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The Response of Ozone to Solar Proton Events During Solar Cycle 21: The Observations

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We have analyzed ozone profile data from the solar backscattered ultraviolet instrument on NIMBUS 7 from 1979 to the present and have found clear cases of ozone destruction associated with five solar proton events (SPE's) of this solar cycle: on June 7, 1979, August 21, 1979, October 13–14, 1981, July 13, 1982, and December 8, 1982. During the SPE on July 13, 1982, the largest of this solar cycle, we observed no depletion at all at 45 km but a 15% ozone depletion at 50 km increasing to 28% depletion at 55 km, all at a solar zenith angle of 85°. We find that there is a strong variation of the observed depletion with solar zenith angle, with maximum depletion occurring at the largest zenith angles (near 85°) decreasing with distance from the terminator. The observed depletion in every case was short lived, disappearing within hours of the end of the SPE, suggesting that HO_x reactions were responsible for the observed ozone depletion.

1. Introduction

During a solar proton event (SPE), large numbers of high-energy protons penetrate the earth's mesosphere and upper stratosphere and perturb the normal chemistry by ionizing molecules and changing the balance of odd nitrogen, oxygen, and hydrogen. While changes in ozone caused by the introduction of chorofluorocarbons would be very gradual and difficult to identify, changes caused by an SPE are produced very rapidly, typically in a matter of hours, and are confined to a limited geographic area, the region above 60° geomagnetic latitude.

Weeks et al. [1972] reported a rocket measurement of decreased ozone between 50 and 70 km during an SPE on November 2, 1969. *Heath et al.* [1977] observed a large ozone decrease near 45 km in the ozone vertical profiles derived from NIMBUS 4 backscattered ultraviolet (BUV) data following the extremely large solar proton event of August 4–8, 1972. *McPeters et al.* [1981] reanalyzed the BUV data and found evidence of ozone depletion during two additional SPE's, in January and September 1971. While ozone depletion following the August 1972 SPE was seen at 4 mbar and persisted for at least a month, indicating that the depletion was caused by NO_x production, the depletion from the January and September events was seen at 1 mbar and above and very short lived, lasting only hours, indicating that HO_x production was the likely mechanism for the ozone decrease. Recently, *Thomas et al.* [1983] found a large reduction in mesospheric ozone (50–85 km) during the SPE on July 13, 1982, from both the infrared spectrometer and the ultraviolet spectrometer on the SME satellite.

In this paper we report our analysis of the response of ozone to the significant SPE's in solar cycle 21 from the NIMBUS 7 launch in October 1978 to date using data from the solar backscattered ultraviolet instrument (SBUV). We examined ozone data during 15 SPE's from this solar cycle and found that ozone depletion occurred during SPE's on at least five dates: June 7, 1979, August 2, 1979, October 13–14, 1981, July 13, 1982, and December 8, 1982. None of the SPE's in this solar cycle were comparable to the giant event of August 1972; the ozone depletion in each case was short lived and at 50 km and above. In a companion paper, *Jackman and McPeters* [1985] will examine model predictions for these SPEs.

2. The Ozone Measurements

The SBUV instrument, an improved version of the NIMBUS 4 BUV instrument, is a nadir pointing double monochromator [*Heath et al.*, 1975] designed to measure total ozone and ozone profiles along the satellite orbital track. SBUV measures backscattered radiances at 12 wavelengths from 255 to 340 nm with a scan to scan precision of better than half a percent. Ozone profiles are inverted using the backscattered albedos, the ratio of the backscattered radiance to the solar irradiance at each wavelength. The solar irradiance used in this ratio is measured daily by deploying an onboard diffuser plate. The fact that this is a ratio measurement greatly increases the accuracy and stability of the system.

A serious problem in analyzing SPE data from BUV [*McPeters et al.*, 1981] was that energetic particles directly caused a "dark current" signal in the instrument that had to be subtracted from the measured signal in order to find the corrected radiance, leading to some uncertainty in the derived ozone profiles. Energetic particles apparently cause fluorescence in optical elements of the instrument, producing this dark current signal. In SBUV a chopper wheel operating at 50 Hz subtracts the instantaneous dark current (from whatever source) so that the instrument is completely insensitive to direct particle effects. We can detect no evidence of signal contamination from particles even at night in the highest particle flux region of the South Atlantic anomaly particle belt.

NIMBUS 7 is in a sun synchronous polar orbit that covers the entire earth between 80°S and 80°N each day with orbits crossing the equator at 26° longitude intervals at local noon. The normal operating cycle for SBUV is three days on and one day off, so occasional one or two day gaps appear in the data. The geometry for one orbit on July 13, 1982, is shown in Figure 1. The satellite crosses the equator at local noon, reaches a maximum latitude of 80°N, then crosses the terminator into the night side (represented by the hatched area) on the descending part of the orbit. Because of the funneling effect of the earth's magnetic field, the solar protons are directed to an area in the polar region above a cutoff latitude of about 60° geomagnetic latitude (outlined by the dashed line).

