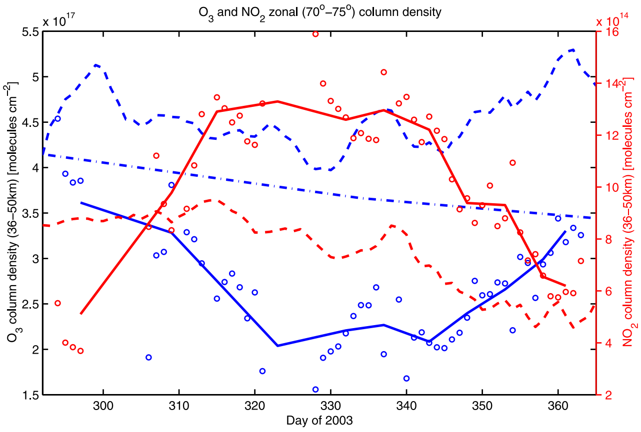


Figure 3. O_3 (blue) and NO_2 (red) column densities. Daily (circle) and 5-day mean (solid line) calculated from GOMOS daily zonal average profiles for latitudes 70°–75° and altitudes 36–50 km. The dash-dot line is [Fortuin and Kelder, 1998] O_3 column (36–50 km) for latitude 72.5° and the dashed lines are O_3 and NO_2 columns (37–47 km) from the FinRose-CTM model. The FinRose-CTM model includes no SPE forcing.

the event and exceed the modelled values. At the end of December the values are still over 50% larger than before the October 28. The observed ozone column decrease coincides with the NO_2 column enhancement and the correlation coefficient r for the Oct–Dec daily O_3 and NO_2 columns is −0.77 indicating a strong negative correlation.

[12] The temporal evolution of O_3 and NO_2 at 46 km (latitudes ≥45°) is shown in Figure 4 together with the measurement locations. Before Oct 28 the ozone values are in agreement with the climatology values. After the 28th the density decreases particularly near the magnetic polar area. The ozone depletion area near the end of December is restricted between longitudes ~±80°. Comparing the O_3 and NO_2 maps we notice that the areas of largest ozone depletion coincide with the areas where NO_2 enhancement is most significant. To verify this we calculated correlation coefficients for the NO_2 and O_3 measurements at 46 km for 5-day periods. Figure 5 shows the measured values for one time period and variation of the correlation coefficient during Oct–Dec and the number of measurements used to calculate each correlation. Before the SPEs NO_2 and O_3 are positively correlated. However, after the SPEs they become strongly negatively correlated with r approaching a value of −0.8.

