Northern Hemisphere atmospheric effects due to the July 2000 solar proton event

Charles H. Jackman, Richard D. McPeters, Gordon J. Labow[1], Eric L. Fleming[1]

NASA Goddard Space Flight Center, Greenbelt, Maryland

Cid J. Praderas

Emergent Information Technologies, Inc., Arlington, Virginia

James M. Russell

Hampton University, Hampton, Virginia

Abstract. The third largest solar proton event in the past thirty years took place during July 14-16, 2000, and had a significant impact on the earth's atmosphere. These energetic protons produced both HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) constituents in the mesosphere and upper stratosphere at polar latitudes (> 60° geomagnetic) of both hemispheres. The temporal evolution of increases in NO and NO_2 during the event at northern polar latitudes were measured by the UARS HALOE instrument. Increases in mesospheric NO_x of over 50 ppbv were found in the HALOE measurements. Measurements from the UARS HALOE and NOAA 14 SBUV/2 instruments indicate short-term (~day) middle mesospheric ozone decreases of over 70% caused by short-lived HO_x during the event with a longer-term (several days) upper stratospheric ozone depletion of up to 9% caused by longer-lived NO_x. We believe this is the first time that the three constituents NO, NO_2, and ozone were all measured simultaneously during a proton event. The observations constitute a dramatic confirmation of the impact of a large particle event in the control of ozone in the polar middle atmosphere and offer the opportunity to test theories of constituent changes driven by particle precipitation.

1. Introduction

A solar flare with an associated coronal mass ejection occurred in mid-July 2000 and caused a solar proton event (SPE). Not since October 1989 has the Earth's atmosphere been subjected to such an intense flux of solar protons. These solar events are natural occurrences that produce HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) constituents in the polar middle atmosphere, which are capable of influencing ozone.

The SPE-produced HO_x constituents are relatively short-lived and lead to short-term ozone decreases lasting several hours to a few days in the mesosphere and upper stratosphere [e.g., *Swider and Keneshea* 1973; *Frederick* 1976; *Solomon et al.,* 1983; *Jackman and McPeters*, 1985]. The longer-lived SPE-produced NO_x species may influence the stratosphere over periods of months to years, depending on the season in which the SPE occurred, and can impact ozone and the other NO_y constituents (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, $ClONO_2$, $BrONO_2$) over these time periods [e.g., *Rusch et al.,* 1981; *Jackman et al.,* 1990; *Reid et al.,* 1991; *Jackman et al.,* 2000].

The July 14-16, 2000, SPE caused very significant changes in middle atmospheric constituents during and after the event. The measured temporal influence of this SPE is captured in the UARS HALOE NO and NO_2 and the UARS HALOE and NOAA 14 SBUV/2 ozone observations at northern polar latitudes. To the best of our knowledge, this is the first time that the temporal behavior of the three constituents NO, NO_2, and ozone were all measured simultaneously during a proton event.

This SPE offers an opportunity to test theories of middle atmospheric photochemistry caused by a large particle precipitation event. The focus of this study is on the summer polar Northern Hemisphere (NH) constituent effects during and shortly after the July 2000 SPE. Significant effects in the polar Southern Hemisphere (SH) due to this large SPE, which occur weeks to months after the event, are discussed in Randall *et al.* [2001].

2. Observations of Northern Hemisphere Polar Atmospheric Influence

The July 2000 SPE impact on mesospheric ozone is illustrated in Figure 1, which shows the NH polar ozone maps from NOAA 14 SBUV/2 for the 0.5 hPa level. In order to produce a daily map, the SBUV/2 ozone data was interpolated along the orbital tracks and filled between successive orbits using the Delauney triangulation method discussed in Stolarski *et al.* [1997]. The plot on the left indicates ozone amounts on July 13, before the SPE. The plot on the right indicates ozone amounts on July 14-15, during the maximum intensity of the SPE. The polar cap (> 60° geomagnetic), where the solar protons are predicted to interact with the atmosphere, is indicated by the thick white oval. This figure illustrates the very significant reduction in the ozone amounts at this level in or near the polar cap during this SPE. The ozone reduction slightly outside the polar cap near 90°E longitude is probably caused by the Earth's magnetic

[1]Also at Science Systems and Applications, Inc., Lanham, Maryland.