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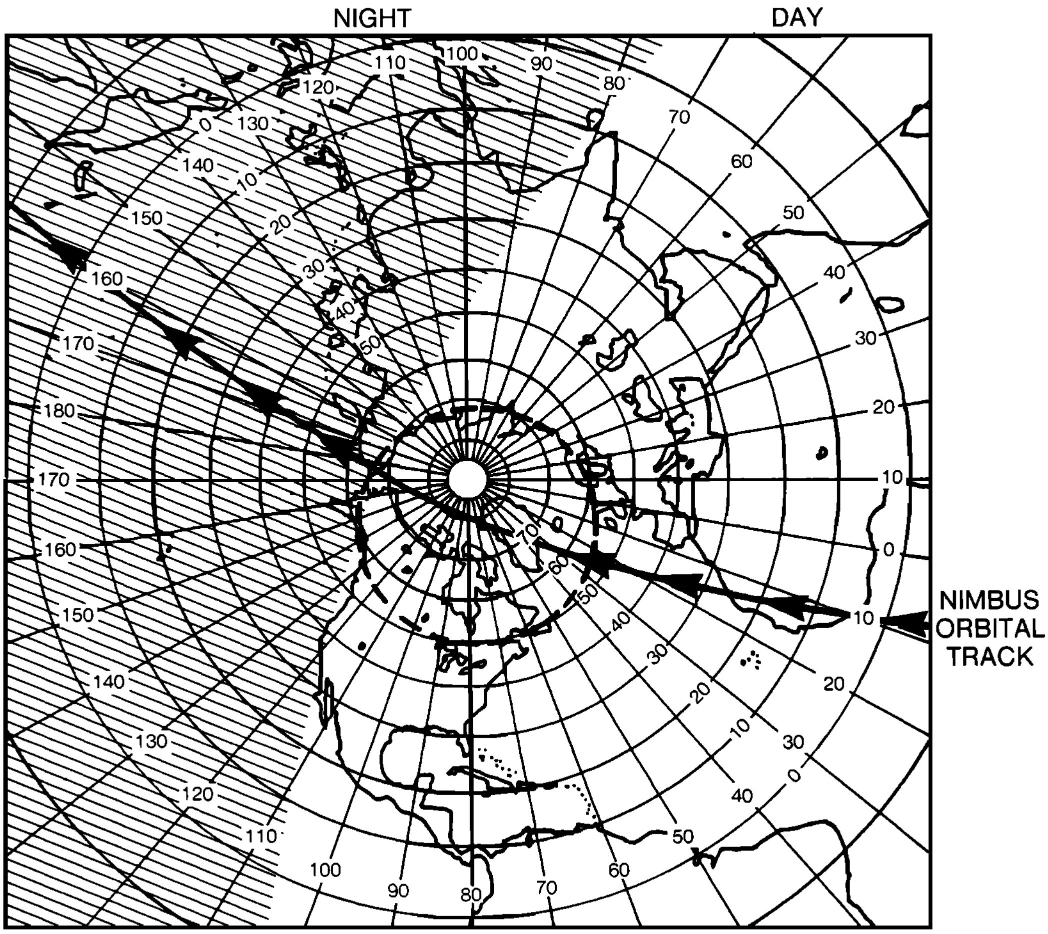

Fig. 1. The orbital geometry of SBUV as it crosses the polar region. The area above 60° geomagnetic latitude is marked by the dashed circle.

Any ozone depletion caused by an SPE should be seen exclusively in this area. An interesting feature of the orbit during polar summer is that the satellite crosses the same latitude in daylight twice at different local times and different solar zenith angles. In Figure 1, SBUV measures ozone profiles at 70°N latitude, first on the ascending part of the orbit at 10:15 A.M. LT with a solar zenith angle of 50°, then again on the descending part of the orbit at 2:00 A.M. LT with a solar zenith angle of 84°. Having ozone measurements at the same latitude but at different solar zenith angles is very useful for differentiating zenith angle dependent effects from latitude-dependent effects.

The algorithm used to calculate ozone vertical profiles from the measured backscattered albedos has been described in detail by *Klenk et al.* [1983] and briefly by *McPeters et al.* [1984]. Ozone profile calculation is possible because light at a given wavelength is backscattered mostly in a limited altitude region of the atmosphere determined by a balance between scattering increasing with atmospheric pressure and absorption increasing with ozone optical depth. Since this altitude region varies with wavelength, a wavelength scan is equivalent to an altitude scan. The profile inversion is done using a partial derivative algorithm that uses an optimum statistical technique [*Rodgers*, 1976] to combine measurement information with a priori information in the form of climatological ozone profiles. The resulting covariance matrix provides an estimate of the error in each layer.

3. Analysis of the Ozone Data

In principle, our strategy for detecting ozone changes caused by SPE's is simple: we observe ozone at a given pressure as a function of time and look for a correlation of ozone change with the arrival of the solar protons. In practice, we must discriminate any changes caused by the solar protons from the normal variability of the ozone field with latitude, longitude, time, and solar zenith angle. As a further complication, there may be a spatial variability of the proton flux as it enters the atmosphere.

We first consider the problem of the spatial variability of ozone, the strongest variation usually being with latitude. In July at the 1-mbar pressure level we normally see a latitude-dependent ozone gradient of 25% between 50°N and 80°N. Had we chosen to bin by geomagnetic latitude, a natural coordinate in which to examine charged particle effects, we would have been sampling across the geodetic latitude gradient from orbit to orbit, producing a spurious time-dependent ozone behavior.

To avoid this problem, we bin the ozone data into solar zenith angle zones, which is equivalent to binning by latitude but separating the ascending and descending parts of the orbit. Of course, this means that we are sampling different geomagnetic latitudes from orbit to orbit, which could be a problem if there were a strong gradient in the proton flux. Fortunately, the flux of protons would be expected to be fairly

TABLE 1. Significant Solar Proton Events of Solar Cycle 21

Date of Event	Comment
June 7, 1979	ozone depletion observed
August 20–21, 1979	ozone depletion observed
September 17, 1979	marginal depletion observed
July 18, 1980	no measurements for ZA > 75
April 11, 1981	no depletion observed
April 24–26, 1981	no depletion observed
May 10, 1981	no depletion observed
July 20, 1981	no measurements for ZA > 75
October 13–14, 1981	ozone depletion observed
January 31, 1982	SBUV off
July 13, 1982	ozone depletion observed
July 23, 1982	no depletion observed
December 8, 1982	ozone depletion observed
December 28, 1982	no depletion observed
February 3–4, 1983	no depletion Feb. 3 SBUV off on Feb. 4

uniform above the geomagnetic cutoff latitude, unlike electrons which are concentrated into the auroral zone. *Reagan et al.* [1981] observed a polar plateau in the proton flux measured by the 1971-089A polar orbiting satellite during the proton events of August 1972 for geomagnetic latitudes above the cutoff latitude of approximately 58° geomagnetic. Also, for the SPE's of January and September 1971 we found [*McPeters et al.*, 1981] that the BUV instrument in the night polar region acted as a very efficient particle detector for protons of $E > 65$ MeV. We could find no consistent pattern of variation with geomagnetic latitude until close to the cutoff latitude at 60° geomagnetic, though we did see high flux variability. At worst, we will be finding the average effect on ozone of protons from a range of geomagnetic latitudes.