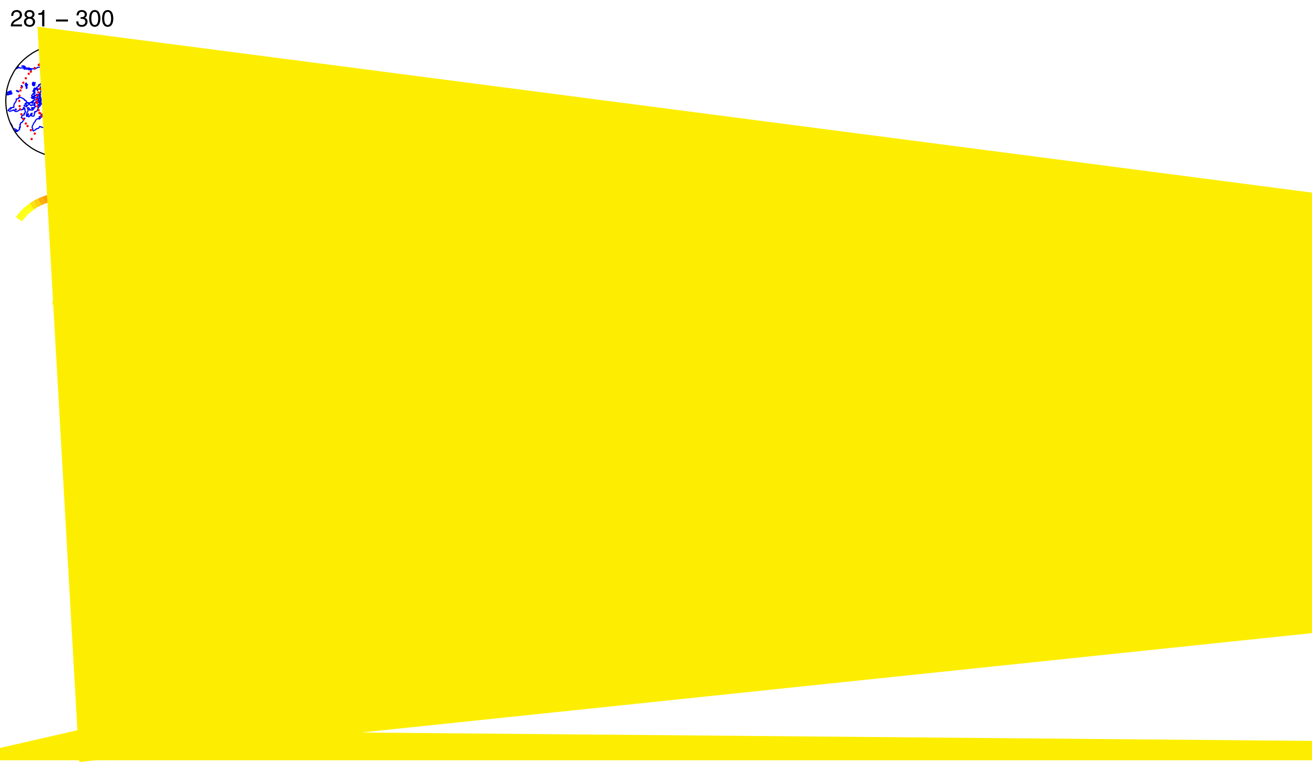
5. Discussion

[13] GOMOS observations show significant changes in NO_2 and ozone due to the October–November 2003 solar proton events. An order-of-magnitude increase in NO_2 results in up to 60% ozone depletion in the upper stratosphere. Even two months after the SPEs the effect can still be seen. This is the first time that SPE effects have been observed in the polar winter middle atmosphere with a good spatial and temporal coverage.

[14] NO_2 and NO participate in the catalytic reaction cycle which destroys ozone but neither creates nor destroys odd nitrogen. Therefore, in general it might be more beneficial to observe changes in the sum NO + NO_2. However, in the nighttime stratosphere and lower mesosphere practically all NO is converted to NO_2. Therefore we are confident that our nighttime NO_2 measurements are a good tracer for the total odd nitrogen changes.

[15] Ozone is also affected by HO_x production during the events. However, this effect should be present only for a few days after the events, i.e., between Oct 26 and Nov 5 (days 299–310), because of the relatively short lifetime of HO_x in the upper stratosphere. Therefore, after day 310 we can assume that the effect on ozone is solely due to the increase of NO_x.

[16] The correlation between the concentrations of NO_2 and ozone is positive before the SPEs (Figure 5). FinRose results, as well as GOMOS measurements (January, 2003, and early October, 2003) confirm that without the SPEs the correlation is positive, possibly reflecting the same latitudi-



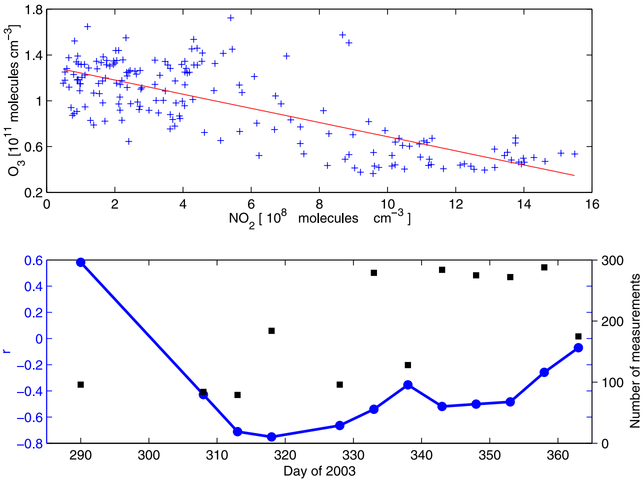


Figure 5. Correlation of NO_2 and ozone at altitude 46 km (latitudes $\geq 45°$). Upper panel: Measured NO_2 and O_3 number densities (days 316–320). The red line is a first degree polynomial fit to the data points. Lower panel: Correlation coefficient r for 5-day periods (blue circles) and the number of used measurements (black squares).

nal dependence of NO_2 and O_3. The correlation becomes strongly negative after the SPEs indicating a large increase in NO_2 and resulting ozone depletion.

[17] An interesting feature in Figure 1 is the increase of O_3 at 60–75 km after the events (days 311–340). The reason for this increase is presumably the development of the tertiary ozone maximum, which is known to exists in the high-latitude mesosphere [Marsh et al., 2001].

[18] The MIMOSA advection model [Hauchecorne et al., 2002] shows that when the SPEs occurred, the polar vortex was well formed in the upper stratosphere and almost coincident with the polar cap (not shown here). Most of the air with depleted ozone and enhanced NO_2 is located within the polar vortex as long as it is stable. The descent of NO_2 peak (Figure 2) is clearly related to the diabatic descent in the vortex which is very strong at the beginning of the winter. The rate of descent is few km/10 days, which is comparable to values reported by Eluszkiewicz et al. [1996] and Summers et al. [1997]. At the end of December, the dynamical situation changed and a sudden warming occurred in the upper stratosphere. As a result, the vortex was displaced from the pole and the latitude band 70°–75° no longer was fully inside the vortex. This explains the rapid increase of O_3 at this time between 40 and 60 km (Figure 1, days 351–360).

[19] It would be interesting to study the effects of these SPEs also in the southern hemisphere. There we would expect only a short-term decrease of ozone, mainly due to an increase of HO_x, because in summer the increase in NO_x is quickly balanced by photodissociation. When GOMOS data for 2004 becomes available, we will continue this study and follow the evolution of NO_2 and ozone throughout the polar night.

[20] **Acknowledgment.** The work of AS was supported by the Academy of Finland (MAIST: Middle Atmosphere Interactions with Sun and Troposphere).

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