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Effect of Solar Proton Events in 1978 and 1979 on the Odd Nitrogen Abundance in the Middle Atmosphere

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Daily average solar proton flux data for 1978 and 1979 have been used in a proton energy degradation scheme to derive ion pair production rates and, subsequently, atomic nitrogen production rates. These atomic nitrogen production rates are computed in a form suitable for inclusion in an atmospheric two-dimensional time-dependent photochemical model. Odd nitrogen (N, NO, NO_2, NO_3, HNO_3, HO_2NO_2, N_2O_5, and $ClONO_2$) distributions are computed from the model including the atomic nitrogen production from solar protons and are compared with baseline distributions. Comparisons show that the average effect of the solar protons in 1978 and 1979 was to cause changes in odd nitrogen only above 10 mbar and at latitudes only above about 50° in both hemispheres. The influence of the solar-proton–produced odd nitrogen on the local abundance of odd nitrogen depends primarily on the background odd nitrogen abundance as well as the altitude and season. The odd nitrogen change in the atmosphere due to solar protons during the solar proton events (SPEs) in 1978 and 1979 is important for 2–3 months, but it is generally negligible 6 months after the SPE. Inclusion of the SPEs' production of odd nitrogen does not produce a substantial change in the agreement between the model results and the Limb Infrared Monitor of the Stratosphere (LIMS) NO_2 and HNO_3 data.

INTRODUCTION

Solar proton events (SPEs) are an integral part of every solar cycle; thus the quantifiable SPE effect on minor constituents in the atmosphere should be included for more accurate model computations. Much work has already been completed on the effects of SPEs on ozone, HO_x (H, OH, and HO_2), and odd nitrogen (N, NO, NO_2, NO_3, HNO_3, HO_2NO_2, N_2O_5, and $ClONO_2$), both through observations [*Weeks et al.*, 1972; *Heath et al.*, 1977; *McPeters et al.*, 1981; *Thomas et al.*, 1983; *Solomon et al.*, 1983*a*; *McPeters and Jackman*, 1985; *McPeters*, 1986] and theory [*Swider and Keneshea*, 1973; *Crutzen et al.*, 1975; *Frederick*, 1976; *Reid et al.*, 1976; *Swider et al.*, 1978; *Fabian et al.*, 1979; *Crutzen and Solomon*, 1980; *Jackman et al.*, 1980; *Rusch et al.*, 1981; *Solomon and Crutzen*, 1981; *Solomon et al.*, 1981, 1983*a*, *b*; *Reagan et al.*, 1981; *McPeters et al.*, 1981; *Orsini and Frederick*, 1982; *Jackman and McPeters*, 1985, 1987].

SPEs are believed to produce HO_x and odd nitrogen, both of which can decrease ozone. The HO_x species have lifetimes only of the order of hours in the middle atmosphere, while the odd nitrogen can remain for several days to several months, depending on its altitude of formation and transport after formation. We focus on the odd nitrogen production by SPEs because of the long lifetime of odd nitrogen in the middle atmosphere and the possibility that the odd nitrogen will influence other regions of the atmosphere besides just the area of direct production. We investigate the production of odd nitrogen by SPEs during 1978 and 1979, since some global data are available from the Limb Infrared Monitor of the Stratosphere (LIMS) measurements for the two odd nitrogen species NO_2 and HNO_3.

BACKGROUND ATMOSPHERIC ODD NITROGEN

Stratospheric odd nitrogen is mainly produced by reaction of nitrous oxide (N_2O) with $O(^1D)$:

$$N_2O + O(^1D) \rightarrow 2NO$$

This source is thought to provide about 90% of the odd nitrogen in the stratosphere [e.g., *Johnston et al.*, 1979; *Jackman et al.*, 1980] (see also *Crutzen and Schmailzl* [1983] and *Jackman et al.* [1987] for a more accurate and updated computation of odd nitrogen from N_2O oxidation).

Stratospheric odd nitrogen is also probably affected by the downward transport of thermospheric odd nitrogen, relativistic electron precipitation events, galactic cosmic rays, lightning, and nuclear explosions, as well as the solar proton events investigated in this study. These other sources are believed to be minor when compared to the oxidation of N_2O source. The two minor odd nitrogen sources which are influential in the same altitude range (middle to upper stratosphere) as the SPEs are (1) the downward transport of thermospheric odd nitrogen and (2) relativistic electron precipitation events. The other minor sources of odd nitrogen are believed to be significant only in the lower stratosphere.