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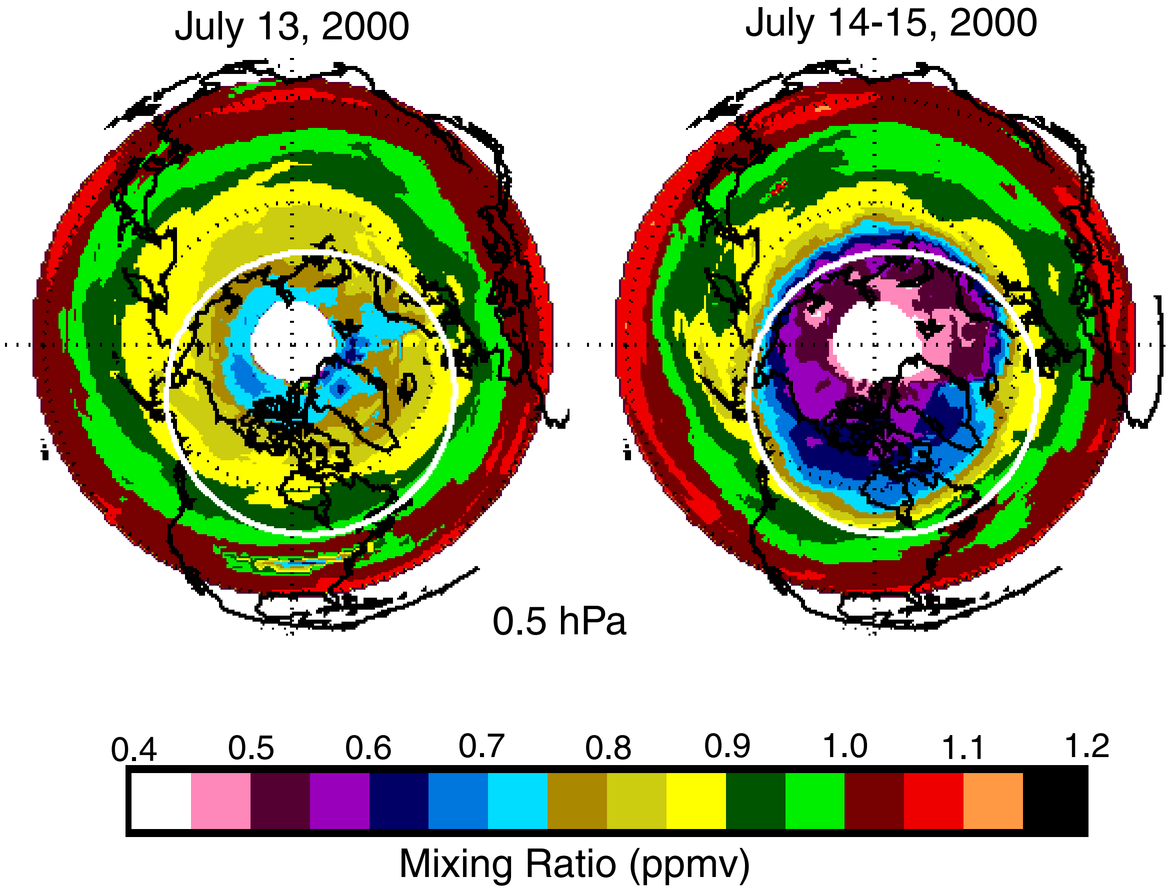

Figure 1. NOAA 14 SBUV/2 Northern Hemisphere polar ozone in ppmv before (July 13, 2000) and during (July 14/15) the SPE period at 0.5 hPa.

field being perturbed somewhat during this very significant solar disturbance.

The UARS HALOE instrument observed the Northern polar cap region during the period July 12-15, 2000. The impact of this event on the atmosphere at sunrise is shown in Figure 2 from the HALOE Version 19 observations for the north polar region on July 14-15. The HALOE observed constituent changes during July 14-15 were calculated by comparing to background atmospheric amounts before the SPE, defined as the average of the July 12-13 measurements. Although the HALOE measurements were taken at different longitudes and slightly different latitudes (65.4°N to 68.5°N) over the July 12-15 period, we found that the NO, NO_2, and ozone changes resulting from the July 2000 SPE dominated any geographically-caused differences.

