Energetic Electrons and their Effects on Upper Stratospheric and Mesospheric Ozone in May 1992

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The increased fluxes of precipitating energetic electrons ($E > 1$ MeV) during highly relativistic electron events (HREs) produce ion concentrations in the upper stratosphere and lower mesosphere that exceed the background concentrations. Coupled ion-neutral chemistry models predict that this increased ionization should drive HO_x reactions and deplete mesospheric ozone by up to roughly 25%. As HREs become more intense and frequent during the declining phase of the solar cycle, it was also predicted that mesospheric ozone would show a solar cycle modulation as a result of these events. To calibrate the effect HREs have on mesospheric ozone, we have studied the May 1992 HRE with several instruments on the UARS. Electron fluxes measured with HEPS give the duration and spatial coverage of the HRE. Ozone data from MLS, CLAES, and HRDI were examined for the chemical signature of the HRE, ozone depletions within the magnetic L-shell limits of $3 \leq L < 4$. Using the multiple viewing angles of HRDI, we can compare mesospheric ozone at similar local solar times before, during, and after the HRE. This removes some of the ambiguity caused by progressive sampling of the diurnal cycle over a yaw cycle of the satellite. Although we analyzed one of the most intense HREs in the UARS database, we did not find HRE-induced changes in the ozone mixing ratio between altitudes of 55–75 km. Detecting a long-term trend in the ozone driven by precipitating electrons appears to require a substantial increase in the signal-to-noise ratio of the satellite measurements.

1. INTRODUCTION

Signatures of solar activity in the terrestrial atmosphere are often simple correlations of some climate measurement with sunspot number or solar radiative output at some particular wavelength. One highly publicized example is the correlation of the length of the sunspot cycle with the increase in average Northern Hemisphere temperature over the last century [*Friis-Christensen and Lassen*, 1991]. Although climate changes are correlated with solar activity, the radiative output of the Sun does not vary with an amplitude sufficient to cause the observed temperature increase.

Fluxes of charged particles emitted by the Sun as the solar wind are also modulated by the solar cycle and could affect the Earth's climate. When these particles enter the Earth's atmosphere they are slowed and stopped by succes-

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sive ionizations of atmospheric gases. The produced ions can alter the chemical composition of the atmosphere by changing the concentration of compounds that serve as catalysts in photo-chemical reactions. Solar proton events are one example of a particle influence on the stratosphere. Energetic protons are able to reach the stratosphere and destroy ozone by enhancing NO_x-catalyzed reactions [e.g., *Thomas et al.*, 1983; *McPeters and Jackman*, 1985; *Jackman et al.*, 1990].

More frequent and longer lasting than solar proton events are increases in the flux of electrons with energies in excess of 1 MeV, termed highly-relativistic electron events (HREs) [*Baker et al.*, 1993]. Solar wind electrons are injected into the magnetosphere and then accelerated to these high energies as they diffuse inward toward the Earth. As a result, the highest fluxes are observed at the inner edge of the outer radiation belt, near a magnetic L-shell coordinate value of $L = 3$. While solar protons can reach and influence the stratosphere, energetic electrons can penetrate only to the mesosphere and upper stratosphere before depositing their energy. Photochemical models have shown that the enhanced ionization during an HRE should deplete ozone in the mesosphere by changing the concentration of HO_x compounds [*Goldberg et al.*, 1994; 1995a,b; *Aikin and Smith*, 1999]. For the range of electrons in air used in *Goldberg et al.* [1984] electrons with $0.1 \leq E \leq 1$ MeV will produce HO_x radicals between altitudes of about 60 and 80 km and could affect the ozone balance in that region. Unlike the burst-like, geographically-limited nature of low energy electrons linked to auroral activity, electrons with $E > 0.1$ MeV have drift periods less than 0.1 days [*Walt*, 1994]. This means that the HRE electron flux is independent of magnetic local time and is roughly constant along a magnetic L-shell [*Vampola and Gorney*, 1983]. Thus, not only are HREs long lasting, they affect a large geographic area while they are active. A typical flux value affecting this region can be derived by averaging all measured precipitating fluxes within a band of L.

We describe here an attempt to detect these effects during what we consider to be an optimum energetic electron event, the highly relativistic electron event of May 1992. We first discuss the variation of the energy input into the mesosphere due to energetic electrons as measured by PEM/HEPS. Next, we outline our expectations of how that input would change the ozone in the stratosphere and mesosphere, and finally, the MLS, CLAES, and HRDI measurements that test these expectations.