An SPE is a transient event lasting only a matter of hours to a few days at most. Also, at 50 km and above, the effect of the particles on ozone is mainly due to the HO_x which is produced, and the time scale of this chemistry is again only a matter of hours. Thus we find it necessary to analyze the ozone data on an orbit by orbit basis to resolve this rapidly changing behavior. It would have been more convenient to deal with daily average ozone values in order to average out longitudinal variability. Each orbit is 26° advanced in longitude, so longitudinal variations in the ozone field will masquerade as apparent time variations. But since we scan through 360° of longitude each day, we would expect longi-

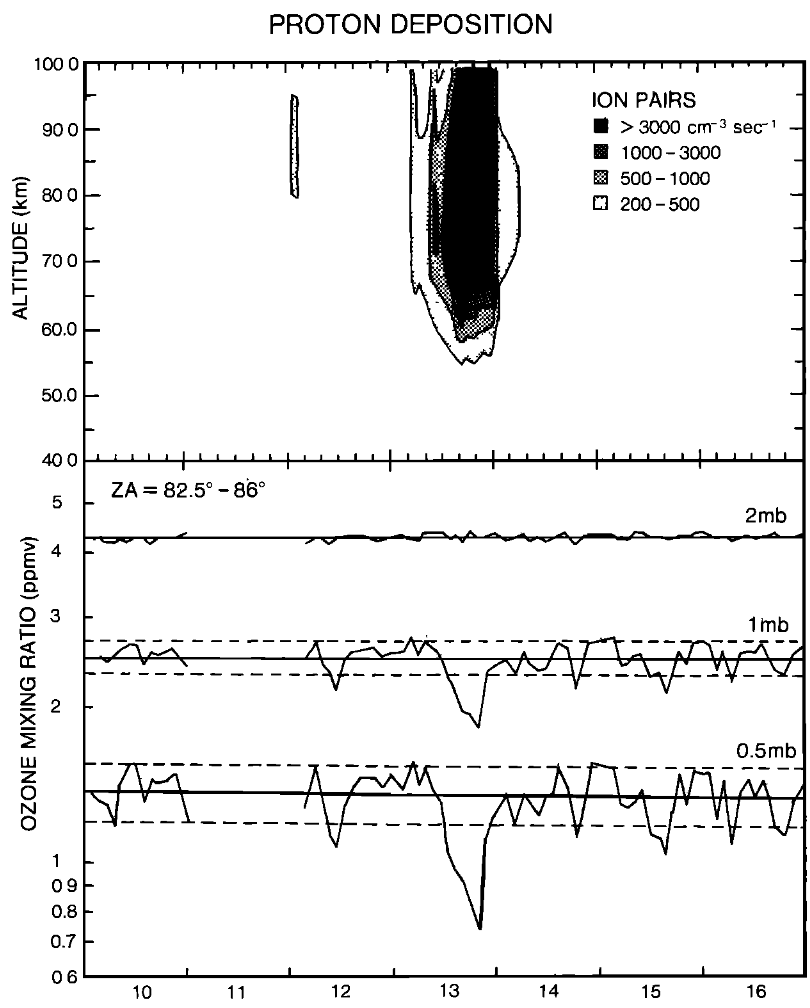

Fig. 2. The time dependence of the ozone mixing ratio during the July 1982 solar proton event is shown for three pressure levels: 0.5, 1.0, and 2.0 mbar, corresponding approximately to 55- 50- and 45-km altitude, for the solar zenith angle range 82.5°–86°. The non-SPE ozone average (solid line) and standard deviation (dashed line) are indicated. The upper part of the figure gives the simultaneous altitude dependence of the proton ion pair production contoured as indicated.

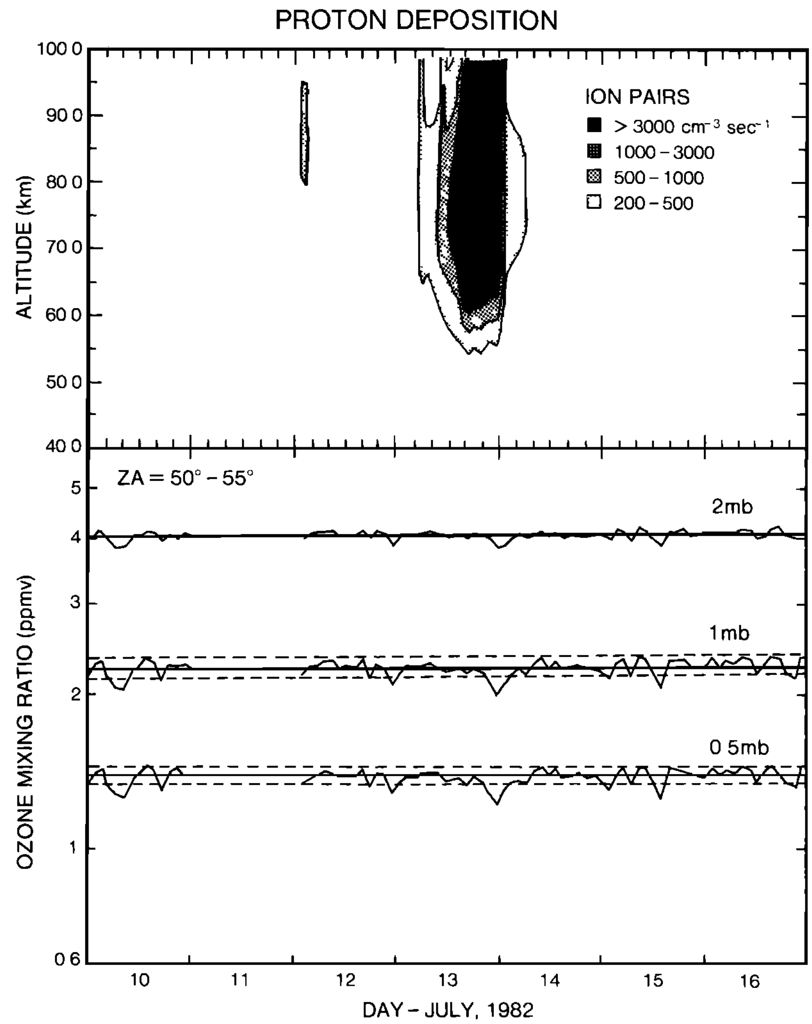

Fig. 3. An identical plot to Figure 2 but for the solar zenith angle range 50°–55°.

tudinal features to repeat from day to day, whereas an SPE-produced feature should appear only during and after the SPE. Examination of the ozone record before and after the SPE should help distinguish between temporal variations and longitudinal variations.

The time dependence and energy spectrum of the proton flux were measured by instruments on IMP 8 and NOAA 6. As will be described in the companion paper [*Jackman and McPeters*, this issue], an energy deposition code was used to model the penetration and energy degradation of particles in each SPE as a function of altitude and time. For each SPE we correlate the ozone behavior with a contour plot of the proton ion pair production as a function of time and altitude. This information is necessary since an intense but soft (low energy) SPE might have no particles that penetrate below 60 km, while a smaller event with a hard energy spectrum might have significant penetration to 40 km and affect the local chemistry there.

