THE EFFECTS OF SOLAR PARTICLE EVENTS ON THE MIDDLE ATMOSPHERE

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INTRODUCTION

Solar particle events (SPEs) have been investigated since the late 1960's for possible effects on the middle atmosphere. Solar protons from SPEs produce ionizations, dissociations, dissociative ionizations, and excitations in the middle atmosphere. Either directly or through a photochemical sequence both HO_x (H, OH, HO_2) and NO_x (N, NO, NO_2) are produced as well. These HO_x and NO_x constituents are important because they can lead to the destruction of ozone. Most of these investigations have been primarily focused on the effects of SPEs on ozone, however, a few have been related to the effects of SPEs on odd nitrogen (N, NO, NO_2, NO_3, N_2O_5, HNO_3, HO_2NO_2, and $ClONO_2$) constituents.

The SPEs are good tests for model validation because the large perturbations to the atmosphere associated with SPEs are confined to high latitudes, last only for days to months, and are easily distinguished in satellite data. This allows the comparison of measurements with a wide variety of models, ranging from simple point models to two-dimensional models.

Ozone depletions have been observed during and after nine separate SPEs over the past two solar cycles (HEATH et al. 1977; MCPETERS et al. 1981; THOMAS et al. 1983; SOLOMON et al. 1983; MCPETERS and JACKMAN, 1985). SPEs have also been observed to increase NO during one SPE (MCPETERS, 1986).

The production of HO_x and NO_x and their subsequent effects on ozone can also be computed using energy deposition and photochemical models. We discuss the effects of SPE-produced NO_x species on the odd nitrogen (NO_y) abundance of the middle atmosphere as well as the SPE-produced long-term effects on ozone. The influence of HO_x species on ozone has been discussed in other papers (e.g., SOLOMON et al. 1981; JACKMAN and MCPETERS, 1985) and will not be repeated here.

ODD NITROGEN (NO_y) VARIANCE DUE TO SPEs

The production of NO_y species by SPEs has been predicted since the mid 1970's (CRUTZEN et al. 1975). Recently, a satellite measurement (MCPETERS, 1986) was made of the NO increase after a major SPE (July 1982). This measured NO increase was in good agreement with our predicted NO increase, computed

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assuming 1.25 nitrogen (N) atoms produced per ion pair (PORTER et al. 1976). The agreement between the predicted and measured NO increase has given us confidence in the reliability of the computations for NO_y species' increase caused by SPEs.

A dataset of proton fluxes has become available from Thomas Armstrong and colleagues (University of Kansas) which allows for a daily computation of ion pair production and, subsequently, NO_y production due to SPEs. The proton fluxes are given in integral form for energies greater than 10 MeV, 30 MeV, and 60 MeV. The data are available for the time period 1963 through 1985. We have used those data in a manner similar to that discussed in JACKMAN and MEADE (1988) and compute a daily ion pair production over the 23 year time period in a form suitable for inclusion in our model.

The ion pair production computed with the use of the daily average proton flux data of T. Armstrong compares favorably with the ion pair production computed using the hourly average proton flux data found in the Solar Geophysical Data publication for most SPEs. However for the August 1972 SPE, the ratio of the hourly computed ion pair production to the daily computed ion pair production ranges from about 3.7 in the stratosphere to near 1.0 in the mesosphere. We have normalized the daily to the hourly computed ion pair production for this one SPE only for two reasons: 1) the hourly computed ion pair production is believed to be more accurate than the daily computed ion pair production and 2) the August 1972 SPE is the most important SPE in the last two solar cycles for its effects on the middle atmosphere.

The ion pair production was input into our two-dimensional photochemical model (DOUGLASS et al. 1989) whose vertical range has been extended to be from the ground to about 90 km with about a 2 km grid spacing and from -85°S to 85°N with a 10° grid spacing. It was assumed that 1.25 N atoms are produced per ion pair in this model computation. The SPE production of N atoms was only input at geomagnetic latitudes above 60° (see JACKMAN and MEADE, 1988, for an explanation).