Both the downward transport of thermospheric odd nitrogen [*Solomon et al.*, 1982; *Frederick and Orsini*, 1982; *Solomon and Garcia*, 1983, 1984] (see, also, *Russell et al.* [1984] for LIMS measurements of NO_2 in the winter mesosphere and upper stratosphere) and relativistic electron precipitation events [*Thorne*, 1977, 1980; *Baker et al.*, 1987] have been postulated to affect the upper stratosphere. Since there is a large uncertainty in the magnitude of these odd nitrogen sources as well as a probable variability over the solar cycle,

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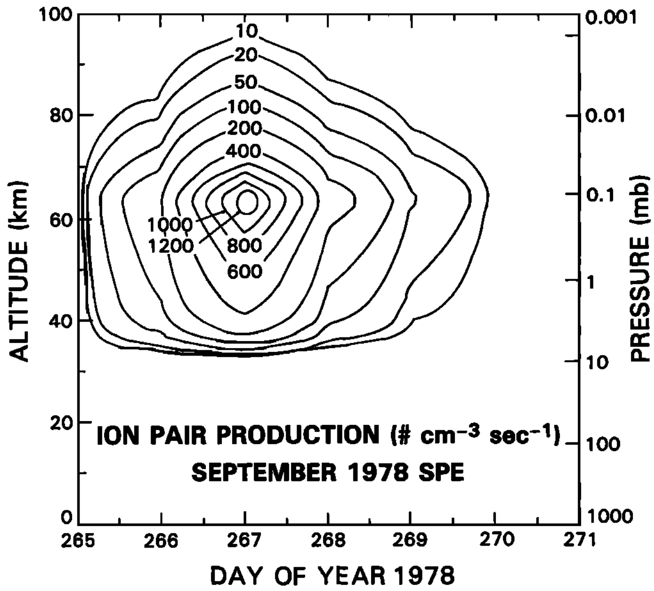

Fig. 1. Ion pair production rate due to the September 1978 solar proton event, the most intense event in the 1978–1979 time period. This is the production rate over the polar caps (greater than 60° geomagnetic latitude).

we do not include them in our model computations. Instead, we compare the SPE source of odd nitrogen only to the major source of stratospheric odd nitrogen, oxidation of N_2O.

We compute odd nitrogen using N_2O, CH_4, and temperature measurements from the Stratospheric and Mesospheric Sounder (SAMS), along with LIMS H_2O measurements and O_3 measurements from the Solar Backscatter Ultraviolet (SBUV) instrument, using the same methodology and two-dimensional model described by *Jackman et al.* [1987]. We do include two minor changes in this study. Hydrogen peroxide (H_2O_2) and its set of reactions (given in the appendix) are added to the model computations, and the reaction rates are taken from the new NASA-recommended list [*DeMore et al.*, 1987]. The odd nitrogen two-dimensional distributions, using this modified species and chemistry set, exhibit only minor changes from the odd nitrogen species' distributions given by *Jackman et al.* [1987].

SOLAR PROTON EVENT PRODUCED ODD NITROGEN

One difficulty in undertaking a study like this is the synthesis and accumulation of solar proton flux data in a daily average format. Solar protons have been measured by various satellites for over two decades and these data are available from Solar Geophysical Data in a graphical form, which can be accessed tediously, if necessary. Thomas Armstrong and colleagues from the University of Kansas have alleviated the problem of finding easily available solar proton flux data by compiling a synthesized daily averaged proton flux dataset, which has been discussed by *Armstrong et al.* [1983]. We use an updated version of this data set (obtained from T. Armstrong, private communication, July 1986), which includes proton data for two solar cycles from 1963 through 1985. The data are given in flux units (cm^{-2} s^{-1} sr^{-1}) for protons with energies greater than 10, 30, and 60 MeV.

We require differential flux spectra of protons in our proton energy deposition code (discussed by *Jackman et al.* [1980]), so we tried to represent the data by two empirical forms that are commonly used to fit differential proton spectra from SPEs. These two empirical data representations are the e-folding form, where

$$dF/dE = F_0 \exp(-E/E_0) \qquad \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{MeV}^{-1}$$

(F is the proton flux in cm^{-2} s^{-1} sr^{-1}, F_0 and E_0 are parameters, and E is the proton energy), and the power law form, where

$$dF/dE = F_0(E/E_0)^{-n} \qquad \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{MeV}^{-1}$$

(F is the proton flux, F_0 and n are parameters, E is the proton energy in megaelectron volts (MeV), and E_0 is simply set to 1 MeV for all fits). The best fit to the proton data was found with the power law form, using a least squares fitting solution. The values for the F_0 parameter varied over a large range, while the values for n were close to 2.

