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SOLAR PROTON EFFECTS ON AUSTRAL OZONE DURING THE FINAL MONTHS OF 1989

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ABSTRACT

Intense solar activity during 1989 prompted six major particle events. Four of these occurred between August and December. Energetic solar protons are a natural source of ozone depletion due to the nitric oxides they produce in the polar atmospheres. In particular, modelling (Reid *et al.*, 1991) of an event that peaked on October 20 (with > 10 MeV proton flux of 73000 particles cm^{-2} s^{-1} $ster^{-1}$) yields 55% column density enhancements of NO over the southern polar cap.

Total column ozone data from the TOMS instrument aboard the Nimbus 7 satellite used at times when solar illumination facilitates measurements by TOMS over the entire southern polar regions. The impact of odd nitrogen enhancements on the spatial extent of low total column ozone and of the total ozone mass, over a region extending from 90°S to 70°S, is determined for the period August to December. Comparisons are made with previous years (1984 to 1988) of moderate solar activity. The effect, if any, of these events on ozone during times of heterogeneous chlorine chemistry and dynamic processes is discussed.

INTRODUCTION

Energetic solar protons are a natural source of ozone depletion over the polar caps (Stephenson and Scourfield, 1991). They can penetrate the earth's atmosphere at high latitudes (> 60°) where they produce secondary electrons. These secondaries ionize and dissociate N_2 to produce odd nitrogen species which in turn can react with molecular oxygen or ozone to form nitric oxide (Crutzen *et al.*, 1975). Nitric oxide is then able to deplete ozone via the following catalytic reactions:

$$NO + O_3 \longrightarrow NO_2 + O_2$$

$$NO_2 + O \longrightarrow NO + O_2$$

This paper investigates a means by which odd nitrogen species, produced by solar protons, enhance chlorine-catalysed ozone depletion in the austral spring.

In the last five months of 1989 intense solar activity resulted in four large solar proton events (SPE's). By definition, a solar proton event is said to have occurred when the flux of > 10 MeV protons exceeds 10 particles $cm^{-2}s^{-1}ster^{-1}$. Each SPE was characterized by substantial fluxes of high energy protons recorded by the GEOS-7 satellite. The onset dates and fluxes (particles $cm^{-2}s^{-1}ster^{-1}$) were: 12 August 9200; 29 September 4500; 19 October 73000 and 30 November 7300. A 2-D coupled dynamical/chemical model (Reid *et al.*, 1991) forecasts 55% column density enhancements in nitric oxide for these four events over the southern polar cap. Jackman (1991) predicts that altitude ranges attained by solar protons of the SPE's in 1989 would promote measurable stratospheric ozone depletion.

TOMS satellite ozone data were processed for the period from late August (day number 240) 1989 to the end of that year. We have calculated the total mass of ozone (at STP), taking into account the cosine dependence of the cell size of TOMS with latitude, from the south pole to latitude 70°S.

RESULTS

A plot of daily ozone mass, from 90°S-70°S, for day number 240 to 365 (a period during the austral spring that includes the ozone hole) of 1989 is shown as a slender line in Figure 1. Arrows indicate the onset of SPE's the effects of which, since the lifetime of odd nitrogen in the stratosphere is days to months (Reid *et al.*,1991), may be accumulative. In order to assess any effect the SPE's may have had on ozone, a typical mass profile of previous periods including chlorine-catalysed ozone holes must be computed. A baseline comprising of five years of daily ozone masses averaged over 1984, 1985, 1986, 1987 and 1988 (all solar quiet years) was evaluated. This is represented as the broad line in Figure 1. The error bars represent the standard deviation, for consecutive 20 day periods, of all the daily ozone masses over five years. Until day number 300 the 1989 ozone mass profile is always well under the lower limit of these standard deviations.