The two-dimensional model was run to an annual equilibrium condition in which the seasonal values of constituents repeat yearly. The model was then run for 23 years from 1963 through 1985 and investigated for changes. For all model runs in this investigation the ultraviolet flux was not allowed to vary with the solar cycle.

Figure 1a illustrates the variability of NO_y at 1.7 mb (44 km) and 75°N over the 23 year period. Note that NO_y can vary dramatically after an SPE, especially after the August 1972 SPE, but the NO_y values generally return to their ambient levels 2 to 6 months after the event. The NO_y seems to be affected only by those SPEs which have an ion pair production over about 100 ion pairs (cm^{-3} sec^{-1}). This is not a strict rule as the time of year and, therefore, the ambient NO_y amount help determine the magnitude of the NO_y change at a certain level (see JACKMAN and MEADE 1988 for further discussion). Some downflux of NO_y from the SPE's mesospheric production of NO_y is also associated with the SPEs and is important during certain seasons (late fall, winter, and early spring). This downflux can also influence the amount of NO_y in the upper stratosphere.

Figure 1a, as well as our analysis of NO_y at other altitudes and latitudes, indicate that the NO_y produced by SPEs over solar cycle time periods does not build up, but can be important at high latitudes on seasonal time-scales. This result is not surprizing given the small fraction of the annual odd nitrogen budget that was computed by JACKMAN et al. (1980) to result from SPEs. The majority of the annual production of odd nitrogen is a result of nitrous oxide oxidation and was recently computed (JACKMAN et al. 1987) to be 2.7 X 10^{34} NO molecules per year. The largest production of NO molecules from SPEs was in the

year 1972 at the level of 6.4 X 10^{33} NO molecules per year, only 24% of the nitrous oxide source. The production of NO molecules from SPEs in other major SPE-active years is typically half or less than that computed for 1972.

LONG-TERM OZONE VARIANCE DUE TO SPEs

Figure 1b illustrates the variability of ozone at 1.7 mb (44 km) and 75°N over the 23 year period. The ozone decreases are directly correlated with the NO_y increases presented in Figure 1a.

The percentage change in modeled ozone as a result of the August 1972 SPE is given in Figure 2 at two latitudes. The latitudes in the Northern Hemisphere (N.H) at 75°N (Figure 2a) and 55°N (Figure 2b) indicate a larger ozone depletion at 75°N than at 55°N. Other latitudes investigated from our model results show a similar behavior with the larger ozone depletions being associated with the higher latitudes. This behavior was also observed in the BUV ozone data (JACKMAN and MCPETERS, 1987). The magnitude of the depletion observed in the BUV dataset was similar to that predicted by the model computation. For example, about a 15-25% maximum ozone depletion was observed between 70° and 80°N and about a 5-15% maximum ozone depletion was observed between 50° and 60°N.

Our model results at 55°S (not shown) indicates over a 20% ozone depletion, but the model at 55°N indicates a 5-10% depletion in the time period 20 to 60 days after the SPE, implying a large hemispheric difference in the level of ozone depletion. MAEDA and HEATH (1980/81) showed that the S.H. did experience a larger ozone loss than did the N.H. SPE-produced NO_y in winter has a far greater effect on ambient NO_y amounts and, therefore, on ozone levels than does SPE-produced NO_y in summer (see JACKMAN and MEADE, 1988, for more discussion on SPE effects on NO_y amounts).

DISCUSSION AND CONCLUSIONS

Model computations indicate fairly good agreement with ozone data for the SPE-induced ozone depletion caused by NO_y species connected with the August 1972 SPE. Future studies should include a more detailed intercomparison of the ozone behavior with altitude, latitude, and time. It would also be useful to compare these detailed studies with another large SPE, perhaps one that occurs during the current solar active period. Since NO_y constituents are responsible for over 70% of the ozone loss in the stratosphere (JACKMAN et al. 1986), it is useful to validate the NO_y photochemistry which is used in atmospheric models to predict ozone amounts.