2. HIGHLY RELATIVISTIC ELECTRON MEASUREMENTS FROM UARS

The Particle Environment Monitor (PEM) High Energy Particle Spectrometer (HEPS) instrument on the Upper Atmosphere Research Satellite (UARS) provides pitch-angle- and energy-resolved measurements of the low-altitude electron flux between 30 keV and 5 MeV [*Winningham et al.*, 1993]. For this analysis the pitch-angle resolution in the measurements is used to distinguish those electron fluxes that are in the bounce loss cone and will directly precipitate into the atmosphere from those that are stably trapped (i.e., they have estimated mirror altitudes above 100 km).

From surveys performed by the PEM/HEPS team, the highly relativistic electron fluxes of May 1992 were the most intense, most energetic, and longest lived of the events seen by UARS from the launch of UARS through the end of 1993 [*Gaines et al.*, 1995]. Within the belt of magnetic L-shell $3 \leq L < 4$ (or magnetic latitudes between 55° and 60°), the locally precipitating flux of electrons with both $E > 100$ keV and $E > 1$ MeV reached a large value on May 11 and continued at this value until May 21 [*Pesnell et al.*, 2000]. It then decreased by a factor of about eight in magnitude and continued through May 27. Compared to background effects for magnetically undisturbed times and locations, the ion production rate in the lower mesosphere due to electrons increased at least 100 times during this HRE. Other events measured by HEPS were shorter, less intense, or less energetic.

3. PREDICTED ION PRODUCTION RATE AND LOSS OF OZONE DUE TO ELECTRON PRECIPITATION

From the measured precipitating electron energy spectra, we have derived ion-pair production rate (Q) height profiles using the techniques described in *Goldberg et al.* [1984]. Figure 1a shows the ion-pair production rate profiles for day-averaged precipitating fluxes in two bands of $L = \bar{L} \pm 1/8$ and for one large burst observed on May 18, 1992. From these profiles it is apparent that large quantities of ions are produced down to 50 km, far deeper than produced during other kinds of electron precipitation events.

Ions produced during an HRE can, through complicated ion chemistry, enhance HO_x compounds and influence the ozone concentration during the particle event [*Solomon et al.*, 1981; 1983]. Approximately two HO_x species are produced from each ion pair up to about 70 km. However, above 70 km, the production of HO_x species from each ion pair has a strong dependence on the ionization rate and the duration of the particle precipitation event [*Solomon et al.*, 1981]. Our model calculations use the production of HO_x constituents per ion pair as a function of altitude from Figure 2 of *Solomon et al.* [1981] for moderate ionization rates. This accounts for the rapid dropoff in ion-related HO_x production with increasing altitude and is within 5% of their rates for the ion production rates in Figure 1a.

We used an assumed continuous source of HRE-related HO_x production from the ion-pair production rate curves of

