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THE EFFECTS OF THE OCTOBER 1989 SOLAR PROTON EVENTS ON THE STRATOSPHERE AS COMPUTED USING A THREE-DIMENSIONAL MODEL

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Abstract. Very large solar proton events (SPEs) occurred from October 19-27, 1989. These SPEs are predicted to produce short-lived increases in HO_x and long-lived increases in NO_x 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 HO_x and NO_x 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 NO_x and ozone after the SPEs. Our 3D model computations of ozone and NO_x 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 HO_x production during the SPEs. The HO_x-caused ozone depletions are confined to the mesosphere and upper stratosphere and are relatively short-lived, since HO_x 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 NO_x 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.

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Very large SPEs occurred from October 19-27, 1989. The HO_x and NO_x 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 NO_x 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 NO [Zadorozhny et al., 1992] and of reduced ozone [Jackman and McPeters, 1991] during and after the October 1989 SPEs.

We have analyzed ozone data from the NOAA-11 SBUV/2 instrument and find evidence for long term ozone depletion following the SPEs in both hemispheres. The ozone field in the upper stratosphere (2-8 hPa) was significantly perturbed in late spring (SH) and late fall (NH) of 1989, adding uncertainty to the determination of the SPE-produced depletion. We do, however, find a significant interhemispheric difference in ozone depletion even though the proton flux into the two hemispheres should have been roughly equal (McPeters et al., 1981). The 1% decrease observed in the Southern Hemisphere (SH) at 4 hPa is much smaller than the 12% decrease observed in the Northern Hemisphere (NH) at 4 hPa. Our 2D simulations predict that the October SPE-caused ozone depletion should be nearly the same for both hemispheres by December 1989 with a 20% decrease in the SH and a 21% decrease predicted in the NH at 4 hPa for the 60°-80° latitude band.

In an attempt to understand the differences between observations and model results in the first several weeks after the events, we have used the GSFC three-dimensional (3D) chemistry and transport model to simulate the atmospheric response to the October 1989 SPEs. Our 3D model simulations indicate the importance of transport and mixing to the ozone behavior in each hemisphere.

Proton Flux Data and SPE Production of NO_x

Proton fluxes from T. Armstrong and colleagues (University of Kansas, private communication, 1991) allow for daily computation of ion pair production and NO_x 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 HO_x 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 NO_x 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 Porter 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'Neill 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_x, 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_2O_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_x (O_3, O, $O(^1D)$), 2) NO_x (N, NO, NO_2, and NO_3), 3) N_2O_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_2O distribution is fixed to LIMS measurements where possible and is explained in a prior 2D modeling study [Jackman et al., 1987]. The N_2O 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_y since the interference of Cl_x chemistry with the NO_y chemistry is not included (especially the ClO + NO_2 + M --> $ClONO_2$ + 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_y more in winter, when $ClONO_2$ 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_y 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 2D 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_y 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°, therefore, NO_y was increased at the gridpoints in these polar regions. The O_x field and HNO_3, N_2O_5, and NO_x equatorward of geomagnetic latitude 60° 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 the vastly different dynamical regimes. The strong winter-time

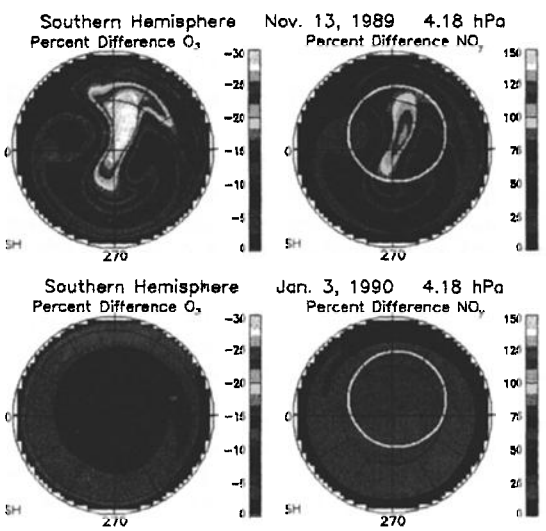

Fig. 1. Top graphs show the SH ozone and NO_y percentage difference predicted for November 13, 1989 at 4.18 hPa. Bottom graphs show the SH ozone and NO_y percentage difference predicted for January 3, 1989 at 4.18 hPa.

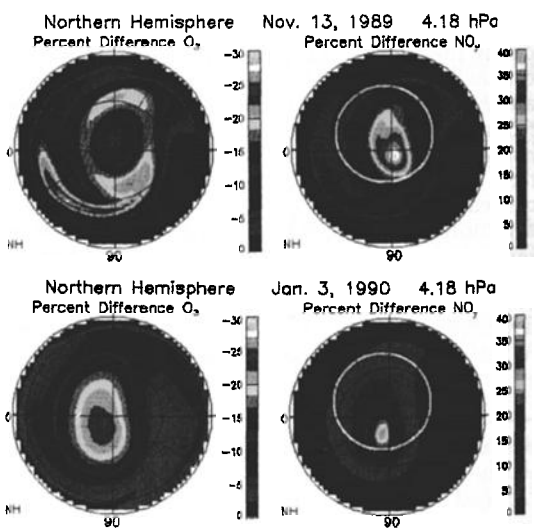

Fig. 2. Top graphs show the NH ozone and NO_y percentage difference predicted for November 13, 1989 at 4.18 hPa. Bottom graphs show the NH ozone and NO_y percentage difference predicted for January 3, 1990 at 4.18 hPa.

vortex breaks down due to dynamical and radiative forcing in the SH in November. This irreversible final warming causes 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_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_y percentage difference predicted for November 13, 1989 at 4.18 hPa. A strong correlation exists between the features of increased NO_y and decreased ozone. The largest predicted increases in NO_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_y-poor air is mixed from lower latitudes during the SH final warming. The strong correlation between NO_y and ozone is due to the continuous presence of sunlight which promotes a steady loss in NO_y during the two-month period. Figure 1 (bottom) shows the SH ozone and NO_y percentage difference predicted for January 3, 1989 at 4.18 hPa. The largest enhancement in NO_y is now only about 30%, whereas the largest depletion in ozone is about -10%.