The proton fluxes were assumed to be valid over the energy limits from 10 to 100 MeV (T. Armstrong, personal communication, 1987) and were divided up into 60 monoenergetic energy intervals, all assumed to be isotropic. The protons were then degraded in energy, with the net result being ion pair production using range energy relations for protons (see *Jackman et al.* [1980] for details of the energy degradation computation). Protons in the 10- to 100-MeV energy range deposit most of their energy between about 90 and 35 km, thus ion pairs will be produced in both the stratosphere and the mesosphere. The ion pair production rate caused by the SPE which occurred in September 1978 is presented in Figure 1. This particular SPE lasted from day 266 to day 270 (September 23–27), peaking on day 267 (September 24).

Atomic nitrogen is produced by the protons, or their secondary electrons, impacting N_2 and causing dissociation, predissociation, or dissociative ionization processes. We compute the atomic N production rate by multiplying the ion pair production rate by a factor of 1.25. This factor is in reasonable agreement with a detailed energy degradation computation [*Porter et al.*, 1976] as well as other calculations [*Frederick*, 1976; *Rusch et al.*, 1981]. These atomic N production rates, which are a function of time and altitude, can then be included in our two-dimensional model as outlined in the following discussion.

Since protons are charged particles, they follow the Earth's magnetic field lines and rarely deposit their energy at geomagnetic latitudes below about 60°. The Earth's geomagnetic pole is offset from the geographic pole by about 10°, which implies that some protons will deposit energy below 60° geographic latitude. A zonally averaged two-dimensional model is used in this study with the domain from −85° to +85° in latitude at 10° latitude intervals. We computed the fraction of the area of the Earth in the 10° geographic latitude bands which are located above 60° geomagnetic latitude. The atomic N production rate for solar protons is included in our two-dimensional model using derived weighting factors of 1.0 for model grid boxes centered on 85°, 0.98 for 75°, 0.60 for 65°, 0.31 for 55°, 0.02 for 45°, and 0.0 for all other latitudes.

We illustrate with the solid line in Figure 2 the atomic N production rate on day 267 from the SPE given in Figure 1. This can be compared to the diurnal average odd nitrogen production from N_2O oxidation in March, which is illustrated by the dashed line in Figure 2 (taken from Figure 9*a* of *Jackman et al.* [1987]). The SPE source is confined to polar latitudes and maximizes near the poles in the lower mesosphere, while the N_2O oxidation source maximizes in the middle stratosphere near the equator. The SPE source is sporadic, while the N_2O oxidation source is continuous as long as there is sunlight.

MODEL EXPERIMENTS AND RESULTS

Two model experiments were investigated in this section. Both model runs had time steps of 1 day and simulated the time period from January 1, 1978, through May 31, 1979. The first model experiment (called the BASE run) was essentially that reported by *Jackman et al.* [1987], except as noted previously.

The second model experiment (called the SPE run) was exactly the same as the first, except atomic N production by SPEs in 1978 and 1979 was included. Year 1978 was quite active with solar protons and was the most solar-proton-active year of solar cycle 21 for protons with energies between 10 and 100 MeV. The total number of N atoms calculated to be produced in the stratosphere was 1.5×10^{32} in 1978 and 3.7×10^{31} in 1979, but since we do not include protons of energy greater than 100 MeV (higher energy cut off), these results represent a lower limit for atomic N production. We also computed the total number of N atoms produced in the mesosphere to be 6.0×10^{32} in 1978 and 1.0×10^{32} in 1979, but since we do not include protons at energies below 10 MeV (lower energy cut off), it also represents a lower limit for atomic N production. As a comparison, the source of odd nitrogen from N_2O oxidation is about 2.6×10^{34} molecules y^{-1} in the stratosphere and 3.1×10^{32} molecules y^{-1} in the mesosphere. The SPE stratospheric source in 1978 is less than 1% of the N_2O oxidation stratospheric source for the whole year, whereas the two sources are of a comparable magnitude in the mesosphere for 1978.