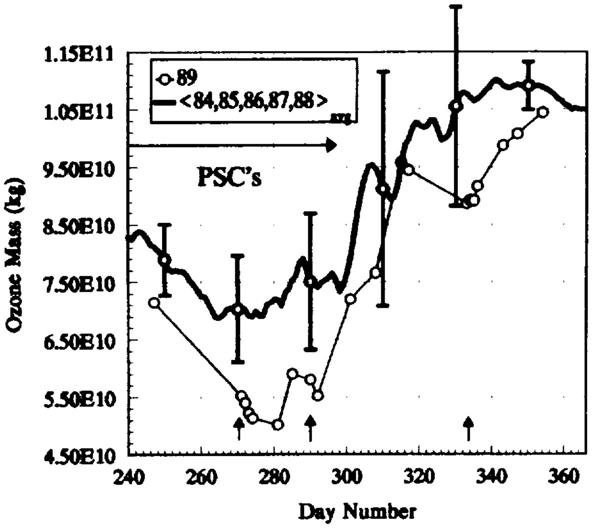

FIGURE 1: The total ozone mass over the zonal band 90°S-70°S for the austral spring of 1989 (slender line) and of a five year average that includes 1984, 85, 86, 87 and 88 (broad line).

Ozone masses are most variable at the time of vortex breakup (whose commencement may vary from year to year), reflected in the high standard deviations, from day number 300 to 340, throughout October and November. Two distinct differences between the 1989 ozone mass profile (slender line) and the 5 year average profile (broad line) are evident. Between day numbers 260 and 305 (end of October) the 1989 ozone hole is considerably deeper than the average profile. A mass difference of 2.2×10^{10} kg around day 280 is over twice the standard deviation. In addition there is a further deviation between the thin and broad lines of Figure 5 from day number 305 to the end of the year. Ozone masses during December 1989 do not recover to those of any of the previous years. A difference of up to $1.9 \pm 1.7 \times 10^{10}$ kg, around day number 333, is evident in this period. Since version 5 (V5) TOMS data were used in computing total ozone mass for 1989 and version 6 (V6) for 1984-88 the slender line representing 1989 data may be 5% too low (Stolarski *et al.*,1990). High zenith angles, as is the case for polar latitudes in winter, usually result in larger errors. However, in austral spring when ozone levels are very low, these errors are minimized.

DISCUSSION

Two of the SPE's (day numbers 272 and 292) were coincident with the ozone hole. During this period of the year polar stratospheric clouds (PSC's), which form in the extreme cold of the Antarctic middle atmosphere, are surfaces for the heterogeneous conversion of passive chlorine reservoirs into reactive chlorine species. The vast majority of PSC's observed are not pure water ice or nacreous clouds since they have extinctions less than 10^{-2}/km (Hamill *et al.*, 1986). They probably consist of a frozen form of nitric acid with three water molecules ($HNO_3.3H_2O$) called nitric acid trihydrate (NAT). These clouds form at a higher temperature (−78°C) than their nacreous counterparts (−83°C). The formation of NAT PSC's results in a highly denitrified stratosphere as removal of reactive nitrogen, which may otherwise trap chlorine into a reservoir molecule $ClONO_2$, is converted into nitric acid.

Peter *et al.*, 1991 have modelled the effect that odd nitrogen from exhaust gases of 600 high-flying aircraft may have on NAT PSC formation probabilities. Since increased concentrations of odd nitrogen lead to a higher saturation temperature (in their case an increment of 3°C), PSC's are able to form at higher temperatures. They predict a doubling in occurrence of NAT PSC's and an even stronger increase of ice condensing on NAT particles for northern polar latitudes. Coincidentally, the mass of odd nitrogen produced by the aircraft is similar to that deposited by a large SPE. The purpose of this work is to ascertain what effect odd nitrogen species may have when added directly to low altitudes in the polar stratosphere (thousands of protons with energies > 100 MeV reaching 30 km and below were detected) during the occurrence of the ozone hole.