Since the amounts of N are very small below 0.01 hPa, the HALOE measurements of the sum of NO and NO_2 are thought to be essentially total NO_x measurements and will be defined as such in this study. The increases in HALOE NO_x above background are illustrated in Figure 2a. The apparent enhancements in HALOE NO_x above 0.03 hPa during the first half of July 14 are probably related to other natural variabilities and not due to the SPE. Enhancements of NO_x greater than 50 ppbv and 200 ppbv are observed at 0.3 hPa and 0.01 hPa, respectively, near the end of July 15. Background NO_x levels are typically 1-5 ppbv at 0.3 hPa and 20-60 ppbv at 0.01 hPa, thus the NO_x increases caused by this SPE are very large.

Nitric oxide enhancements due to SPEs have been observed before at fixed times [*McPeters* 1986; Zadorozhny *et al.,* 1992]; however, HALOE provided the additional information of the temporal changes in middle atmospheric NO_x during the event.

Percentage decreases in the HALOE Version 19 ozone from the background amounts are presented in Figure 2c for July 14-15. HALOE observed ozone reductions start on July 14 and reach over 70% during most of July 15 in the middle mesosphere between 0.3 and 0.01 hPa.

The ozone changes for a suite of pressure levels within the polar cap and for solar zenith angles between 65° and 70° are indicated in Figure 3 from the SBUV/2 instrument. Although ozone depletions of about 35-40% are measured at 0.5 hPa during the SPE, the ozone returns to background values after the SPE. Longer term depletions (after July 15) of about 7, 9, and 5% are observed at the lower levels of 1, 2, and 4 hPa, respectively. An SBUV profile retrieval is usually considered fully valid from 30 hPa to 1 hPa. The ozone change at 0.5 hPa given in Figure 3 was likely somewhat larger than shown because of reduced sensitivity of the retrieval. Since the largest observed ozone changes are in the mesosphere and upper stratosphere, where the contribution to total column ozone is relatively small, the total ozone reductions associated with this event are small (<1%) in the polar NH.

The model results presented in Figures 2 and 3 will be discussed in section 4.

3. Proton Fluxes and NO_y Production

The solar protons, which caused the observed NO_x and ozone changes, were measured by instruments aboard the NOAA GOES-10 satellite and are available in several energy intervals from >1 MeV up to >100 MeV every five minutes during the July 14-16 time period. These data were accessed via the web at the NOAA site (http://sec.noaa.gov/Data/goes.html) and used in our proton energy deposition model [*Jackman et al.,* 1980] to compute hourly average ion pair production profiles. As in our previous studies [e.g., *Jackman et al.,* 1990], we assume that the solar protons deposit their energy uniformly at geomagnetic latitudes above 60°. This assumption seems to be fairly well substantiated, given the NOAA 14 SBUV/2 instrument measurements presented in Figure 1. The proton flux was also assumed to be the same in both hemispheres.

We used the computed ion pair production from the solar proton fluxes in the latest version of the GSFC 2-D atmospheric model [*Fleming et al.,* 1999; *Jackman et al.,* 2000] to predict the influence of this SPE on the Earth's polar atmosphere. Ion chemistry is not included, thus the production of HO_x constituents by the SPE was included following *Solomon et al.* [1981]. Each ion pair produces about two HO_x constituents up to an altitude of approximately 70 km with less HO_x constituents being produced per ion pair above 70 km [*Solomon et al.,* 1981, Figure 2]. A production of 1.25 N atoms per ion pair is assumed for all our model computations [e.g., see *Porter et al.,* 1976]. This source of N atoms increases the entire NO_y family, which are primarily NO_x constituents in the mesosphere and upper stratosphere.