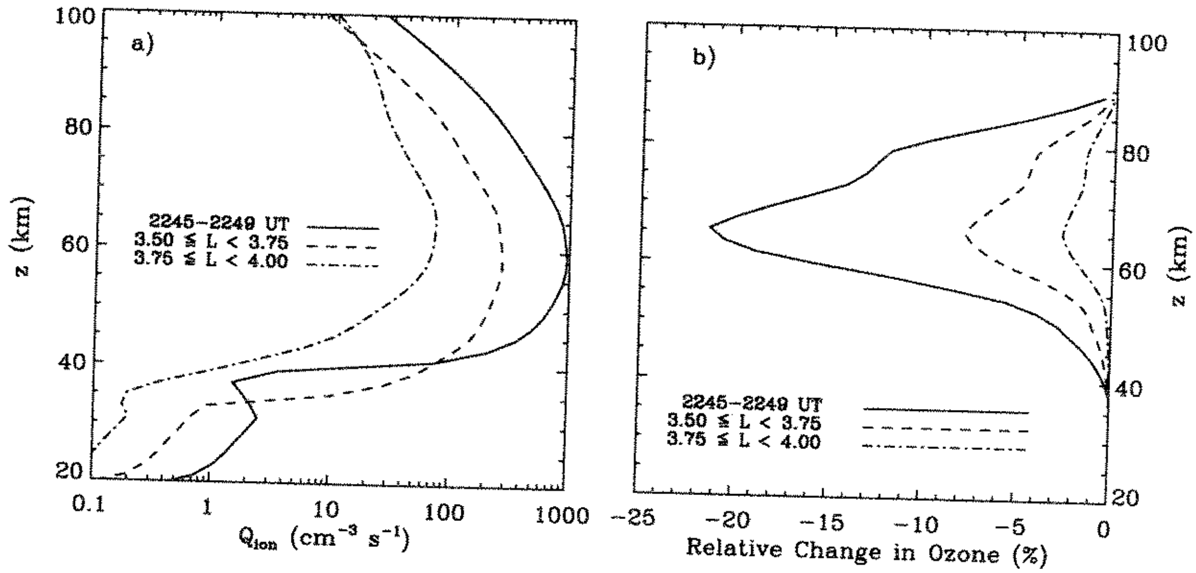

Figure 1. On left (a), ion-production rates for the day-averaged electron fluxes of May 18, 1992 for two ranges of L and for a large localized precipitating burst of electron flux that was measured between 2245 and 2249 UT near $L = 3.75$. In (b), the modeled ozone depletion for those ion production rates.

Figure 1a in the GSFC-2D chemistry and transport model of *Jackman et al.* [1990; 1996] at 65°N to predict the ozone change. Our simulated ozone percentages change due to the HREs were computed by comparing a model run that includes the electron-induced ions calculated with the May 18 HRE fluxes shown in Figure 1a with another model run without the HRE flux are presented in Figure 1b. When ion-production rates caused by measured instantaneous electron fluxes are used in both steady-state and time-dependent (*Aikin and Smith* [1999]) photochemical models, ozone depletions up to about 20% are predicted at mesospheric altitudes. Although the ozone data has considerable noise, a depletion of 20% should be observable in the data. We have also displayed the ion-pair production rates and relative ozone depletions of the more conservative daily averaged electron fluxes, which should be a reliable indicator of the impact of the HRE on the mesosphere. The peak computed ozone decrease due to the day-averaged HRE precipitation is about 7.5% at $\sim$ 65 km. In addition, the time-dependent model shows that the response of mesospheric ozone to the HO_x radicals produced by the electron flux is greatest in the mid-morning portion of the diurnal cycle.

4. OZONE MEASUREMENTS FROM UARS

UARS ozone measurements should be able to quantify the ozone change and determine if the May 1992 HRE was responsible for a significant ozone variation. Although large bursts of electrons are seen in the HEPS data, we were unable to find a corresponding 20% depletion of ozone in the composition measurements. We then searched for reductions in the ozone mixing ratio that would correspond to the day-averaged HRE electron flux. This requires comparing ozone measurements taken within the affected L-shells but across times when the electron flux changes rapidly. Due to the way UARS samples the diurnal cycle of material in the mesosphere and upper stratosphere, we must also compare ozone measurements made at similar local solar times as well.

To resolve the diurnal cycle of ozone, we use the precessing orbit of UARS to scan the instruments 24 hours in local solar time (LST). While the cryogenic limb array etalon spectrometer (CLAES) and microwave limb sounder (MLS) measure thermal radiation and can see the entire diurnal cycle, the high resolution doppler imager (HRDI) measures scattered sunlight, and no data is returned from any branch when the sun is absent. At the beginning of a yaw cycle, ozone measurements are made at two values of LST, one in the A.M. branch near noon and one in the P.M. branch near midnight. As the yaw cycle progresses both branches move to earlier values of LST, reaching near midnight and noon, respectively, just before the turning of the satellite that starts the next yaw cycle. Complete coverage of the available portion of the diurnal cycle is available for a given latitude band by combining observations of the A.M. and P.M. branches observed over a yaw cycle. The cold side of UARS was pointed north during May 1992, so all of the ozone measurements are in the northern polar region throughout the event.

Altitude profiles of CLAES and MLS measurements were obtained from the UARS Central Data Handling Facility at the Goddard Space Flight Center. Altitude profiles of HRDI measurements were supplied as 3AT files by the HRDI Sci-

