Abstract. Very large solar proton events (SPEs) occurred from October 19-27, 1989. These SPEs are predicted to produce short-lived increases in HOx and long-lived increases in NOx species, which both can lead to ozone destruction. December 1989 SBUV/2 measurements of upper stratospheric ozone show substantially more ozone depletion in the Northern than in the Southern Hemisphere even though the amount of HOx and NOx produced in both hemispheres should be similar from these SPEs. Our two-dimensional (2D) model simulations predict only a modest interhemispheric difference in the ozone depletion in December caused by the October 1989 SPEs. In an attempt to better understand the interhemispheric difference in the observed ozone depletion, we have used the GSFC three-dimensional (3D) chemistry and transport model to simulate the distribution of NOx and ozone after the SPEs. Our 3D model computations of ozone and NOx behavior for two months after the October 1989 SPEs indicate differences in the constituent behavior in the two hemispheres during the October-November-December 1989 time period which are qualitatively consistent with SBUV/2 ozone observations. These differences are caused by: 1) Substantial mixing of perturbed air in the Southern Hemisphere from the polar region with unperturbed lower latitude air during the November final warming; and 2) Significant confinement of the photochemically perturbed air in the Northern Hemisphere in the winter-time polar vortex.

Introduction

Solar proton events (SPEs) have been associated with measured ozone loss in several studies over the past 20 years [e.g., Weeks et al., 1972; Heath et al., 1977; McPeters et al., 1981; Thomas et al., 1983; Solomon et al., 1983; McPeters and Jackman, 1985]. The ozone depletion observed in most of these SPEs is believed to have primarily been caused by the HOx production during the SPEs. The HOx-caused ozone depletions are confined to the mesosphere and upper stratosphere and are relatively short-lived, since HOx lifetimes and ozone recovery times in this region are only on the order of hours. The August 1972 SPEs were the only events in the 1963-84 time period (solar cycles 20 and 21) that created enough NOx to cause a significant ozone depletion in the middle to upper stratosphere [e.g., Crutzen et al., 1975; Solomon and Crutzen, 1981; Reagan et al., 1981; Rusch et al., 1981; Jackman et al., 1990]. Solar cycle 22 has proved to be quite active with large SPEs recorded in 1989 in the months of March, August, September, and October.

Very large SPEs occurred from October 19-27, 1989. The HOx and NOx increases which result from these SPEs were predicted to lead to >20% depletions in upper stratospheric ozone at polar latitudes using two-dimensional (2D) models [Reid et al. 1991; Jackman and McPeters, 1991]. Transport of the long-lived NOx constituents in the middle and lower stratosphere is predicted in these 2D models to prolong the ozone depletion for several months to a year following the SPEs. Commensurate with these predictions were measurements of enhanced NOx at mid and low latitudes in the Northern Hemisphere from the October 1989 SPEs. In an attempt to understand the interhemispheric difference in ozone depletion even though the proton flux into the two hemispheres should have been roughly equal (McPeters et al., 1981).

Proton Flux Data and SPE Production of NOx

Proton fluxes from T. Armstrong and colleagues (University of Kansas, private communication, 1991) allow for daily computation of ion pair production and NOx production due to SPEs in 1989. These fluxes were measured on the IMP-8 satellite and are given in daily average differential form (units are cm−2 s−1 sr−1 MeV−1).

The protons were divided up into 60 monoenergetic energy intervals between 0.29 and 440 MeV, all assumed to be isotropic, and then were degraded in energy following Jackman et al. [1980] to give a daily average ion pair production profile. Since the HOx produced by SPEs is short-lived (lasting only hours after the events have abated) and we are interested in the longer-term ozone influence by the October 1989 SPEs, we will only consider the longer-lived NOx produced by the SPEs in our model simulations. We assume that 1.25 N atoms are produced per ion pair. This is similar to the value given by Porters et al. [1976], which was derived using a detailed theoretical energy degradation computation. The protons are assumed to enter the atmosphere uniformly for latitudes ≥60° geomagnetic.
Three-Dimensional Model Description

A global spectral mechanistic model generates the winds and temperatures which are used in the offline 3D transport simulation. The design and performance of the spectral model is similar to that of other stratospheric mechanistic models (e.g., O'Neil and Pope, 1988; Fairlie et al., 1990). That is, the model does not attempt to simulate the troposphere. Instead, the lower boundary is isobaric (100 hPa) and is continuously "mechanically stirred" with NMC observed geopotentials. This forces the vertically propagating planetary waves to conform to the observed spectrum in the lower stratosphere. The heating and cooling rates are provided by the radiative transfer scheme of Rosenfield et al. (1987). The 3D chemistry and transport model, CTM, (Allen et al., 1991; Rood et al., 1992) extends from 100 to 0.01 hPa and is operated upon the mechanistic model's thirty equally spaced (in log pressure) levels. With 80 equally spaced longitudes on 65 equally spaced latitudes, the CTM's horizontal grid closely approximates the horizontal resolution of the mechanistic model's Gaussian grid.