4. Ozone Depletion During the SPE's

We have examined data from 15 possibly significant solar proton events listed in Table 1. In 10 of the events, no depletion is observed for one reason or another. The September 17, 1979, SPE was very small, producing a maximum of 50 ion pairs/(cm^3 s) at 80 km. We observe a small depletion of ozone during this event for the 0.5-mbar level, but the results are marginal, and we do not include this as a clear case of SPE-produced ozone depletion. During the July 1980 and July 1981 events the instrument was switched to its solar flux measurement mode at 75° solar zenith angle in the northern hemisphere on every orbit, so no data are available for large zenith angles. The April 1981 events may have produced some ozone depletion, but the background ozone variability was too large to be certain. The instrument was not in its ozone measurement mode on January 31 or February 1, 1982, so no data are available during that SPE. On December 28, 1982, the background ozone variability was unusually low, so that even a small ozone depletion would have been detectable, yet none was observed. The remaining five SPE's do appear to have produced measurable ozone depletion at the 0.5- and 1-mbar levels. In none of the events was there discernible ozone depletion at 2 mbar, nor did the depletion observed persist more than a few hours after the end of each SPE.

We first examine the largest SPE of this solar cycle, that on July 13, 1982. In Figure 2 we plot the ozone mixing ratio for every orbit for one week centered on the SPE for three pressure levels: 0.5, 1.0, and 2.0 mbar, corresponding approximately to 55-, 50-, and 45-km altitude. Here the solar zenith angle zone was 82.5°–86.0°, corresponding to an average latitude of 72.2°N on the descending part of the orbit. Figure 3 is an identical plot but for the solar zenith angle zone 50°–55°, corresponding to almost the same average latitude, 71.0°N,

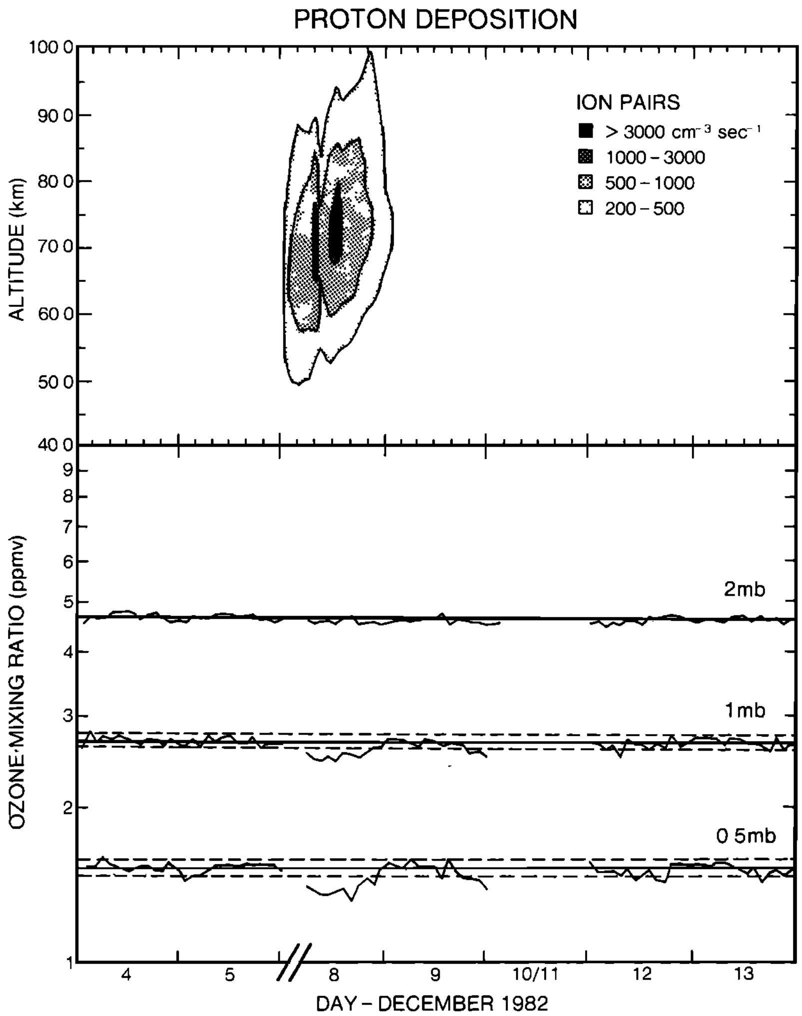

Fig. 4. The time dependence of the ozone mixing ratio during the December 1982 solar proton event is shown for the 82.5°–86° solar zenith angle range. Note that SBUV was off December 6–7 and 10–11.

but on the ascending part of the orbit. In the upper part of each figure we show a contour plot of the ion pair production as a function of time and altitude.

The solid straight line plotted for each pressure level for reference purposes is a linear fit to approximately 3 weeks of ozone data excluding July 13. A linear fit is made to account for possible long-term (seasonal) ozone changes. The bounding dashed lines give the one-sigma variance over the averaging period. It is interesting to note that the ozone variability was higher by about a factor of 2 during this July than is normal during polar summer. (See Figures 4, 5, and 6 for instance.) During the July 1982 SPE at 1 mbar we find $\sigma = 0.164$, while for approximately the same conditions during the December 1982, June 1979, and August 1979 SPE's we find $\sigma = 0.073$, 0.069, and 0.133, respectively.

It is clear from Figure 2 that during and immediately after the SPE, ozone at 0.5 and 1 mbar decreases much more than would be expected from normal variability, while at 2 mbar there is no sign of ozone depletion. During the SPE we see an average 28% ozone depletion from the long-term average ozone at 0.5 mbar, a 15% depletion at 1 mbar, but an insignificant increase of 0.9% at 2 mbar. Values of the ozone mixing ratios and variabilities for each event are given in Table 2. The coincidence of the ozone depletion with the SPE and the persistence of the decrease for seven orbits argue that the depletion was caused by the proton event.

Figure 3 is a similar plot for the same time period and the same latitude, but for the ascending part of the orbit (solar zenith angle zone 50°–55°). Here there is a small decrease in ozone on July 13, but not much larger than the normal variance. We observe a 4.6% decrease in ozone at 0.5 mbar and a 4% decrease in ozone at 1 mbar. Comparison of Figures 2 and 3 suggests that there is a strong solar zenith angle dependence in the observed ozone depletion. A similar dependence of ozone depletion on solar zenith angle was observed by the Solar Mesosphere Explorer (SME) [*Thomas et al.*, 1983]. The explicit solar zenith angle dependence will be discussed later.