A study by Steele *et al.* (1983) showed that PSC observations are highly correlated with low temperatures. Cloud is continuous in regions where temperatures are around or below −85°C (McCormick *et al.*, 1985), inferring that the primary prerequisite for PSC formation is temperature. Assuming that NAT PSC's may form at temperatures of −76°C, due to the increased concentrations of odd nitrogen, we infer that from temperature data at 50 hPa for Sanae (70°S, 2°W), Antarctica that days of PSC formation are from day number 155 to 290 in 1989 as indicated by the horizontal arrow in Figure 1. Of course the underlying assumption here is that Sanae is representative of the area under consideration viz 90°S-70°S.

In order to quantify any effects on ozone concentrations due to additional NAT PSC's we calculated the extent in area of low ozone, < 250 DU within the latitude regions 90°S-70°S and 80°S-70°S. The difference in areas covered by this contour between 1989 and a five year average (1988, 1987, 1986, 1985 and 1984) are shown as thick lines in Figure 2. Solid lines indicate 90°S-70°S and the broken lines 80°S-70°S.

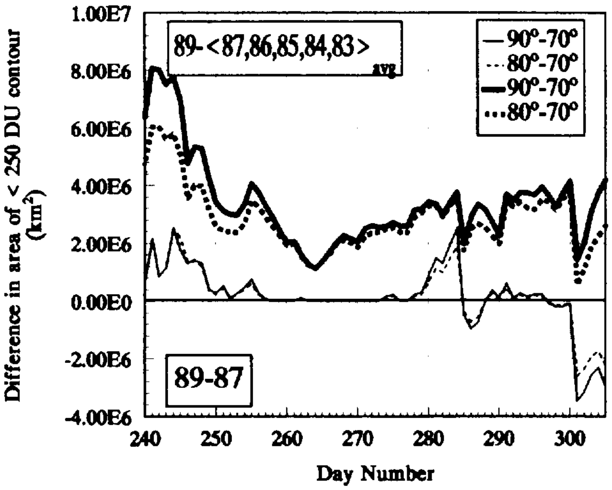

FIGURE 2: The difference in area (km^2) occupied by < 250 DU between 1989 and a five year average (thick lines) and 1987 (thin lines). Solid lines, in both cases, are representative of the difference in area in the latitude region 90°S-70°S, and broken lines 80°S-70°S.

A noticeable feature of the thick lines in Figure 2 is that they are very similar in variance and magnitude, from which we may infer that any changes in area are largely in the zonal band 80°S-70°S. This is what we might expect since lower stratospheric ozone poleward of 80°S is almost totally absent throughout the ozone hole period and the processing by PSC's is therefore saturated. These very low total column values indicate only residual tropospheric and upper stratospheric ozone (Stolarski, 1989). The increase in area of the < 250 DU contour between 80°S and 70°S in 1989, compared with the mean of previous years, varies between 1.3 and 6.0 $\times 10^6$ km^2, well outside any error that maybe incurred by the difference in data versions. To reaffirm this increase a similar analysis between 1989 and 1987 (thin lines in Figure 2) was performed. Again, the solid line is for the region 90°S-70°S and the broken for 80°S-70°S which once again match each other in variance and magnitude. The year 1987 was chosen as it was the 'worst case' ozone hole in the five year period 1984-1988. Areas of increased ozone depletion can be up to 2.632 $\times 10^6$ km^2. The accuracy of the results ($\approx 10^3$ km^2) is limited only by the TOMS polar latitude cell size since V5 TOMS data were used for both 1987 and 1989 data.

The effect of the final SPE in 1989 (day number 334) is hard to quantify as the vortex began to erode in the last two weeks of October (Stolarski *et al.*, 1989) so that ozone temporal and spatial variations were high. However it is likely that ozone destruction, this time via homogeneous gas phase reactions stated in the beginning of this paper, would have occurred.

In summary, an increase in the spatial extent of the 1989 ozone hole compared to previous years was detected. The enhancement of NO_x concentrations due to SPE's may be seen as a likely source to increase the probability of NAT PSC formation. However, the addition of NO_x may, in some instances, result in larger ice particles rather than increasing the area of coverage of PSC's. In addition, extra odd nitrogen will have no effect in regions where processing of ozone is complete.

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