Our model computations indicate that NO_y will not be substantially changed over a solar cycle by SPEs. The changes are mainly at high latitudes and are on time scales of several months, after which the NO_y drifts back to its ambient levels.

ACKNOWLEDGEMENTS

The authors would like to thank Thomas R. Armstrong (University of Kansas) for sending solar proton data that was used in the ion pair production computations for this paper. We would also like to acknowledge Sushil Chandra of NASA Goddard Space Flight Center for useful comments on an earlier version of this manuscript.

REFERENCES

Crutzen, P. J., I. S. A. Isaksen, and G. C. Reid, Solar proton events: Stratospheric sources of nitric oxide, Science, 189, 457-458, 1975.

Douglass, A. R., C. H. Jackman, and R. S. Stolarski, Comparison of model results transporting the odd nitrogen family with results transporting separate odd nitrogen species, in press, J. Geophys. Res., 1989.

Heath, D. F., A. J. Krueger, and P. J. Crutzen, Solar proton event: Influence on stratospheric ozone, Science, 197, 886-889, 1977.

Jackman, C. H., and R. D. McPeters, The response of ozone to solar proton events during solar cycle 21: A theoretical interpretation, J. Geophys. Res., 90, 7955-7966, 1985.

Jackman, C. H., and R. D. McPeters, Solar proton events as tests for the fidelity of middle atmosphere models, Physica Scripta, T18, 309-316, 1987.

Jackman, C. H., and P. E. Meade, Effect of solar proton events in 1978 and 1979 on the odd nitrogen abundance in the middle atmosphere, J. Geophys. Res., 93, 7084-7090, 1988.

Jackman, C. H., J. E. Frederick, and R. S. Stolarski, Production of odd nitrogen in the stratosphere and mesosphere: An intercomparison of source strengths, J. Geophys. Res., 85, 7495-7505, 1980.

Jackman, C. H., R. S. Stolarski, and J. A. Kaye, Two-dimensional monthly average ozone balance from limb infrared monitor of the stratosphere and stratospheric and mesospheric sounder data, J. Geophys. Res., 91, 1103-1116, 1986.

Jackman, C. H., P. D. Guthrie, and J. A. Kaye, An intercomparison of nitrogen-containing species in Nimbus 7 LIMS and SAMS data, J. Geophys. Res., 92, 995-1008, 1987.

Maeda, K., and D. F. Heath, Stratospheric ozone response to a solar proton event: Hemispheric asymmetries, Pageoph., 119, 1-8, 1980/81.

McPeters, R. D., A nitric oxide increase observed following the July 1982 solar proton event, Geophys. Res. Lett., 13, 667-670, 1986.

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., C. H. Jackman, and E. G. Stassinopoulos, Observations of ozone depletion associated with solar proton events, J. Geophys. Res., 86, 12,071-12,081, 1981.

Porter, H. S., C. H. Jackman, and A. E. S. Green, Efficiencies for production of atomic nitrogen and oxygen by relativistic proton impact in air, J. Chem. Phys., 65, 154-167, 1976.

Solomon, S., D. W. Rusch, J.-C. Gerard, G. C. Reid, and P. J. Crutzen, The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere, 2, Odd hydrogen, Planet. Space Sci., 29, 885-892, 1981.

Solomon, S., G. C. Reid, D. W. Rusch, and R. J. Thomas, 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., C. A. Barth, G. J. Rottman, D. W. Rusch, G. H. Mount, G. M. Lawrence, R. W. Sanders, G. E. Thomas, and L. E. Clemens, Mesospheric ozone depletion during the solar proton event of July 13, 1982, 1, Measurement, Geophys. Res. Lett., 10, 253-255, 1983.