Another large proton event of this solar cycle occurred on December 8, 1982. In Figure 4 we plot data for the 82.5–86° solar zenith angle zone, but now at 71°S. We use southern hemisphere data for two reasons: first, the ozone measurement can only be made in sunlight and this solar zenith angle in the northern hemisphere occurs near 60° geodetic latitude so that much of the data would be below the geomagnetic cutoff latitude and, second, the winter ozone field is extremely variable, so that even a 20% ozone depletion would be difficult to detect. The southern hemisphere ozone variability was very low at this time, much lower than in July 1982 and a more typical summer ozone variability.

We find the same pattern of ozone depletion in this SPE as in the July SPE: a clear coincidence of ozone decrease at 0.5 mbar with the SPE itself, a smaller, coincident depletion at 1

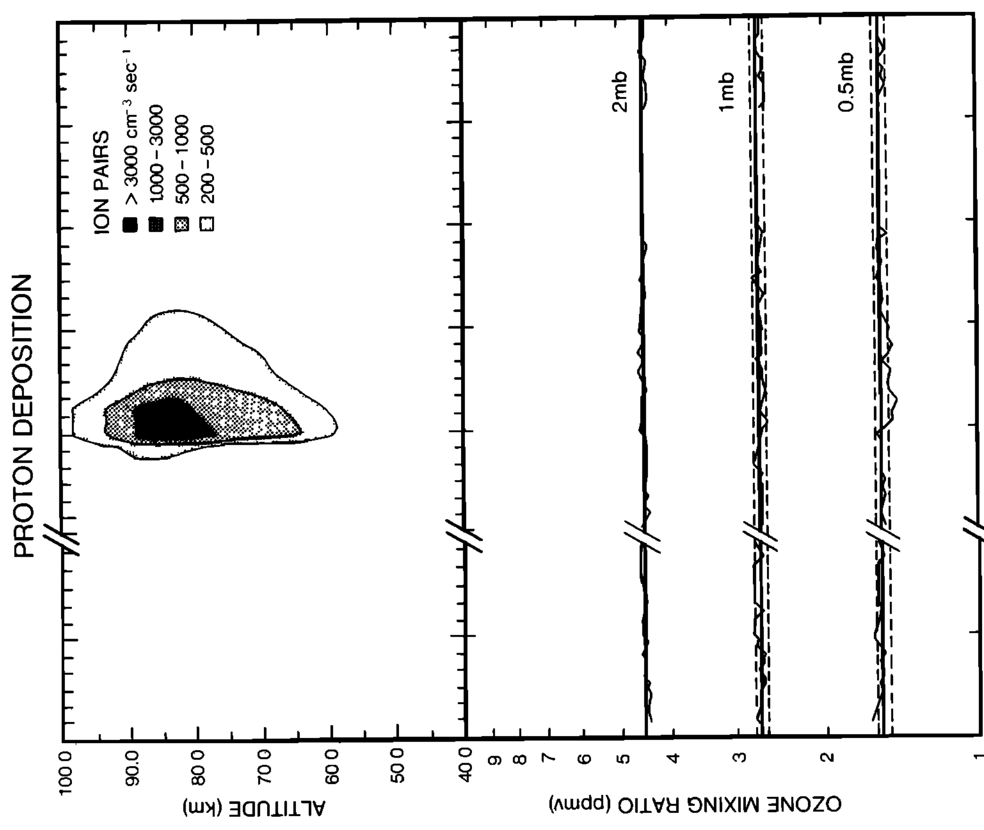

Fig. 5. The ozone mixing ratio at three levels during the June 1979 solar proton event for the 82.5°–86° solar zenith angle zone.

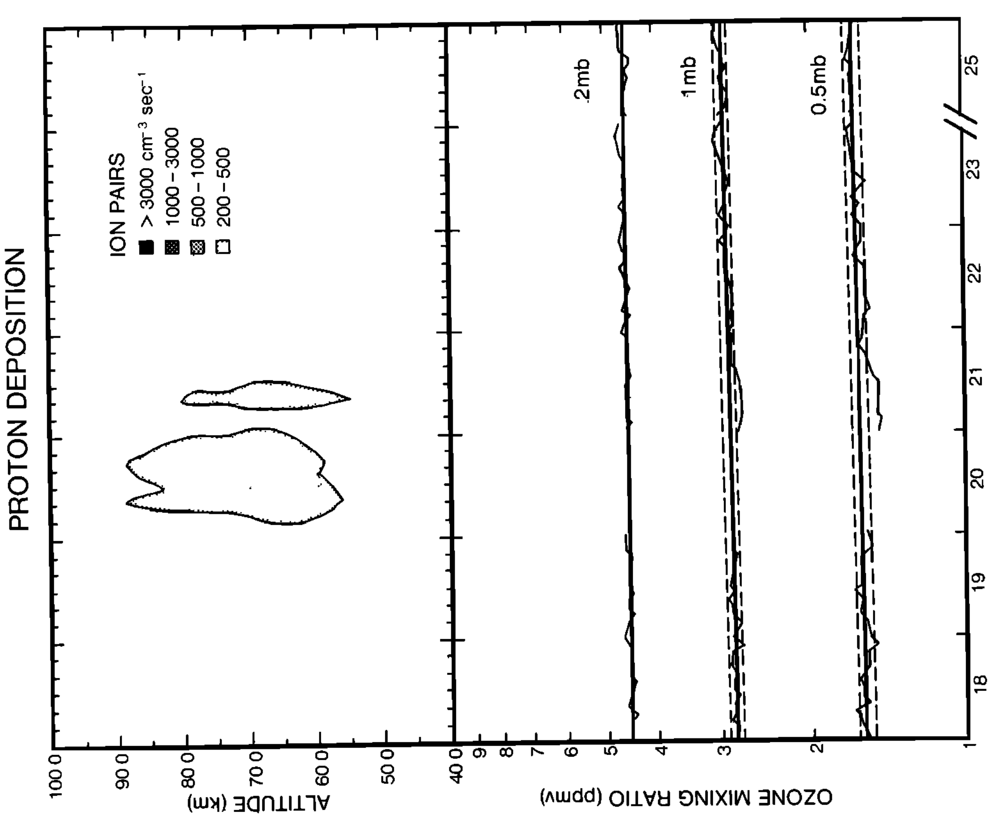

Fig. 6. The ozone mixing ratio at three levels during the August 1979 solar proton event for the 82.5°–86° solar zenith angle zone.