The first significant SPE in 1978 occurred on day 45 (February 14) and reached a maximum ion pair production rate of over 600 ion pairs cm^{-3} s^{-1} at about 63 km (0.1 mbar). We present the odd nitrogen (atomic nitrogen) production as a function of day of model run in Figure 3 for 1 mbar at +75° by the dark solid line and the ratio of odd nitrogen in the SPE model run to the BASE model run, also at 1 mbar for +75°, by the dashed line. The BASE and SPE model runs are compared at 10-day intervals. The BASE and SPE runs are essentially the same through day 40, because only some very minor SPEs occurred in the time period from day 1 through day 40. The BASE and SPE runs are fairly different on day 50, however. On this day the SPE run shows a factor of 1.7 more odd nitrogen at 1 mbar and +75° and shows a factor of 1.15 more odd nitrogen at 1 mbar and −75°. The hemispheric asymmetry in the background atmospheric concentration of odd nitrogen is the reason for this asymmetric response of the atmospheric odd nitrogen to the SPE. Some of this odd nitrogen increase remains in the atmosphere until the next significant SPE. The next significant SPE then increases the odd nitrogen beyond this "already enhanced" level.

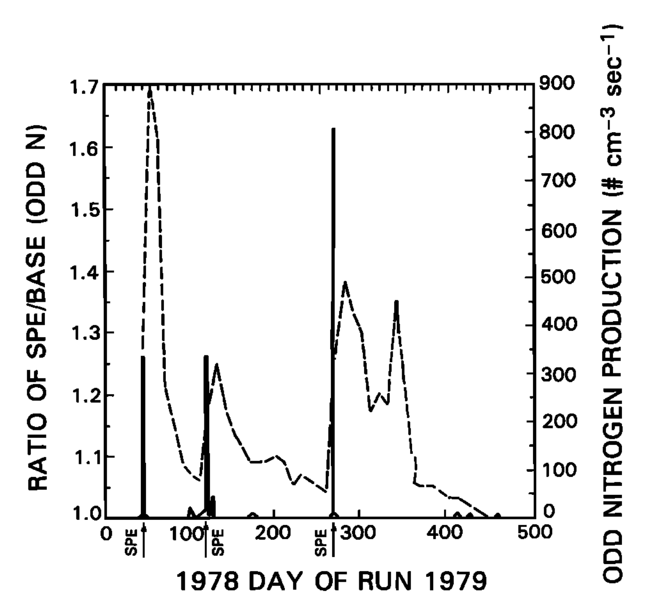

Fig. 3. Comparison of odd nitrogen (atomic nitrogen) production due to solar protons (dark solid line) and the ratio of the SPE/BASE odd nitrogen model results (dashed line) as a function of day of model run at 1 mbar, +75°. Note that the peak on day 340 in the SPE/BASE odd nitrogen is a transport effect.

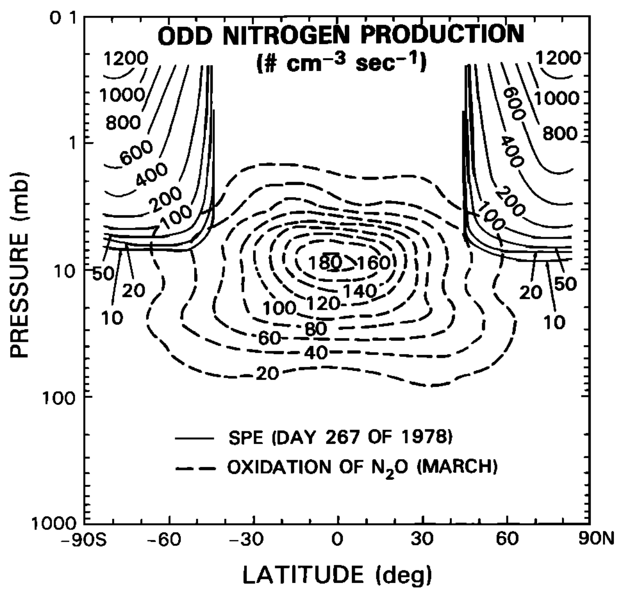

Fig. 2. Comparison of the maximum atomic nitrogen production rate due to the September 1978 solar proton event (solid line) and the diurnal average odd nitrogen production by N_2O oxidation for March (dashed line; taken from Figure 9*a* of *Jackman et al.* [1987]).

There are no more significant SPEs until day 120 (April 30), when the atmosphere again is perturbed by an ion pair production rate with a maximum of over 600 cm^{-3} s^{-1}. This SPE causes substantial changes in the lower mesosphere, raising the odd nitrogen concentration at 1 mbar by over a factor of 1.2 in both hemispheres at high latitudes. The odd nitrogen, which is produced or transported to levels below 1 mbar, can remain in the atmosphere for a couple of months in either hemisphere, but it is transported to lower altitudes in the southern hemisphere because of the downward transport during the subsequent winter season. The atmospheric odd nitrogen in the SPE run for both hemispheres has almost relaxed back to that observed in the BASE run by day 260, being different by only several percent in a few scattered regions at high latitudes in the upper stratosphere and lower mesosphere.