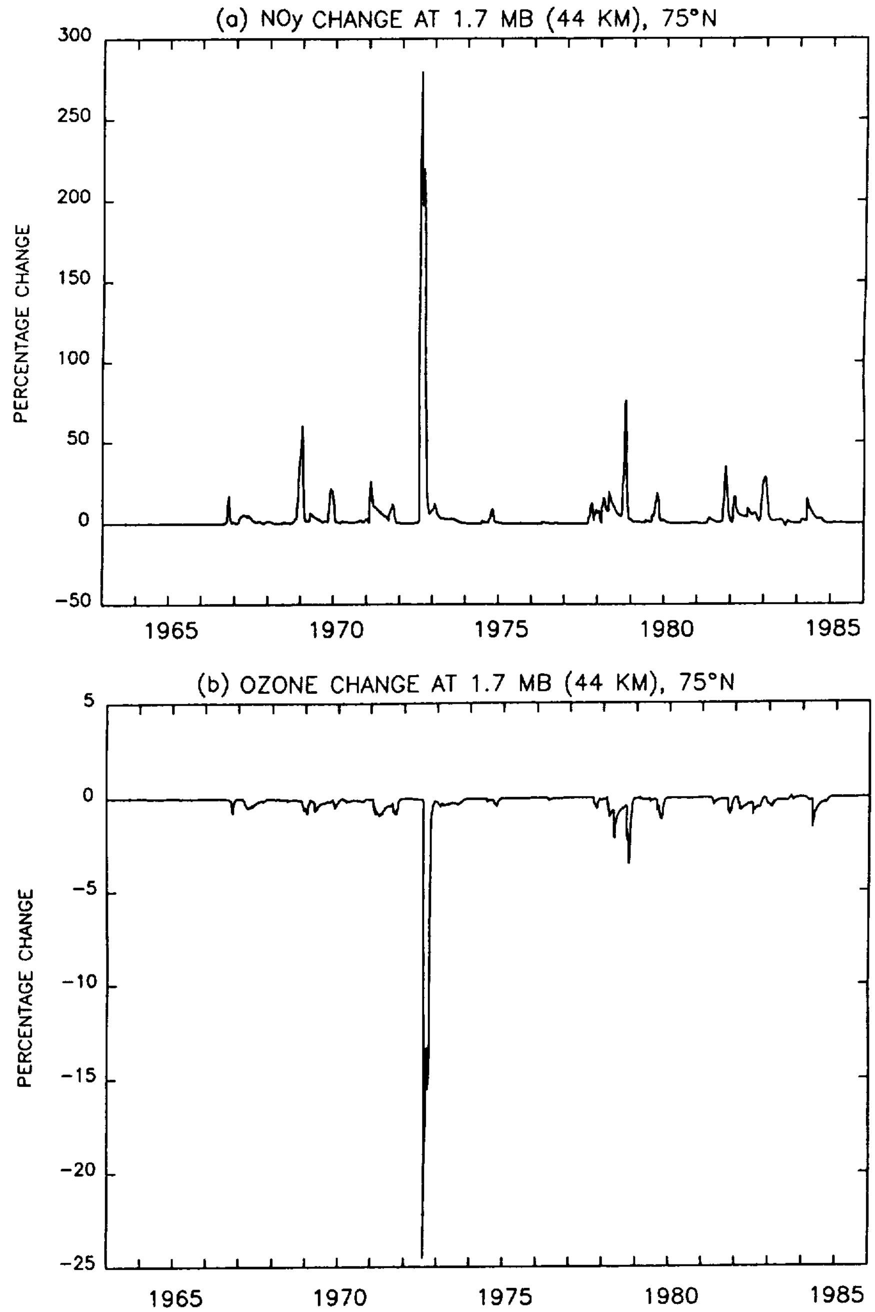

Figure 1. (a) Model predicted NO_y percentage change at 1.7 mb (44 km) and 75°N. (b) Model predicted ozone percentage change at 1.7 mb (44 km) and 75°N.