For the SPE experiment a simplified homogeneous photochemistry 3D model, which includes complete O$_3$, NO$_x$, and HO$_x$ chemistry with 9 photodissociation processes and 26 binary and tertiary reactions, was developed. Twelve minor constituents (O$_3$, O, O(1D), N, NO, NO$_2$, NO$_3$, N$_2$O$_5$, HNO$_3$, H, OH, and HO$_2$) are calculated in the model with four constituents/families being transported. The transported constituents include: 1) O$_3$ (O$_3$, O, O(1D)), 2) NO$_x$ (N, NO, NO$_2$, and NO$_3$), 3) N$_2$O$_5$, and 4) HNO$_3$. The HO$_x$ (H, OH, and HO$_2$) species are calculated using photochemical equilibrium assumptions. The stratospheric and mesospheric H$_2$O distribution is fixed to LIMS measurements where possible and is explained in a prior 2D modeling study [Jackman et al., 1987]. The N$_2$O distribution is taken from a 2D model simulation of October 23, 1989 - January 3, 1990.

We have omitted chlorine and bromine chemistry from these studies due to computational constraints. Reactions involving bromine species are important mainly in the lower stratosphere and are of minimal importance to this study. Omission of chlorine species increases the sensitivity of ozone to NO$_x$ since the interference of Cl$_x$ chemistry with the NO$_x$ chemistry is not included (especially the ClO + NO$_2$ + M --> ClNO$_2$ + M and the ClO + NO --> Cl + NO$_2$ reactions). Our 2D model simulations show that including chlorine species would reduce the ozone sensitivity to NO$_x$ more in winter, when ClNO$_2$ can build up in low sun conditions, than in summer. While our lack of complete chemistry is a barrier in simulating the correct quantitative changes in NO$_x$ and ozone which result from the SPEs, these 3D simulations should qualitatively reproduce the photochemical and dynamical processes which influence the ozone behavior.

The mechanistic model experiment was initialized on October 23, 1989 with NMC data and allowed to run until November 1 to generate a dynamically balanced wind field. This procedure is especially important in the tropics and the upper stratosphere where the NMC data have known dynamical inconsistencies. Two 3D CTM calculations of the November 1, 1989 to January 3, 1990 period were performed. The base calculation was initialized by mapping output from the 3D model for October 23, 1989 of a calculation without SPEs onto a 3D grid using the method of Douglass et al. (1990). The base calculations were run from October 23, 1989 until January 3, 1990. The perturbed initial condition was obtained by blending the November 1, 1989 model output from the base run with the NO$_x$ perturbation obtained from 2D calculations with SPEs but without Cl$_x$ and Br$_x$. SPEs affect regions of the earth's atmosphere poleward of approximately geomagnetic latitude 60$^\circ$, therefore, NO$_x$ was increased at the gridpoints in these polar regions. The O$_3$ field and HNO$_3$, N$_2$O$_5$, and NO$_x$ equatorward of geomagnetic latitude 60$^\circ$ were unchanged from the base run. The results of the base and perturbed simulations were compared.

3D CTM Results

Asymmetries between the two hemispheres can be caused by differing solar or dynamical conditions. The 3D CTM brings the capability to study these vastly different dynamical regimes. The strong winter-time...
vortex breaks down due to dynamical and radiative forcing in the SH in November. This irreversible final warming causes a large-scale mixing of polar and middle latitude air. The winter-time polar vortex is forming in the NH in November. There is tremendous radiative cooling during NH fall, leading to descent of air in the polar regions and the spinup of the vortex. This is expected to 'isolate' the polar regions from the middle latitudes for a few months.

Since large increases in NO\textsubscript{y} and large decreases in ozone are predicted and measured in the upper stratosphere, we focus our attention on that region. Southern and Northern Hemisphere polar projections of the 3D CTM results are shown for 4.18 hPa (see Figures 1 and 2) for November 13, 1989 and January 3, 1990.

The Southern Hemisphere percentage differences between the perturbed and the base simulations are given in Figure 1. The center of each orthographic plot is the geographic pole, with the dark latitude circles indicating 60°, 30°, and 0°. The white circle indicates the region of influence by the SPEs (greater than 60° geomagnetic).

Figure 1 (top) shows the SH ozone and NO\textsubscript{y} percentage difference predicted for November 13, 1989 at 4.18 hPa. A strong correlation exists between the features of increased NO\textsubscript{y} and decreased ozone. The largest predicted increases in NO\textsubscript{y} (about 130%) correspond directly to the largest decreases in ozone (about -30%). This correlation holds throughout the SH simulation, even when ozone-rich and NO\textsubscript{y}-poor air is mixed from lower latitudes during the SH final warming. The strong correlation between NO\textsubscript{y} and ozone is due to the continuous presence of sunlight which promotes a steady loss in NO\textsubscript{y} during the two-month period. Figure 1 (bottom) shows the SH ozone and NO\textsubscript{y} percentage difference predicted for January 3, 1989 at 4.18 hPa. The largest enhancement in NO\textsubscript{y} is now only about 30%, whereas the largest depletion in ozone is about -10%.

