Seasonal variation of auroral electron precipitation

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[1] Global observations of nitric oxide obtained from the Student Nitric Oxide Explorer (SNOE) have been used to determine the density of nitric oxide in the lower thermosphere. A thermospheric model which takes into account all of the photochemical processes that produce and destroy nitric oxide has been used to deduce the flux of precipitating auroral electrons that produce nitric oxide. The results of this analysis allow us to infer the daily variability of precipitating electron energy deposition. The most important result of this paper is that there is a clear-cut minimum in the electron flux at the time of the summer solstice in both hemispheres. This seasonal dependence of precipitating auroral electrons supports the idea that auroral arcs are suppressed in the solar-illuminated hemisphere due to high ionospheric conductivity. The strength of the seasonal variations suggests that the bulk of the energy deposition may be due to discrete auroral events. *INDEX TERMS:* 0310 Atmospheric Composition and Structure: Airglow and aurora; 0358 Atmospheric Composition and Structure: Thermosphere— energy deposition; 2704 Magnetospheric Physics: Auroral phenomena (2407); 2716 Magnetospheric Physics: Energetic particles, precipitating; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions. **Citation:** Barth, C. A., D. N. Baker, and S. M. Bailey (2004), Seasonal variation of auroral electron precipitation, *Geophys. Res. Lett.*, *31*, L04809, doi:10.1029/2003GL018892.

1. Introduction

[2] A seasonal variation in the field-aligned electron precipitation was first noted by *Berko and Hoffman* [1974] in their analysis of OGO-4 particle data. In a large survey of electron precipitation events using DMSP data, *Newell et al.* [1996] found that the occurrence rate of discrete aurora is suppressed by sunlight indicating a seasonal variation in electron precipitation. Using the ultraviolet imager on the Polar satellite, *Liou et al.* [1997] studied four months of global images utilizing Lyman-Birge-Hopfield bands of molecular nitrogen which are produced by auroral electron precipitation. They found a systematic decrease in the intensity of the UV aurora from April to July in the northern hemisphere.

[3] Auroral electrons produce ionization and luminosity when they precipitate into the upper atmosphere. Electrons in the $E = 3-4$ keV range deposit their energy in the $100-110$ km altitude region where they excite molecular nitrogen

and atomic oxygen to produce the emissions of the visible and ultraviolet aurora [*Bailey et al.*, 2002]. These same electrons create excited nitrogen atoms that lead to the production of nitric oxide in the thermosphere. Nitric oxide molecules have the property that they fluoresce when illuminated by solar ultraviolet radiation. The measurement of the intensity of these fluorescing nitric oxide molecules provides a method of measuring the density of nitric oxide. We use the measured density of nitric oxide to determine the flux of precipitating electrons.

[4] A two and a half year set of global observations of nitric oxide in the lower thermosphere obtained from the Student Nitric Oxide Explorer (SNOE) is employed for this analysis [*Barth et al.*, 2003]. This dataset starts on March 20, 1998 at the time of northern spring equinox and extends to September 23, 2000 at time of the northern fall equinox. This was a period of increasing solar activity. The spring and early summer of 1999 were periods of low geomagnetic activity.

[5] In addition to electron precipitation in the auroral region, solar soft x-rays in the $2-20$ nm wavelength region also produce nitric oxide in the lower thermosphere. A thermospheric model that takes into account both of these energy sources is used to calculate nitric oxide for comparison to the measured nitric oxide dataset [*Bailey et al.*, 2002]. This model has been used previously with only the solar soft x-rays as an energy source and the results have been compared with the nitric oxide dataset [*Barth and Bailey*, 2004]. At low latitudes, the comparison of the model with the data is excellent particularly in the $100-120$ km region. In this paper, we add the auroral electron energy source to the model and compare the results with the high latitude SNOE data in order to determine the seasonal variability of auroral electron precipitation.