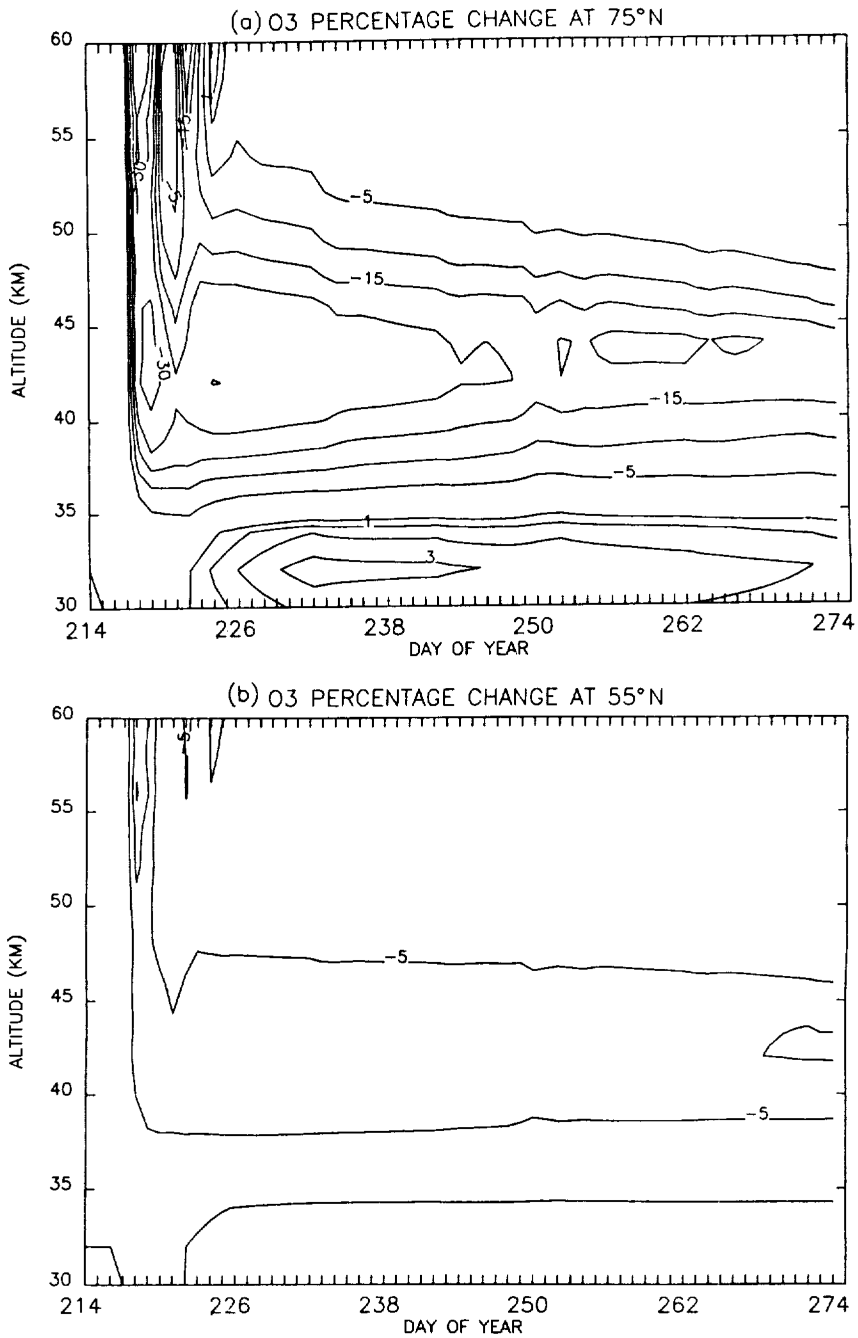

Figure 2. Model predicted ozone percentage change as a function of day of year in 1972 for (a) 75°N and (b) 55°N. The ozone change is a result of the August 1972 SPE and is given at the contour levels of -40, -30, -20, -15, -10, -5, 0, +1, +2, and +3%.