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A Search for Relativistic Electron Induced Stratospheric Ozone Depletion

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Abstract

Possible ozone changes at 1 mb associated with the time variation and precipitation of relativistic electrons are investigated by examinating the NIMBUS 7 SBUV ozone data set and corresponding temperatures derived from NMC data. No ozone depletion was observed in high-latitude summer when temperature fluctuations are small. In winter more variation in ozone occurs, but large temperature changes make it difficult to identify specific ozone decreases as being the result of relativistic electron precipitation.

Introduction

The deposition of energetic electrons and protons in the mesosphere and stratosphere creates N, NO, HNO_3, and OH from molecular oxygen, nitrogen and water. The increase in these minor species causes ozone to be destroyed (Weeks et al, 1972 ; Heath et al, 1977). These initial detections of the ozone-depleting effects of energetic charged particles were associated with energetic protons originating in solar flares. The recovery time for stratospheric and mesospheric ozone was several days. However, these events are the result of the largest proton event, August 1972, and another large flare. Most proton flares produce a measurable effect in the stratosphere, 2 to 0.5 mb, which is much smaller and often lasts for only a few hours (McPeters and Jackman,1985). The number of such flares is limited to several per year, with some years having very few, depending on solar sunspot cycle (Jackman and McPeters,1985).

It is well established that the terrestrial radiation belts contain fluxes of relativistic electrons, some with energy in excess of 1 MeV. Such energy is sufficient to allow the electrons to penetrate below 50 km in the atmosphere. These fluxes of electrons exhibit rapid time variation (Nagai, 1988). It has been suggested that the large temporal variations correspond to deposition of these electrons into the atmosphere (Thorne, 1979; Baker et al, 1986,1987). Direct measurements of relativistic electron flux events have been reported by Herrero et al (1991). It has been suggested that the electron density enhancements below 70 km observed above Scott Base, Antarctica are the result of relativistic electron precipitation (von Biel, 1991). An examination by Aikin (1992) failed to establish any correlation in the summer events studied. Southern hemisphere high-latitude winter and spring ozone changes have been correlated with orbiting electron flux changes (Callis et al, 1991). The present paper is a more extensive investigation of the NIMBUS 7 data set for the effect on ozone of eneregetic electron events.

Relativistic Electron Fluxes and Their Regions of Precipitation

Large fluxes of electrons with energies greater than 1 MeV are observed in the radiation belts (Baker et al, 1986, 1987). A sample of such observations for parts of 1984 and 1985 is shown in Figure 1., which is adapted from Nagai (1988). Flux changes of several orders of magnitude are observed within a period of several days. These large changes in flux would seem to indicate that the electrons have been deposited in the