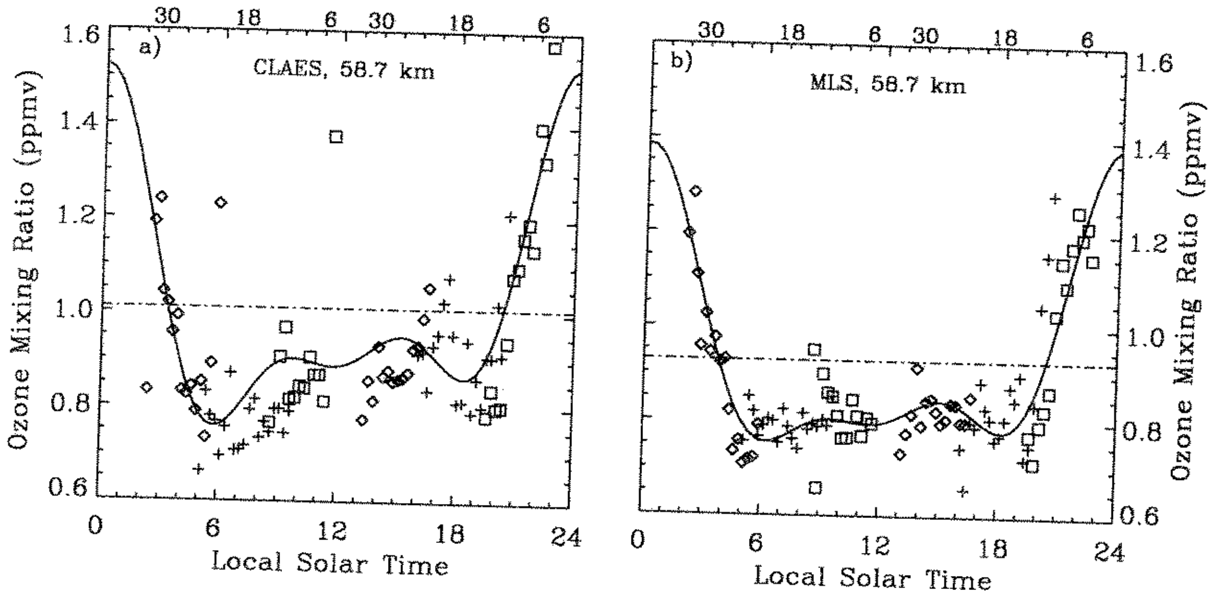

Figure 2. Ozone mixing ratios in the upper stratosphere measured by CLAES (a) and MLS (b) between May 6 and May 30, 1992 with $3 \leq L < 4$ are shown. Data taken during the HRE (5/11-5/21) are labeled with a '+' sign, data after 5/21 are labeled with a '◇' and before 5/11 with a '□'. Numbers across the top of each graph show the approximate day in May 1992 when that LST was measured. Solid lines are a low-order Fourier fit to the data and the dot-dashed lines are the average ozone values derived from that fit.

ence Team at the University of Michigan. Each 3AT file contains a day's worth of data sampled at intervals of 65.536 s. Profiles of measured quantities are given on fixed altitude grids. Data from May 1992 with geographic locations within the magnetic L-shell band $3 \leq L < 4$, where significant long-lived fluxes of precipitating electrons are seen, were extracted from the data files and analyzed using algorithms described in *Pesnell et al.* [1999; 2000].

In order to average the data, without further mixing undisturbed ozone values with those exposed to the HRE, which would further reduce the strength and significance of the depletion signal, we averaged ozone values that were measured before May 11, after May 21, and from May 11 to May 21 (when the HRE flux is present) within 15 m (CLAES and MLS) or 30 m (HRDI) LST bins. When plotted against LST, we would expect the ozone values measured during the HRE would show a downward shift compared to the ozone when the HRE is not in progress. Ozone mixing ratios from CLAES and MLS are shown as a function of LST in Figures 2a and 2b, where ozone mixing ratio data at 59 km altitude for May 6–30, 1992, with geographic locations in the range $3 \leq L < 4$, are shown. As can be seen in Figures 2a and 2b, there is no consistent downward shift of the ozone mixing ratio in the upper stratosphere when the HRE flux is present. Since these measurements are on the bottomside of a steeply sloped functions (see Figure 1b), measurements in the altitude region of the predicted maximum ozone depletion near 65 km would be a useful extension of the CLAES and MLS data. Such data is available from the HRDI instrument.

An advantage of the multiple viewing angles of HRDI is the overlapping coverage of the diurnal cycle. As can be seen in Figure 3a, there are four bands of LST values where ozone is measured in two of the three conditions: before, during, or after the May 1992 HRE. We show the LST variation at one altitude and then the altitude variation within the overlapping measurements in the mid-morning. The diurnal cycle in averaged values as observed by HRDI at 69 km agrees with the time-dependent model of *Aikin and Smith* [1999], with a maximum near noon and a minimum near 1500 LST (Figure 3a). In Figure 3a the error bars are drawn to illustrate one standard deviation. As with the MLS and CLAES data, no downward shift is seen in the ozone data taken with the HRE flux compared to that without.