The next SPE maximizes on day 267 (September 24). This was the largest SPE in 1978, with maximum computed ion pair production rates of over 1200 cm^{-3} s^{-1} (see Figure 1). The N atom production (as illustrated in Figure 2 for day 267)

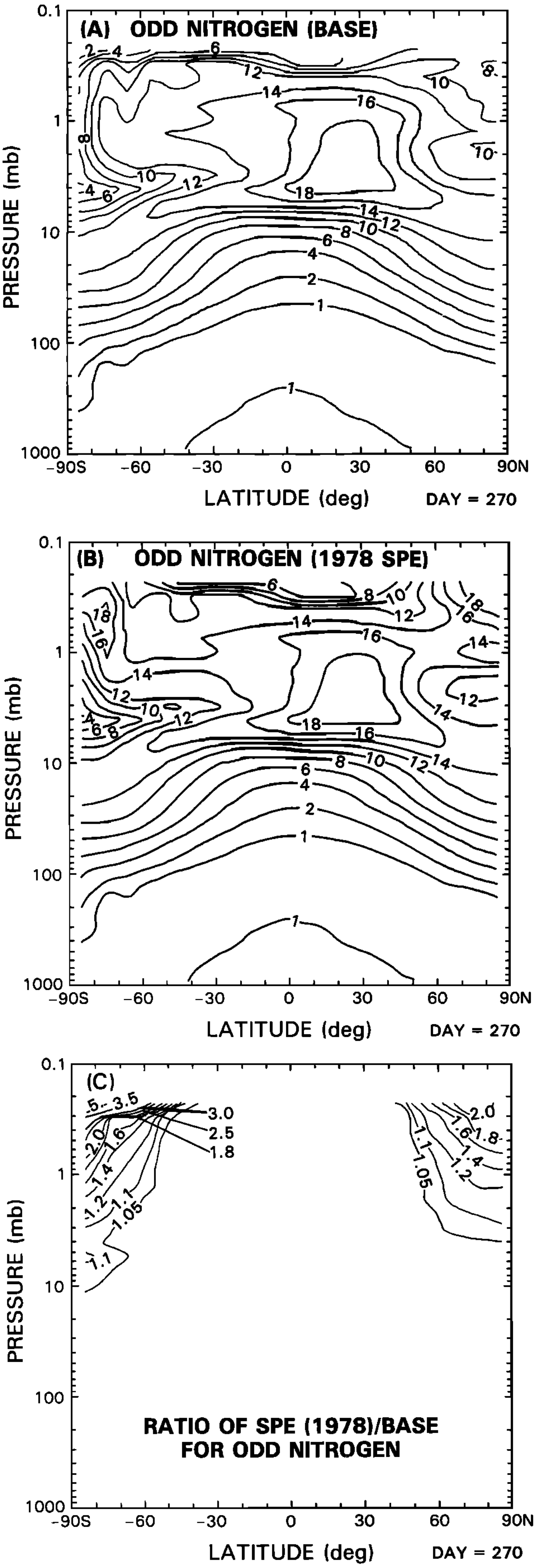

Fig. 4. Comparison of the two-dimensional odd nitrogen model distribution on day 270 from (*a*) the BASE run, (*b*) the SPE run, and (*c*) the ratio of the SPE/BASE runs.

was input into the two-dimensional model for all days of this SPE.

Note that for the three major SPEs that occur (designated by arrows and "SPE" in Figure 3), the ratio of the SPE/BASE odd nitrogen increases. The increase is not linearly dependent on the atomic N production of the SPE but depends more importantly on the background mixing ratio of odd nitrogen. At day 50 (1 mbar, +75°) the BASE odd N mixing ratio is about 3.5 parts per billion by volume (ppbv), at day 120 (1 mbar, +75°) the BASE odd N mixing ratio is 8 ppbv, and at day 270 (1 mbar, +75°) the BASE odd N mixing ratio is 11 ppbv. The model does not anticipate the SPE occurrences, as it seems on first glance at Figure 3. The proton fluxes are daily data, whereas the model output results are taken only every 10 days, thus it appears that the model odd nitrogen increases before the protons actually affect the atmosphere. The peak on day 340 in the SPE/BASE odd nitrogen is a transport effect, caused by the downward movement of enhanced odd nitrogen air to lower altitudes. The vertical velocity increases from -0.4 cm s^{-1} in September to -0.8 cm s^{-1} in January at 1 mbar, +75°.