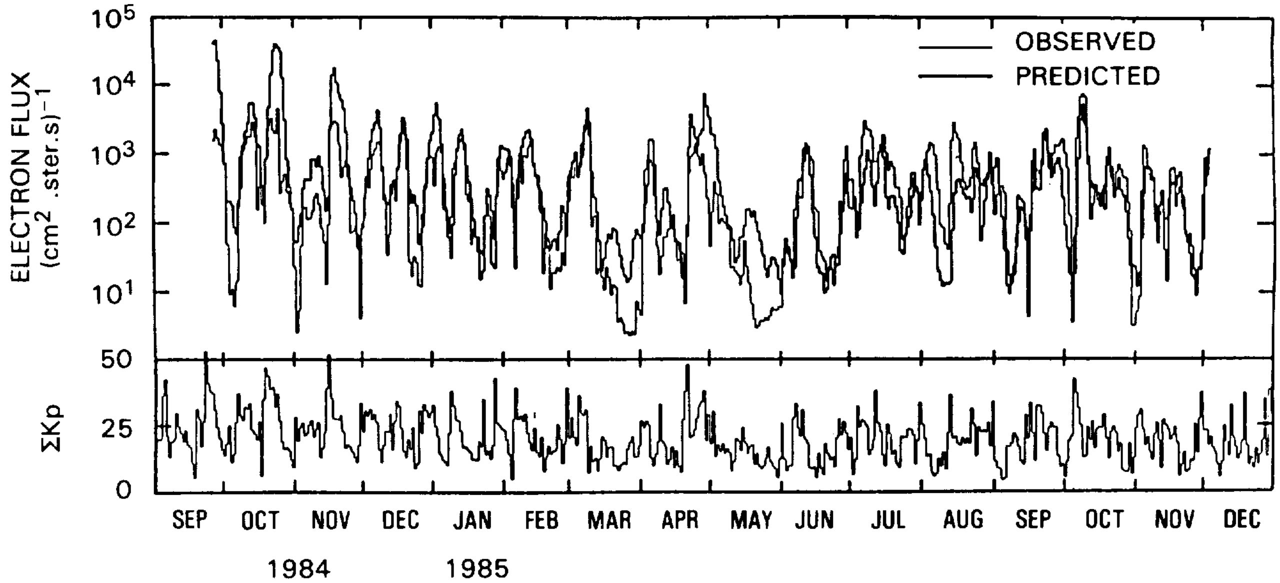

Figure 1 Geosynchronous orbit relativistic electron fluxes for 1984 and 1985 together with predicted flux variations. (Adopted from Nagai, 1988).

atmosphere. Their energies are sufficient in some cases to be deposited at altitudes as low as 45 km.

Analysis of Relativistic Electron Flux Decay Periods for Evidence of Stratospheric Ozone Depletion

The flux changes depicted in Figure 1 are used to identify periods when relativistic electron precipitation should occur. The ozone data set acquired with the SBUV instrument on NIMBUS 7 was used to provide ozone mixing ratios at a pressure level of 1 mb (48 km). Data are averaged over the designated time periods. Since all longitudes are not covered each day, data gaps will be present when only one or two days are considered. Ozone data are displayed in the form of polar projection maps. The ozone amounts at each location are expressed in μg/g and displayed as different colors. The legend for these amounts is included on each color panel.

Using data taken from the NOAA satellites, temperature is also displayed for each period studied for ozone changes. These data termed NMC, are displayed on a polar plot for the pressure level of 1 mb. Depending on season, temperature can exhibit differing degrees of zonal asymmetry and temporal variability. Temperature changes affect ozone through the rate coefficients, which are temperature dependent, so that it is advisable to chose time periods when the temperature is zonally symmetric between 60° latitude and the north or south poles. Summer is the best season to meet this criterion.

The Event of June 1985

Figure 1 shows that there is a two orders of magnitude change in electron flux, which began in mid-June of 1985. The predicted relativistic electron flux changes are based on a model, which utilizes the magnetic index Kp. Flux decreases begin around 10 June and reach a minimum at 20 June. The beginning of June is characterized by a buildup in radiation belt flux, so large amounts of relativistic electron flux precipitation will be negligible in this period.

During the month of June, the temperature field north of 60° is uniform with the highest global temperatures of the 1 mb pressure surface found in this region. This is illustrated in Figure 2, which presents a series of polar plots covering the periods from 1 to 7, 8 to 14, 21 to 27, and 28 to 30 June 1985. Between 60° and 70°, the temperature distribution is zonally symmetric, with values between 270°K and 275°K. The region between 70° and the pole has temperatures lying between 275°K and 280°K. This picture of a two-temperature spatially uniform representation north of 60° is valid for the entire month of June. Temperature changes are not an important factor in any ozone change seen at 1 mb during June 1985.

The corresponding polar plots of ozone at 1 mb cover the same time periods in June as the temperature, are also shown in Figure 2. Here the ozone mixing ratio is displayed according to the color legend given on the side of each panel. The ozone distribution north of 60° latitude exhibits a decrease as the month progresses. The maximum decrease is on the order of 50 $x10^{-2}$ μg/g at latitudes greater than 70°. Zonal symmetry about the north pole is maintained throughout the month. There is no spatial dependence, which might be attributed to relativistic electron precipitation within the auroral zone. This effect may be canceled by a very rapid zonal circulation producing symmetry. Alternatively, it may be that any ozone reduction potential produced by electron of nitric oxide is overwhelmed by the production caused by normal photochemistry in the presence of sunlight.