TABLE 2. Statistics for Solar Proton Events

	N	0.5 mbar	1.0 mbar	2.0 mbar	Lat.
		July 13, 1982, ZA = 82.5°–86.0°			
MR-norm	173	1.350 ± 0.162	2.489 ± 0.164	4.266 ± 0.062	72.2
MR-spe	7	0.974 ± 0.173	2.129 ± 0.218	4.303 ± 0.046	72.0
Diff		−27.8%	−14.5%	+0.9%	
		−4.8σ′	−4.2σ′	+1.8σ′	
		July 13, 1982, ZA = 50.0°–55.0°			
MR-norm	200	1.394 ± 0.047	2.265 ± 0.086	4.096 ± 0.094	71.0
MR-spe	7	1.331 ± 0.058	2.175 ± 0.092	4.043 ± 0.073	71.0
Diff		−4.6%	−4.0%	−1.3%	
		−2.9σ′	−2.5σ′	+1.4σ′	
		December 8, 1982, ZA = 82.5°–86.0°			
MR-norm	221	1.570 ± 0.046	2.760 ± 0.073	4.767 ± 0.120	−71.5
MR-spe	10	1.427 ± 0.043	2.594 ± 0.049	4.686 ± 0.046	−71.4
Diff		−9.1%	−6.0%	−1.7%	
		−7.0σ′	−6.1σ′	+1.6σ′	
		June 7, 1979, ZA = 82.5°–86.0°			
MR-norm	169	1.558 ± 0.042	2.673 ± 0.069	4.462 ± 0.113	71.3
MR-spe	4	1.487 ± 0.023	2.646 ± 0.015	4.512 ± 0.040	71.6
Diff		−4.6%	−1.0%	+1.1%	
		−3.0σ′	−1.2σ′	+0.7σ′	
		August 20–21, 1979, ZA = 82.5°–86.0°			
MR-norm	184	1.589 ± 0.086	2.844 ± 0.133	4.508 ± 0.188	79.1
MR-spe	5	1.478 ± 0.025	2.745 ± 0.027	4.511 ± 0.033	79.0
Diff		−7.0%	−3.5%	+0.1%	
		−2.8σ′	−1.7σ′	+0.0σ′	
		October 13–14, 1981, ZA = 82.5°–86.0°			
MR-norm	174	2.160 ± 0.123	4.207 ± 0.234	6.172 ± 0.674	73.4
MR-spe	18	1.868 ± 0.167	4.077 ± 0.256	6.483 ± 0.556	73.7
Diff		−13.5%	−3.1%	+5.0%	
		−9.6σ′	−2.2σ′	+1.2σ′	

MR-norm, average mixing ratio and standard deviation for normal (non-SPE) atmosphere; MR-spe, average mixing ratio and standard deviation during the SPE; Diff, percent change in mixing ratio during the SPE.

mbar, and no depletion at all at 2 mbar. We see a 9.1% depletion at 0.5 mbar and a 6.0% depletion at 1 mbar (see Table 2). Although not shown here, data from the same latitude but for the 50°–55° solar zenith angle zone again show evidence of little ozone depletion.

The behavior of ozone during the SPE's of June and August 1979 are shown in Figures 5 and 6, respectively. Neither event was large, but that in August was relatively long lived, which is fortunate since SBUV was off during the first day of the event. The ozone depletion during the June 7 SPE just barely exceeds the variance; the average depletion is 4.6% at 0.5 mbar and 1.0% at 1 mbar. Only the very low background variability permits this small a depletion to be clearly identified. The August 1979 SPE was less intense but harder than that of June. For 1-MeV protons the June event was approximately 5 times larger than the August event, but for 10-MeV protons the two events were of comparable size. The ion pair production for the August event peaks on the August 20, when no data are available, but there is a secondary peak on August 21. We see an average ozone depletion of 7.0% at 0.5 mbar and 3.5% at 1 mbar.

The final SPE in which ozone depletion is observed is that of October 13–14, 1981, shown in Figure 7. Unlike the other events for which relatively low variance summer data are available, for this event we must use either northern hemisphere fall data or southern hemisphere spring data. We find that the high variability found in the winter zone continues into the spring, while fall data are relatively less variable; consequently, we chose to analyze fall data. At this time the 82.5°–86° zenith angle zone corresponds to a latitude of 73° but on the ascending part of the orbit only. We observe an average depletion of 13.5% at 0.5 mbar and 3.1% at 1 mbar. The background variance is relatively high, 5.7% at 0.5 mbar.

The behavior of the 2-mbar ozone was very unusual at this time. We mentioned earlier that longitudinal ozone variations could appear as temporal variations, and this is what we see at 2 mbar. The apparent daily repetition of the sharp ozone decrease at 2 mbar is caused by passage of the satellite over a persistent ozone low located near 90°W longitude that lasted for more than 2 weeks. This ozone low is intense between 2 and 10 mbar, but hardly visible at 1 or 0.5 mbar. We could find no correlating feature in the 2-mbar stratosphere sounding unit (SSU) temperature data for this period, though there was a temperature minimum located 90° away in longitude. We speculate that this feature is somehow generated by the dynamics of the nighttime polar region transporting low ozone mixing ratio air into this longitude zone.

5. Discussion

We summarize the results of our ozone depletion analysis in Table 2. For each of the five events for which ozone depletion was observed and for two solar zenith angle zones for the July 1982 event, we list the average mixing ratio and standard deviation for three pressure levels. For July 13, 1982, for the 82.5°–86° solar zenith angle zone we first determine the non-SPE behavior using approximately 3 weeks of data. A total of 173 orbits of ozone information were used in a linear fit to determine that the average mixing ratio at 0.5 mbar on July 13 should have been 1.350 ppmv and that the standard deviation was 0.162 ppmv. Normally in each orbit, two ozone profiles are measured 32 s apart within each zenith angle zone and averaged to produce one data point. The two measurements are independent, but the ozone field from sequential measurements is so highly correlated that we treat them as one measurement. The seven orbits of ozone actually measured during the SPE, taken as lasting from hour 12 to hour 24 on July 13, had an average mixing ratio of 0.974 ppmv, representing a 28% reduction in ozone at 0.5 mbar.