We show the odd nitrogen distributions from both the BASE run and the SPE run, as well as the ratio of the SPE to the BASE run for day 270 in Figure 4. There is roughly a symmetric change in the two hemispheres due to this SPE.

The three major factors that determine the influence of SPEs on the odd nitrogen distributions are (1) the background atmospheric concentration of odd nitrogen, (2) photochemistry, and (3) transport. The same production rate of N atoms acting on a 10-ppbv background at 2 mbar and +85° will have less of an effect than that same production rate of N atoms acting on a 6-ppbv background at 2 mbar and −85° (observed in Figures 4*a* and 4*c*; also note discussion of Figure 3). On day 270 (September 27) the solar ultraviolet flux is roughly equivalent in both hemispheres. The major loss for odd nitrogen in the upper stratosphere and lower mesosphere at the high latitudes is

$$NO + h\nu \rightarrow N + O$$

followed by

$$N + NO \rightarrow N_2 + O$$

and is very slow. The model has strong downward vertical motion in both hemispheres at this time of the year which is represented by the streamlines indicated in Figure 5*a*. The wind fields change in the next few months, and by January (streamlines illustrated in Figure 5*b*) the flow in the upper stratosphere and lower mesosphere will be from the south pole to the north pole, with upward motion in the southern latitudes and downward motion in the northern latitudes. It was assumed therefore that the odd nitrogen produced in the northern hemisphere would remain longer in the atmosphere than that produced in the southern hemisphere. Since the LIMS instrument has measurements to higher latitues in the northern hemisphere (+84°) than the southern hemisphere (−64°), it was postulated that the influence of the SPEs on the odd nitrogen species in the northern hemisphere may be observable in LIMS data.

No significant SPEs occurred during the LIMS observing time frame. The first significant SPE in 1979 occurred on day 158 (June 7) of year 1979, after the LIMS instrument had ceased functioning because of lack of cryogenic coolant [*Gille and Russell*, 1984]. We monitored the effects of the September 1978 SPE on the odd nitrogen at 10-day intervals through

May 1979 in the model and noted these observations:

1. The odd nitrogen produced in the northern hemisphere in the fall remains longer in the atmosphere than that produced in the southern hemisphere in the spring.
2. By day 360 of the model run (December 26, 1978), the odd nitrogen SPE enhancement over the BASE run was reduced to about 10–15% in the northern hemisphere high-latitude middle to upper stratosphere and had only a small, almost negligible, influence on the agreement between model NO_2 and HNO_3 and LIMS NO_2 and HNO_3 (see *Jackman et al.* [1987] for a detailed comparison of model to LIMS NO_2 and HNO_3).
3. By day 445 of the model run (March 21, 1979), the odd nitrogen SPE enhancement over the BASE run was reduced to a few percent in the northern hemisphere high latitudes in the middle stratosphere to the lower mesosphere and is not observable in the southern hemisphere.
4. By day 515 of the model run (May 31, 1979), there is no observable difference between the SPE and the BASE runs.

SENSITIVITY STUDIES

Two-dimensional models best represent the atmosphere away from the polar boundaries, whereas the perturbation to the model considered here is one that peaks at the poles. Our two-dimensional model considers each species individually in the transport scheme and includes chemistry throughout the polar night, therefore we believe that the model represents the odd nitrogen species at all latitudes fairly consistently. We impose a zero-flux boundary condition for all species at the top of the model. This means that there should be no interference in the model by nonphysical sources or sinks of odd nitrogen above the model. It also implies that an odd nitrogen mixing ratio will be maintained near the boundary, until influenced by transport or photochemistry in the model. The boundary condition at the poles is essentially the same as that at the top. The species' mixing ratios at $\pm 90°$ are assumed to be the same as $\pm 85°$.

As indicated in Figure 1, solar protons produce ion pairs and, subsequently, odd nitrogen at altitudes above 0.23 mbar (60 km), the top of our model. By not including some of this mesospheric odd nitrogen production as a flux into our model, we are underestimating the solar proton odd nitrogen input into the stratosphere. We are also underestimating the mesospheric odd nitrogen production by not including the solar protons of energies less than 10 MeV. We performed a sensitivity study in order to ascertain the possible effects of this "above model" solar proton odd nitrogen source on the model odd nitrogen abundance. Solar proton flux data exist in Solar Geophysical Data for proton energies below 10 MeV. We took this proton data for the September 1978 SPE and computed the odd nitrogen produced for days 266 through 273, using spectra good from 1 to 100 MeV.