Other Events Attributed to Relativistic Electron Events

Von Biel (1989) has reported radio wave partial reflection observations of electron densities as large as 10^3 cm^{-3} at 50 km above Scott Base (77°51'S 166°45"E geographic and 79°12'S 315°30'E geomagnetic) near the south geomagnetic pole. Periods of elevated electron densities were compared with ozone maps at 1 and 2 mb by Aikin (1992) to determine if any ozone depletion was associated with these events. Of the events studied. No ozone depletion was found to be associated with the events studied.

Discussion

No ozone depletion was detected in the northern auroral zone during June in spite of the large relativistic electron flux changes observed by high altitude in situ electron measurements. Since the temperature was well behaved north of 60°, exhibiting no large spatial or temporal excursions, the ozone data need not be corrected for temperature.

One possible explanation is that the pitch angle distribution of the precipitated electrons is restricted to angles greater than 30°. This effect has been observed by Herrero et al (1991). The different altitudes for the effective depths of penetration for a 1 MeV electron with a range of incidence angles from 0° to 70° are summarized in Table I. These depths of penetration do not take into consideration bremsstrahlung, caused by electron deceleration and having energy not exceeding the energy of the electron. The depth of penetration of these x-rays is greater than that of electrons of the same energy. However, the contribution of x-rays is a small fraction of the electrons.

If the electron pitch angles are greater than 30°, then the spectrum of electrons deposited below 50 km is restricted to those electrons with energies greater than 2 Mev for pitch angles of 30°, greater than 3 MeV for pitch angles greater than 45°, and 4 MeV for electrons with an angle of 60°. Those electrons with even greater pitch angles must have energies in excess of 4 MeV, a situation unlikely to occur for these precipitation events. In a recent measurement of electron fluxes between the energies of 0.1 and 3.8 MeV during a relativistic electron event from Poker Flat, Alaska,(65.1°N, 147°W), for an L=5.5, Herrero et al (1991) found that for electrons with energies greater than 0.5 MeV that the flux of electrons with a pitch angle of 90° was about 100 times the flux of electrons with 0° pitch angle. This measurement

Table I
Deposition Height (km) for Electrons With Different Energies and Pitch Angles

	Pitch Angle				
Electron Energy (MeV)	0°	30°	45°	60°	70°
1	54	55.5	57.5	59.5	61.5
2	49	50	51	54.5	57.5
3	48	49	50	53.5	56.5
4	44	46	47.5	50.5	53.5

occurred during a small event. During large events, the spectrum will contain more high energy electrons, which penetrate further into the atmosphere. Nevertheless, one cannot avoid the likelihood that the amount of ionization below 50 km created by relativistic electrons may be less than the isotopic pitch angle. One possibility is to examine higher-altitude ozone data. In the case of SBUV this is difficult. Data at 0.5 mb are much less accurate than at lower altitudes.

Because of the influence of disturbed meteorological conditions and the loss of data in regions where sunlight does not penetrate during winter, only summer data were examined in this study. The increased amount of odd hydrogen produced by sunlight in the summer relative to the winter means that the influence of energetic charged particle deposition is reduced by a factor of 2. This translates into an expected change of 6 to 8% for the predicted ionization rates. While the signal-to-noise ratio is better in summer, the magnitude of the expected ozone decrease is better in winter. These figures are baserd on studies of solar flare-produced proton events (McPeters and Jackman, 1985 ; Jackman and McPeters,1985).

Conclusions

There is no evidence of depletion in the events examined here. This eliminates large-scale ozone changes lasting several days.To correctly identify an ozone depletion caused by relativistic electrons, the following criteria should be met. There should be evidence in the radiation belts of large changes in the flux of orbiting electrons. Corresponding to these flux changes there should be detectable enhancements of the electron densities in the lower ionosphere. One added certainety is to examine conjugate observations of electron density changes. Ozone data need to be corrected for local temperature effects and then examined. Data at altitudes above 45 km is the most important. Short time scale events will be more frequent than long-time scale events. The magnitude of the ozone effect in summer will only be 50% that of winter when the solar zenith angle has increased from 50° to near 80°.