The statistical significance of this reduction is shown by expressing this reduction in terms of multiples of the reduced standard deviation. The standard deviation is used to determine the probability that a single sample drawn from a normal population will deviate from the average. The reduced standard deviation is used to determine the probability that a multiple sample drawn from a population that obeys normal statistics will have an average that deviates from the population average. The reduced standard deviation σ' is defined as

$$\sigma' = \frac{\sigma}{N^{1/2}} \tag{1}$$

where N is the number of orbits averaged during the SPE. Examination of the non-SPE ozone shows that the occurrence of low ozone values is more frequent than would be predicted by normal statistics. In order to account for this, the value of σ used in (1) was chosen to accurately reflect the actual probability distribution of ozone values. Using this procedure, the average ozone mixing ratio during the SPE on July 13 was $4.8\sigma'$ lower than the non-SPE average and would certainly be considered statistically significant.

This analysis can establish whether an ozone decrease is statistically significant, but it cannot establish a cause and effect relationship between the decrease and the SPE. If, for

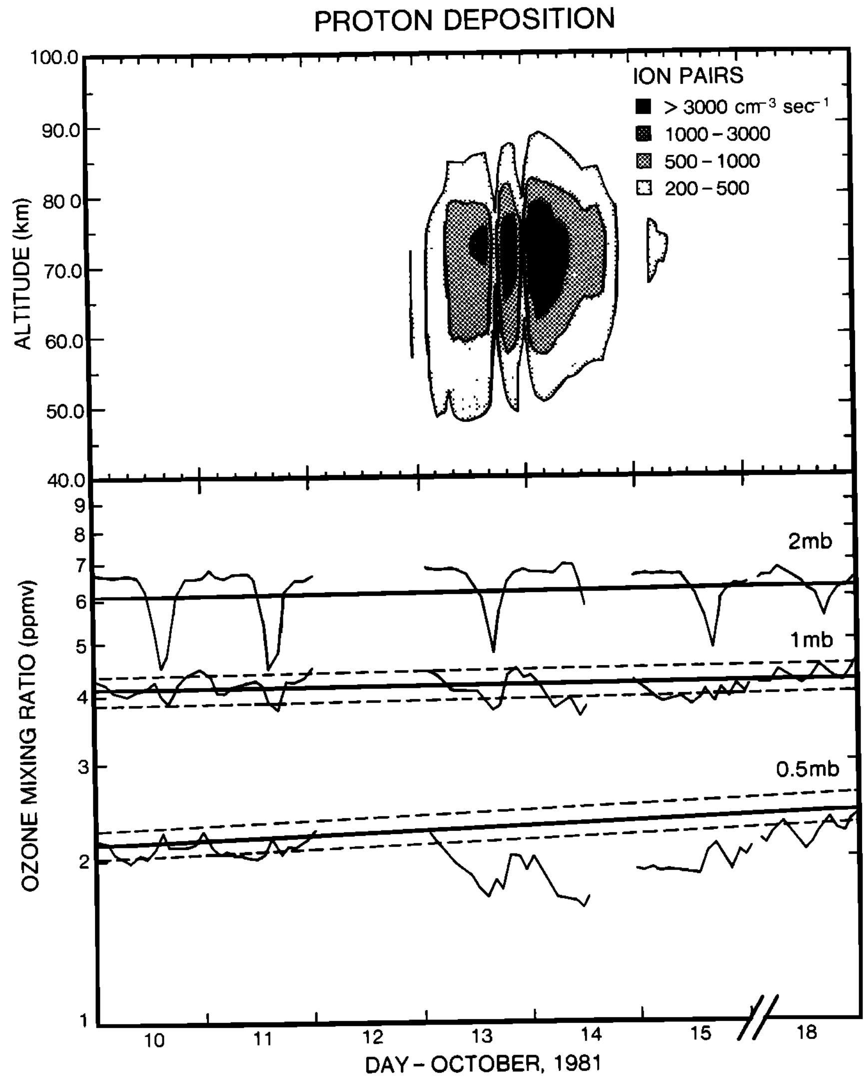

Fig. 7. The ozone mixing ratio at three levels during the October 1981 solar proton event for the 82.5°–86° solar zenith angle zone. Note the persistent local ozone minimum at 2 mbar seen near 90°W longitude each day.

instance, this procedure is applied to a negative ozone fluctuation at 0.5 mbar on July 8, we find a three-orbit average that is $3\sigma'$ less than the long-term average, large enough to be regarded as statistically significant. This is almost certainly a real (nonrandom) change in ozone but caused by some source other than solar protons. We rely on the repeated coincidence of large negative changes in 0.5- and 1-mbar ozone concurrent with solar proton events together with a correlation of ozone change with geomagnetic latitude to argue that the relationship is cause and effect.

Comparison of Figures 2 and 3 for solar zenith angle zones 82.5°–86° and 50°–55°, respectively, indicates a strong solar zenith angle dependence in the response of ozone to an SPE. In Figure 8 we show the explicit solar zenith angle dependence of two SPE's at 0.5 mbar (upper set of curves) and at 1.0 mbar (lower set of curves). The largest SPE, that of July 13, 1982 (solid curve), and a small SPE, that of June 7, 1979 (dashed curve), are shown here. We are plotting the ratio of the ozone during the SPE to the long-term ozone value for each solar zenith angle zone, so that 1.0 represents no depletion at all. Different solar zenith angles correspond to different latitude zones, but since we are comparing each zone with the same zone under non-SPE conditions, the solar zenith angle dependence should be accurate. A strong variation of the proton flux with time of day would distort the zenith angle response function shown in Figure 8, but the fact that the response with zenith angle is similar for each SPE argues against this, since the timing and duration of the events varied considerably. Error bars equal to the reduced standard deviation are plotted for each data point to indicate the significance of the depletion for different solar zenith angles. But, as we noted earlier, nonrandom fluctuations in ozone can occur as a result of dynamical or other processes as well as from the effects of solar protons. Consequently, the reduced standard deviation plotted here probably overstates the significance of ozone changes.