We assume that all the SPE odd nitrogen production above 0.23 mbar is transported as a flux into the top of the two-dimensional model. This assumption is certainly an upper limit and most probably a large overestimate of the SPE odd nitrogen that will be transported to levels below 0.23 mbar. This flux maximizes on day 267 at 1.8×10^9 odd nitrogen molecules $cm^{-2}\ s^{-1}$, about 40% of which comes from protons between 1 and 10 MeV. When we include this flux in our two-dimensional model, the odd nitrogen in the lower mesosphere and upper stratosphere at the highest latitudes for the northern hemisphere is increased substantially over our previous results without this downward flux. At 1 mbar and $+75°$, for example, the odd nitrogen is increased another 100% over the previous results in the time period 1–2 months after the SPE. This odd nitrogen increase (caused by the "above model" odd nitrogen production) will extend the time that the SPE affects the stratosphere by another 1–2 months. The odd nitrogen influence does not extend below about 30 mbar and is reduced to a few percent by day 515. This added flux has very little impact in the southern hemisphere because (1) the hemisphere is in sunlight, which means odd nitrogen is being destroyed as a result of the sink described in the previous section, and (2) the vertical velocity is upward in this region.

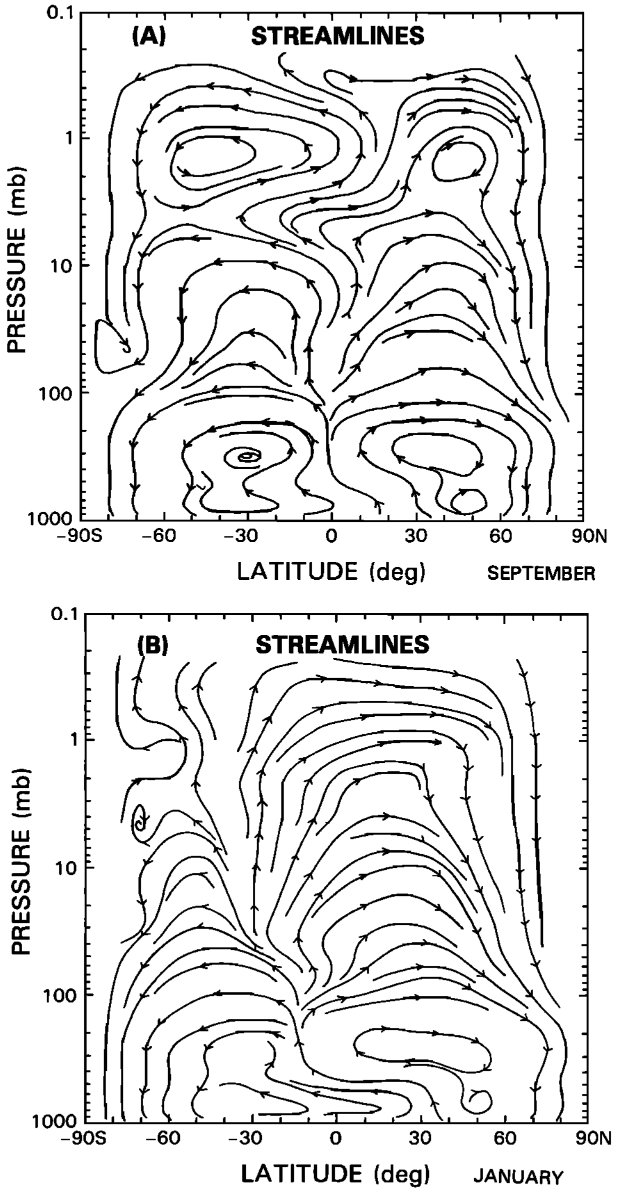

Fig. 5. Transport in two-dimensional model given in stream function form for (*a*) September and (*b*) January.

How does this increased odd nitrogen production affect the agreement between LIMS measurements and model results? *Russell et al.* [1984] presented LIMS NO_2 observations for the upper stratosphere and lower mesosphere polar winter night in which NO_2 mixing ratios exceeded 20 ppbv above 1 mbar at high northern latitudes in December 1978 and January 1979. In this model sensitivity study we compute NO_2 mixing ratios greater than 20 ppbv above 1 mbar at high northern latitudes for about 30–40 days following the September 1978 SPE. By December 1, 1978, the NO_2 mixing ratios have dropped to only a few ppbv above 1 mbar at high northern latitudes. These computations indicate that SPEs had little to do with the high LIMS NO_2 measurements in polar night. Our results are not inconsistent with the conclusions of *Russell et al.* [1984], which indicated that the NO_2 enhancements were probably caused by the downward transport of odd nitrogen.