Figure 2 (top) shows the NH ozone and NO_y percentage difference predicted for November 13, 1989 at 4.18 hPa. The correlation between enhanced NO_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_y constituents is given below:

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$
$$\text{Net:} \quad O_3 + O \rightarrow O_2 + O_2$$

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_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_y of only about 140%. Meanwhile, the predicted maximum increases in NO_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_y increase because transport into and out of sunlit regions allows the chemistry to proceed.

Figure 2 (bottom) shows the NH ozone and NO_y percentage differences 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_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 SH 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 show a larger sensitivity to NO_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_x 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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TABLE 1. Measurements and model predictions of ozone depletion in the latitude band 60°-80° at 4 hPa.

	Southern Hemisphere	Northern Hemisphere
NOAA-11 SBUV/2 measurements (December 1989 compared to December 1990/91 average)	-1%	-12%
2D model predictions (with chlorine chemistry)	-20%	-21%
3D model predictions (without chlorine chemistry)	-8%	-18%

data that were used in the ion pair production computations for this paper. We also thank Walt 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

Allen, D. J., et al., Application of a monotonic upstream-biased transport scheme to three-dimensional constituent transport calculations, Mon. Wea. Rev., 119, 2456-2464, 1991.

Crutzen, P. J., et al., Solar proton events: Stratospheric sources of nitric oxide, Science, 189, 457-458, 1975.

Douglass, A. R., et al., Global three-dimensional constituent fields derived from profile data, Geophys. Res. Lett., 17, 525-528, 1990.

Fairlie, T. D. A., et al., The development of narrow baroclinic zones and other small-scale structure in the stratosphere during simulated major warmings, Q. J. R. Meteorol. Soc., 116, 287-315, 1990.

Heath, D. F., et al., Solar proton event: Influence on stratospheric ozone, Science, 197, 886-889, 1977.

Jackman, C. H., et al., Production of odd nitrogen in the stratosphere and mesosphere: An intercomparison of source strengths, J. Geophys. Res., 85, 7495-7505, 1980.

Jackman, C. H., et al., An intercomparison of nitrogen-containing species in Nimbus 7 LIMS and SAMS data, J. Geophys. Res., 92, 995-1008, 1987.

Jackman, C. H., and R. D. McPeters, Ozone depletion resulting from the large solar proton events of 1989: Observation vs. calculation (abstract), Eos Trans. AGU, 72, Fall Meeting Suppl., 80, 1991.

Jackman, C. H., et al., Effect of solar proton events on the middle atmosphere during the past two solar cycles as computed using a two-dimensional model, J. Geophys. Res., 95, 7417-7428, 1990.

McPeters, R. D., and C. H. Jackman, The response of ozone to solar proton events during solar cycle 21: The observations, J. Geophys. Res., 90, 7945-7954, 1985.

McPeters, R. D., et al., Observations of ozone depletion associated with solar proton events, J. Geophys. Res., 86, 12,071-12,081, 1981.

O'Neill, A., and V. D. Pope, Simulations of linear and nonlinear disturbances in the stratosphere, Q. J. R. Meteorol. Soc., 114, 1063-1110, 1988.

Porter, H. S., et al., Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air, J. Chem. Phys., 65, 154-167, 1976.

Reagan, J. B., et al., Effects of the August 1972 solar particle events on stratospheric ozone, J. Geophys. Res., 86, 1473-1494, 1981.

Reid, G. C., et al., Response of the middle atmosphere to the solar proton events of August-December, 1989, Geophys. Res. Lett., 18, 1019-1022, 1991.

Rood, R. B., et al., Episodic total ozone minima and associated effects on heterogeneous chemistry and lower stratospheric transport, J. Geophys. Res., 97, 7979-7996, 1992.

Rosenfield, J. E., et al., A computation of the stratospheric diabatic circulation using an accurate radiative transfer model, J. Atmos. Sci., 44, 859-876, 1987.

Rusch, D. W., et al., The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere, I, Odd nitrogen, Planet. Space Sci., 29, 767-774, 1981.

Solomon, S., and P. J. Crutzen, Analysis of the August 1972 solar proton event including chlorine chemistry, J. Geophys. Res., 86, 1140-1146, 1981.

Solomon, S., et al., Mesospheric ozone depletion during solar proton events, paper presented at the Sixth ESA-PAC Meeting, Eur. Space Agency, Interlaken, Switzerland, April 12-19, 1983.

Thomas, R. J., et al., Mesospheric ozone depletion during the solar proton event of July 13, 1982, 1, Measurement, Geophys. Res. Lett., 10, 253-255, 1983.

Weeks, L. H., et al., Ozone measurements in the mesosphere during the solar proton event of November 2, 1969, J. Atmos. Sci., 29, 1138-1142, 1972.

Zadorozhny, A. M., et al., Nitric oxide and lower ionosphere quantities during solar particle events of October 1989 after rocket and ground-based measurements, J. Atmos. Terr. Phys., 54, 183-192, 1992.

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