Middle atmospheric NO_y production from SPEs has been quantified before [e.g., *Jackman et al.,* 1990; *Vitt and Jackman* 1996], thus it is possible to compare this large event to other past significant SPEs. We found that the July 2000 SPE, which was calculated to produce 2.7 x 10^{33} NO_y molecules globally, was the third largest solar event in the past thirty years. This event was only smaller than the October 1989 and the August 1972 SPEs, which were computed

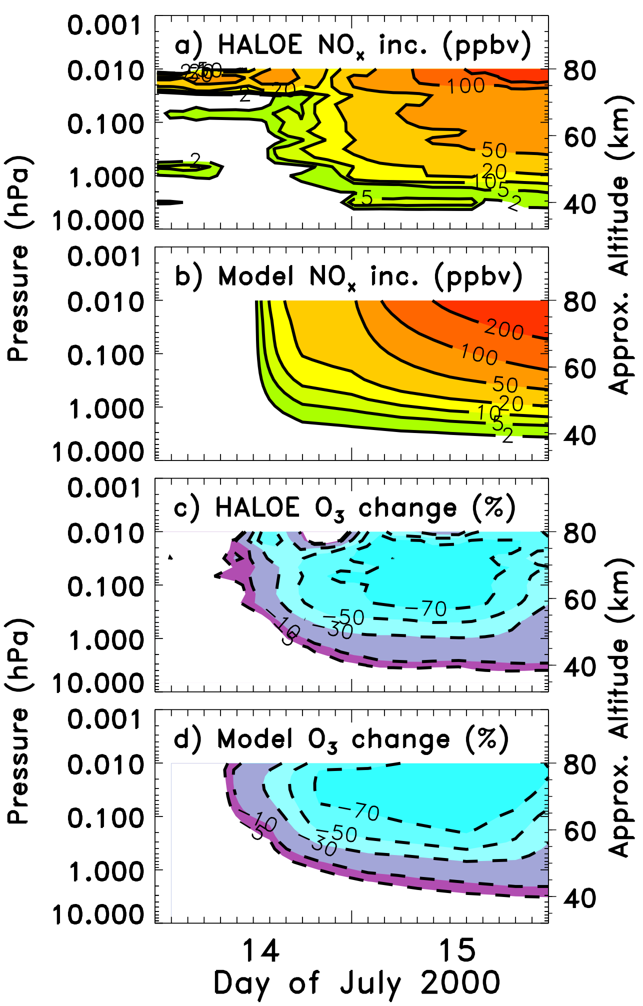

Figure 2. Polar Northern Hemisphere pressure versus time cross sections during the SPE period (July 14-15, 2000) for a) HALOE NO_x and b) model NO_x increases, both for contour levels 2, 5, 10, 20, 50, 100, and 200 ppbv; and c) HALOE ozone and d) model ozone decreases, both for contour levels of -5, -10, -30, -50, and -70%. The HALOE NO_x and ozone changes were computed by comparing to the background average of the July 12-13 observations.