As we noted, the computations discussed in the previous section represent lower limits of odd nitrogen production. When we put in all the odd nitrogen production from an SPE (for protons above 1 MeV) into our model, some local concentrations of odd nitrogen are changed. The effects do remain confined to the higher latitudes and middle to upper stratosphere, but the time period of SPE influence on the local concentration of odd nitrogen is extended.

We used low values of eddy diffusion, K_{yy} (2×10^9 cm^{-2} s^{-1}) and K_{zz} (2×10^3 cm^{-2} s^{-1}) in our model computations discussed previously. In order to evaluate the influence of larger eddy diffusion on our conclusions, we performed two other sensitivity studies. For the first study we used the K_{yy}s from *Newman et al.* [1988] (adapted by *Jackman et al.* [1988]), which were computed from potential vorticity calculations using National Meteorological Center (NMC) temperature data, and reached values of over 4×10^{10} cm^2 s^{-1} at high latitudes in the winter upper stratosphere and the original low K_{zz}s. In the second study we used the K_{zz}s from *Nastrom et al.* [1980] (adapted by *Garcia and Solomon* [1983]), which matched temperature and wind data most consistently reaching values of over 10^5 cm^2 s^{-1} in the upper stratosphere and the original low K_{yy}s. The two sensitivity studies were 100-day model runs, which included the September 1978 SPE near the middle of the run. Both the BASE and the SPE cases had to be run in the two sensitivity studies.

The two enhanced eddy diffusion BASE cases showed increases of odd nitrogen in the upper stratospheric and lower mesospheric regions. This larger BASE odd nitrogen, as well as the increased mixing in these two cases from lower latitudes and lower altitudes, resulted in less of an odd nitrogen increase for the SPE runs when compared to the low K_{yy} and K_{zz} runs. The odd nitrogen increases caused by the September 1978 SPE persisted only for a couple of months in the northern hemisphere instead of the few months observed in the model experiment discussed in the preceding section.

Discussion and Conclusions

Odd nitrogen from these SPEs in 1978 and 1979 was only produced in the upper stratosphere and lower mesosphere and only rarely is transported to 10 mbar and below. The major production region of odd nitrogen from SPEs is above the maximum in odd nitrogen mixing ratio (observed in Figures 4*a* and 4*b*). The SPE-produced odd nitrogen would have to be transported up gradient in mixing ratio in order to affect the lower stratosphere. The continual tendency of motion in the middle and lower atmosphere is to keep species well mixed [*Andrews et al.*, 1987] and to decrease mixing ratio gradients. Our two-dimensional model tends to decrease mixing ratio gradients when caused by photochemical effects.

The timing and size of the SPE is crucial. SPE-produced odd nitrogen in winter or late fall has a far greater effect than it does in summer or late spring on the stratospheric odd nitrogen. The large SPEs in 1978 and 1979 are only moderate-sized events when compared to the gigantic SPE of August 1972. The August 1972 event, because of the large flux of high-energy protons, as well as other very large SPEs need to be investigated separately in order to determine the stratospheric ramifications by the odd nitrogen production from SPEs over time periods of solar cycles.

The N_2O oxidation process is active continuously in sunlight, producing odd nitrogen near the equator and transporting it down gradient to the poles. There is a constant overwhelming of the SPE-produced odd nitrogen near the poles by this lower-latitude source, which prevents the SPE source from having a long-term influence on the atmospheric odd nitrogen, at least in the 1978 and 1979 time period. The SPE-produced odd nitrogen during 1978 and 1979 does, however, influence the upper stratosphere and mesosphere up to 2 to 3 months past the SPE and possibly a month or two longer if the downflux of SPE odd nitrogen production from above the model is accurately included.

Appendix

These additional reactions were added to the two-dimensional model for computations in this study. Other reactions included in this study are given in Table 1 of *Jackman et al.* [1987]. All reaction rates are from *DeMore et al.* [1987].

$$H_2O_2 + h\nu \rightarrow OH + OH$$

$$H_2O_2 + O \rightarrow HO_2 + OH$$

$$Cl + H_2O_2 \rightarrow HCl + HO_2$$

$$OH + H_2O_2 \rightarrow H_2O + HO_2$$

$$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$$

$$HO_2 + HO_2 + M \rightarrow H_2O_2 + O_2 + M$$

$$OH + OH + M \rightarrow H_2O_2 + M$$

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