In Figure 3b we compare mid-morning observations ($0900 < \text{LST} \leq 1000$), where the time-dependent chemistry model of *Aikin and Smith* [1999] predicts the greatest sensitivity to the electrons. At this point in the diurnal cycle the HO_x compounds have increased to a sufficient quantity to have an appreciable effect on the ozone. The profiles in Figure 3b compare data taken across the onset of the HRE, when the precipitating fluxes increased by a factor of 100 at all energies in a short period of time [*Gaines et al.*, 1995; *Pesnell et al.*, 2000]. With the rapid increase in electron flux and the calculated sensitivity to that flux, this is the best opportunity for seeing the predicted effects. However, no consistent de-

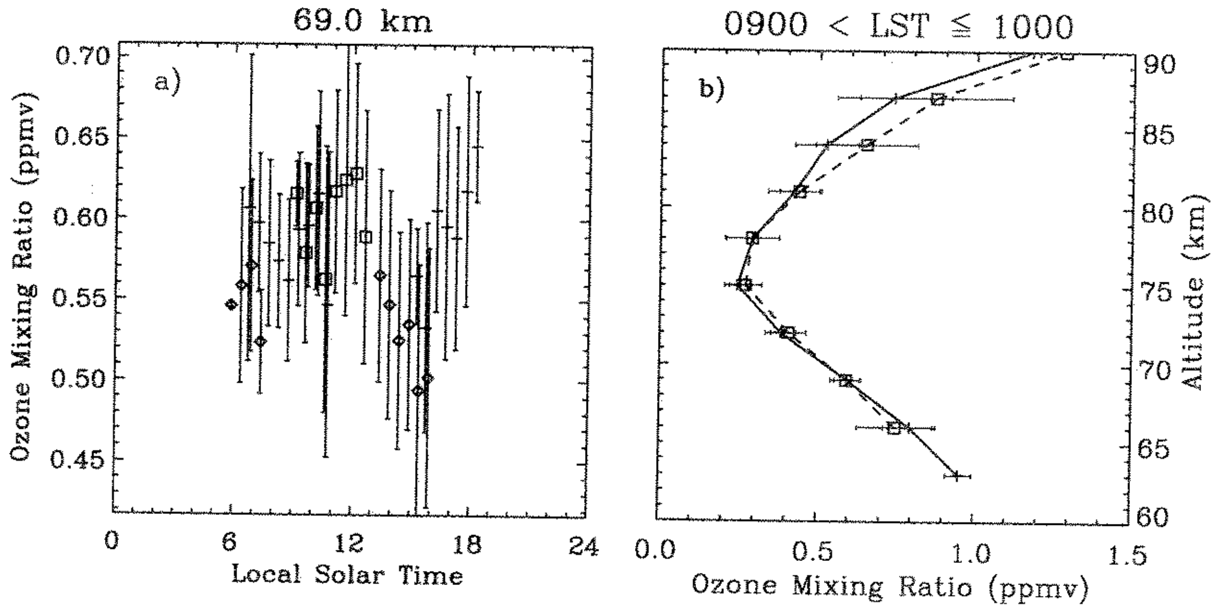

Figure 3. a) Ozone data at 69 km measured by HRDI between May 6 and May 30, 1992, with $3 \leq L < 4$, and averaged over 15 m in LST are shown. Data taken during the HRE (5/11-5/21) are labeled with a '+' sign, data after 5/21 are labeled with a '◇' and before 5/11 with a '□'. In (b) are averages of altitude profiles taken between 0900 and 1000 LST for before ('□', connected with a dashed line) and during ('+', connected with a solid line) the HRE.

creases in the ozone altitude profiles are seen when the measured values between 66 and 81 km from before and during the HRE are compared (Figure 3b).

5. CONCLUSIONS

According to the two models used to predict ozone depletions, it appears possible that highly relativistic electron events should cause measurable, localized depletions of ozone in the upper stratosphere and mesosphere. Furthermore, the chemical models predict that the depletion amplitude should peak in the altitude region we have examined. Ozone data from MLS, CLAES, and HRDI have been examined for evidence of ozone depletions due to the precipitation of relativistic electrons in May 1992. Ozone data between altitudes of 59 and 81 km were examined to determine if the predicted depletions were visible in UARS measurements. Similar relative depletions should have been seen when comparing ozone measurements made at those LSTs that were observed both with and without the HRE irradiation.

Although we have analyzed one of the most intense and longest lasting HRE event seen during the prime mission period of UARS, we found no measurable effect on ozone in the mesosphere (this work and *Pesnell et al.*, 2000]) or the upper stratosphere [*Pesnell et al.*, 1999]. Without a consistent, measurable effect, these results cast doubt on the long-term significance of the effect that highly relativistic electron events have on the overall ozone budget in the mesosphere.

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