Figure 2 (top) shows the NH ozone and NO\textsubscript{y} percentage difference predicted for November 13, 1989 at 4.18 hPa. The correlation between enhanced NO\textsubscript{y} and depleted ozone is not as strong at most latitudes and is not apparent near the pole. The ozone loss catalytic cycle by NO\textsubscript{y} constituents is given below:

\[
\begin{align*}
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2 + \text{O}_2 \\
\text{NO}_2 + \text{O} & \rightarrow \text{NO}^* + \text{O}_2 \\
\text{NO}^* + \text{O} & \rightarrow \text{O}_2 + \text{O}_2 \\
\text{Net:} & \quad \text{O}_2 \rightarrow \text{O}_2
\end{align*}
\]

This photochemical process requires atomic oxygen (O). Atomic oxygen in the upper stratosphere is formed only in the presence of sunlight and is primarily produced by ozone photolysis. Without the sunlight there is no mechanism for the NO\textsubscript{y} to directly affect ozone, hence the correlations are weaker. The predicted maximum ozone depletion (about 27%) lies well off the pole in air which has intervals of access to sunlight and spatially correlates to increases in NO\textsubscript{y} of only about 140%. Meanwhile, the predicted maximum increases in NO\textsubscript{y} near the darkened pole are about 370%. After a few weeks of model simulation, the maximum ozone decrease does correspond to the maximum NO\textsubscript{y} increase because transport into and out of sunlit regions allows the chemistry to proceed.

Figure 2 (bottom) shows the NH ozone and NO\textsubscript{y} percentage difference predicted for January 3, 1990 at 4.18 hPa. The polar vortex has strengthened during the simulation and there has been little mixing of polar and middle latitude air. The maximum ozone decrease is about -25% with the largest NO\textsubscript{y} increase of about 270%. The NH maximum ozone decrease is thus larger than the SH maximum ozone decrease on January 3rd of our simulation.

The 3D simulations indicate substantial interhemispheric differences in the ozone depletion occurring after the October 1989 SPEs. An 8% decrease was predicted in the SH and an 18% decrease was predicted in the NH at 4.18 hPa for the 60°-80° latitude band by the end of December. The 18% decrease predicted for the NH in these 3D simulations is fairly close to the 21% decrease predicted in the 2D simulations discussed earlier. However, the 3D and 2D results are quite different. Our 3D results compare more favorably to 4 hPa NOAA-11 SBUV/2 instrument measurements which show a 1% ozone decrease in the SH and a 12% ozone decrease in the NH for December 1989 compared to December 1990/91 average for the 60°-80° latitude band. Ozone should exhibit a larger sensitivity to NO\textsubscript{y} enhancements in our 3D model simulations without chlorine than would be expected in the actual atmosphere with its background levels of chlorine constituents. This forecast is confirmed by the model predictions and NOAA-11 SBUV/2 measurements. A summary of the polar measurements and model (both 3D and 2D) predictions of ozone depletion is given in Table 1 for 4 hPa.

Our 3D model computations of ozone and NO\textsubscript{y} behavior for two months after the October 1989 SPEs produce a picture of constituent behavior which is very different between the Northern and Southern Hemispheres. These results are qualitatively consistent with SBUV/2 ozone observations, which are derived by comparing ozone levels in December of 1989 with an average of ozone in December of 1990 and 1991. Substantial mixing of the "perturbed" polar air and the "unperturbed" lower latitude air occurs during the final warming event in the Southern Hemisphere. Much less mixing of the "perturbed" polar air with air from other latitudes occurs in the Northern Hemisphere during the build-up of the polar vortex. Our two-dimensional model calculations are not appropriate for this problem because they cannot reproduce the rapid mixing associated with the final warming in the SH which so closely follows these October SPEs.

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<tr>
<th>Northern Hemisphere</th>
<th>Southern Hemisphere</th>
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<tr>
<td>NOAA-11 SBUV/2 measurements (December 1989 compared to December 1990/91 average)</td>
<td>-1%</td>
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<tr>
<td>2D model predictions (with chlorine chemistry)</td>
<td>-20%</td>
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<tr>
<td>3D model predictions (without chlorine chemistry)</td>
<td>-8%</td>
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data that were used in the ion pair production computations for this paper. We also thank Wali Planet and NOAA/NESDIS for furnishing data from the NOAA-11 SBUV/2. We thank two anonymous reviewers for helpful comments. We acknowledge NASA Headquarters Atmospheric Chemistry Modeling and Analysis Program for support during the time that this project was undertaken. Contribution #70 of the Stratospheric General Circulation with Chemistry Project.

References


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