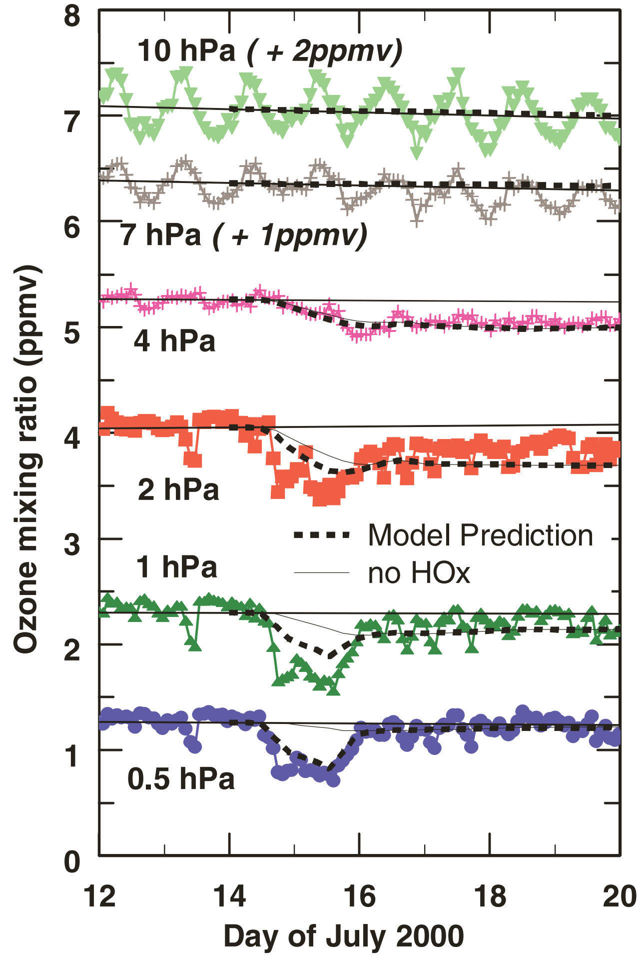

Figure 3. Polar Northern Hemisphere ozone observations from NOAA 14 SBUV/2 measurements and model computations for the 10, 7, 4, 2, 1, and 0.5 hPa levels during the July 12-19, 2000, time period. The colored symbols with connected color lines indicate the measurements and the horizontal solid lines indicate the average background using July 12-13 measurements. The dashed lines indicate the 2-D model predictions with both SPE-driven HO_x and NO_x increases included, while the thin solid lines indicate predictions excluding the SPE-driven HO_x increases.

to produce 6.7 x 10^{33} and 3.6 x 10^{33} NO_y molecules globally, respectively.

4. Model Predicted SPE Impact

The 2-D model predicted NO_x and ozone changes at sunrise for 65°N, approximately colocated with the HALOE data, are given in Figures 2b and 2d, respectively. The increase in the NO_x constituents from the SPE are predicted to be similar to the measurements in the stratosphere and lower mesosphere up to ∼0.3 hPa (see Figures 2a and 2b). In the middle and upper mesosphere (<0.3 hPa), the model predicts larger increases in the NO_x than observed. Further study of these model/measurement NO_x differences is needed, but is beyond the scope of this investigation.

The modeled ozone reductions of over 70% in the mesosphere are primarily caused by computed HO_x increases of over 100%. As seen in Figures 2c and 2d, the model computations of ozone decrease are similar to the HALOE measurements during most of the event.

The model predictions of ozone decreases at several stratospheric and lower mesospheric levels are indicated by the dashed lines in Figure 3. These calculated ozone changes were made within the polar cap and for solar zenith angles between 63° and 73°. The SBUV/2 measured ozone depletions due to this SPE are reasonably well simulated at several levels, however, the model appears to underestimate the depletion during the most intense period of the SPE at 1 and 2 hPa. For example, at 1 hPa the measurements and model indicate a maximum ozone depletion of 28% and 18%, respectively.

We investigated these model/measurement differences using proposed possible HO_x reaction rate adjustments discussed in *Conway et al.* [2000]. The adjustments for model cases B and C in *Conway et al.* [2000] resulted in better model/measurement agreement for OH in the mesosphere. However, both sets of HO_x reaction rate adjustments resulted in predictions of even less SPE-induced ozone depletion predicted at 1 and 2 hPa, than shown by the model computations in Figure 3. These model/measurement differences require a much more detailed analysis than is possible in this study.

For the July 16-20 period, the NO_x constituents are computed to increase by about 200, 55, and 15% at the 1, 2, and 4 hPa levels, respectively, as a result of the SPE for the July 16-20 period. Results from a model simulation, which included only the NO_x increases from the SPE (no HO_x effects), are indicated by the thin solid lines in Figure 3. It is clear that the NO_x increases cause the longer term ozone decreases observed at and below 1 hPa. The NO_x constituents have a fairly long lifetime in the summer polar NH upper stratosphere (several weeks). The influence of the SPE-produced long-lived NO_x constituents is, therefore, expected to last at least several weeks past the event [*Jackman et al.,* 2000].

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E. L. Fleming, C. H. Jackman, G. J. Labow, R. D. McPeters, Atmospheric Chemistry and Dynamics Branch, Code 916, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, (jackman@assess.gsfc.nasa.gov).

C. J. Praderas, Emergent Information Technologies, Inc., Arlington, VA, 22201.

J. M. Russell, Hampton University, Center for Atmospheric Sciences, Hampton, VA, 23668.

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