Since the proton flux drops abruptly to zero between 55° and 60° geomagnetic latitude, a good way to distinguish solar proton related effects from other effects is to compare the behavior of ozone from geomagnetic latitudes greater than and less than the cutoff latitude. The zenith angle dependence plotted in Figure 8 for 10°–45° is for geomagnetic latitudes less than 55°, while the zenith angle dependence plotted for 40°–86° is for geomagnetic latitudes greater than 60°. Thus the 40–45° zenith angle zone has data from both below and above the cutoff latitude for solar protons. For the July event the fact that the 40°–45° zenith angle zone shows depletion when the geomagnetic latitude is 60° or greater while the same zone for geomagnetic latitudes less than 55° shows no depletion clearly

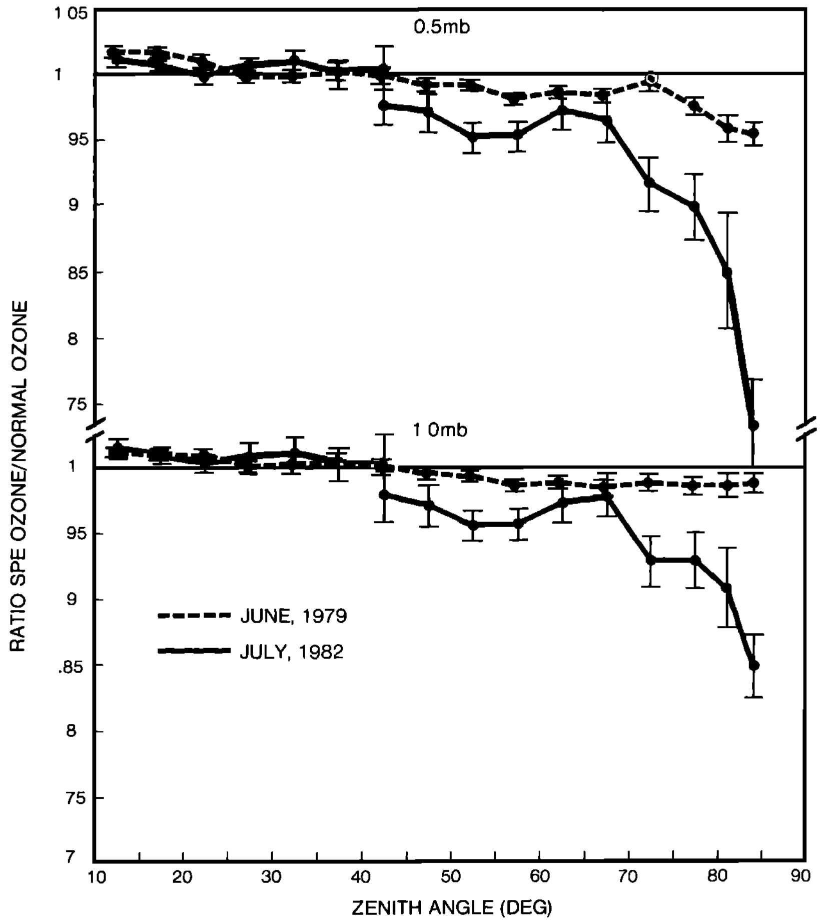

Fig. 8. The solar zenith angle dependence of the observed ozone depletion shown for the July 13, 1982, and the June 7, 1979, solar proton events for the pressure levels 0.5 mbar (upper plot) and 1.0 mbar (lower plot). In each case, data plotted for 0°–45° ZA are from geomagnetic latitudes less than 55°, while data for 40°–86° ZA are from geomagnetic latitudes greater than 60°.

establishes that the ozone depletion was related to the proton event. In the June event, on the other hand, the lack of a transition in the 40°–45° zone indicates that any depletion caused by solar protons at this solar zenith angle was too small to distinguish. Only above 70° solar zenith angle and at 0.5 mbar is ozone depletion clear for this event.

We next address the question of the algorithmic validity of the SBUV profile retrieval; i.e., are the ozone values at 0.5 mbar valid? At large solar zenith angles the increased optical path causes the backscattering contribution functions to peak at higher altitudes, extending the validity range upward. The profile retrieval validity limit is reached when the a priori layer variance based purely on climatology cannot be reduced by the measured radiance information. At moderate solar zenith angles, variance reduction is achieved in the 0.5- to 1-mbar layer, but for solar zenith angles greater than 75°, variance reduction is achieved in the 0.25- to 0.5-mbar layer. For solar zenith angles greater than 82.5°, we believe that we accurately measure ozone to the 0.25-mbar level.

The infrared spectrometer on SME [*Thomas et al.*, 1983] measured a 70% ozone depletion near 80 km during the July 13, 1982, SPE, decreasing to 15% ozone depletion at 55 km. Since we see a 27% depletion at 55 km, we investigated our algorithm to see whether abnormal ozone conditions could produce an error in the retrieved profiles. We checked our algorithm by assuming that the low-altitude depletions measured by SME were correct and calculating the expected backscattered radiances. We then used the calculated radiances in the SBUV inversion algorithm to see whether the input profile could be accurately retrieved. The calculation of radiances from a given ozone profile is quite accurate and, more importantly, unique. A problem common to inversion algorithms is that an infinite variety of possible ozone profiles can match the observed radiances, and constraints and a priori information must be used to select the optimum profile. This procedure of retrieving profiles using calculated radiances is a good way to prove that the algorithm is capable of retrieving a given profile. In this case we find that the algorithm would retrieve the SME profile with very good accuracy below an altitude of 60 km, diverging only at higher altitudes. The SME results at 55 km are therefore inconsistent with the radiances measured by SBUV. The discrepancy may be due to the fact that the same ozone sample is not being observed. SBUV is in a noon orbit and is nadir viewing while SME is in a 2:30 P.M. orbit and is limb viewing. Since the ozone depletion produced by an SPE may depend not only on the instantaneous zenith angle but also on the number of sunlit hours (S. Solomon, private communication, 1984), we may be seeing a sampling difference. The depletion results from SBUV and SME agree fairly well at 60 km; above that altitude the SBUV results are no longer valid.

6. Conclusion

We analyzed ozone data from a total of 15 solar proton events during solar cycle 21 and found evidence of ozone depletion during five of the events. During the large SPE of July

13, 1982, ozone depletion is largest at large solar zenith angles but is significant even at 50° solar zenith angle. The abrupt disappearance of ozone depletion below the 60° geomagnetic cutoff latitude for solar protons is evidence that the depletion is related to the proton flux. In each case, ozone depletion is largest at large solar zenith angles and at the 0.5-mbar level. The depletion is less at the 1.0-mbar level and is not observable in any case at the 2-mbar level. The proton flux during the April 1981 events was large enough that, had the stratosphere been more stable, ozone depletion should have been detectable. The remaining events, in which no ozone depletion was observed, were all smaller than the June 1979 event.

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