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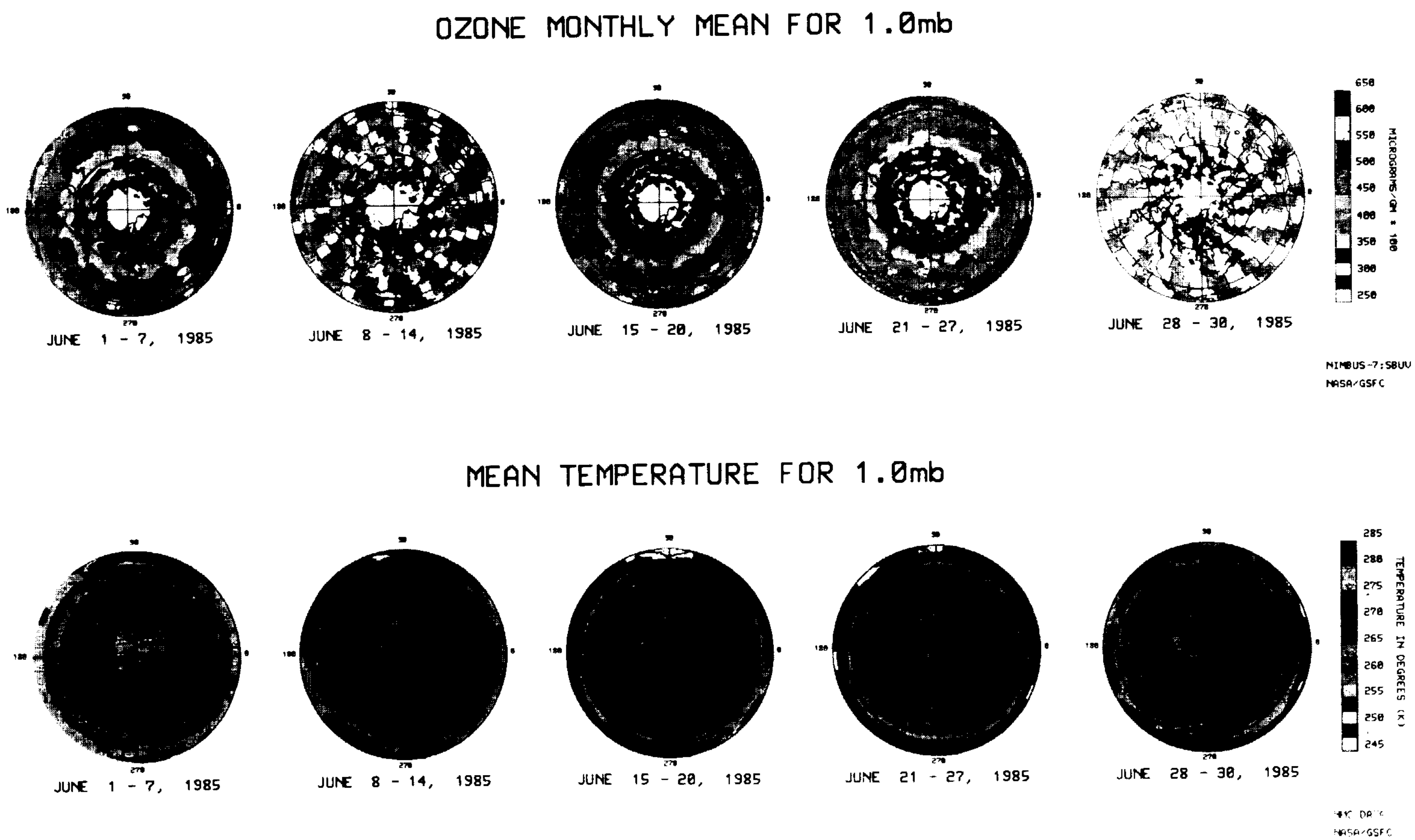

Figure 2 Ozone and temperatures for the month of June 1985 at a pressure level of 1 mb. Temperatures and ozone plotsare colorcoded with the key given on the side of the plots. Ozone amounts are in units of $\mu g/g$ x10^2. Temperatures are displayed in units of ° K.