2. Model Calculations

[6] The model (which is time-dependent) was run for 935 days with the physical conditions of the atmosphere and energy inputs updated 24 times a day. The calculations were made at 2 km intervals between 40 and 250 km taking into account vertical diffusion of nitric oxide in the thermosphere. Daily values of the flux of solar x-rays that were used in the model came from measurements made from SNOE satellite instruments that measure the concurrent solar x-ray flux [*Bailey et al.*, 2000]. For the model calculation, the energy of the assumed incident auroral electrons was 4 keV. The auroral precipitation was on at a constant value from 1800 hours to 0600 hours and was zero

between 0600 hours and 1800 hours. In a previous paper [*Barth et al.*, 2002], we had the electron flux on for a six hour period from 1800 hours to 0000 hours to simulate the period that *Newell et al.* [2001] found had the highest probability for electron precipitation with fluxes greater than 5 mW s^{-1}. In this paper, we extended the period of electron precipitation to 0600 hours to also include the diffuse aurora. For the initial calculation, the electron flux was set at 1 mW s^{-1} for the twelve hour period 1800 hours to 0600 hours for all 935 days of the calculation. While the model calculation does not explicitly calculate horizontal transport, the comparison of the model calculations and the observations has shown that there is horizontal transport of nitric oxide equatorward from the region of electron precipitation [*Barth and Bailey*, 2004].

[7] The model was run at 60°N and S geographic latitude. Since the measurement of nitric oxide requires the atmosphere to be illuminated, this is the highest latitude where there is a continuous set of observations throughout all seasons. (During the polar night, nitric oxide cannot be measured by observing the fluorescing nitric oxide molecules.) If we had used geomagnetic latitudes at 65°N and S, we would have uneven sampling during the time of late fall and early summer. The measurements at 60°N and S latitude are interpreted as indicative of nitric oxide that has been produced at that latitude by auroral electrons or at a higher latitude and then transported equatorward to 60° latitude [*Barth and Bailey*, 2004].

[8] In order to deduce the electron flux necessary to explain the observed nitric oxide density, the model was run with an initial estimate of the electron flux and the model result was compared with the daily average of the nitric oxide density made on fifteen orbits per day at 110 km and at the local time of the SNOE orbit (10:17 AM at the beginning of the 935 day period and 11:11 AM at the end). The nitric oxide is produced at night from electron precipitation and it is measured during the day after the Earth's rotation has moved the region of electron precipitation into sunlight. The ratio of the observed nitric oxide data to the calculated nitric oxide density was used to make a new estimate of the electron flux and the model calculation was repeated. This process was repeated until a consistent result was obtained to produce the results reported in this paper. Typically, it took five iterations to obtain a result that did not differ from the previous result by more than 1%.

3. Results

[9] The estimated fluxes of electrons precipitating into the auroral region as deduced from the model calculations are plotted in Figure 1. The northern hemisphere is in the upper part of the figure and the southern hemisphere in the lower. The first thing to note about the electron flux in both hemispheres is that it is highly variable with time. This result would be expected given the variability of the auroral electron source (see *Petrinec et al.* [2003]). The most important result in Figure 1 is that there is a clear-cut minimum in the electron flux at the time of summer solstice in both hemispheres (i.e., day 172 in the north and day 355 in the south). This is particularly clear on day 172 of 1999 when the solar wind was very quiet and geomagnetic activity was very low. The electron flux is high at times

of large geomagnetic storms such as days 125 and 240 of 1998 (see *Baker et al.* [2001]). The calculated average electron flux is about the same at the equinoxes and at the winter solstices.

[10] To further explore the behavior of the seasonal behavior of the precipitating auroral electron flux the ratios of the northern and southern hemisphere fluxes to each other were calculated. The fluxes for each hemisphere were first smoothed with a 27-day running average and then each of the ratios was calculated, north to south and south to north. The results are plotted in Figure 2. A maximum occurs in each hemisphere at the time of the solstices with the winter hemisphere flux being significantly larger than the summer hemisphere flux. The ratios of the unsmoothed fluxes showed even larger peak values.

[11] In our previous work with the model [*Bailey et al.*, 2002], we found that the relationship between the nitric oxide density and the electron flux is nearly linear. The nitric oxide density is approximately proportional to the fluence of the electron precipitation. In presenting the electron fluxes in Figure 1, we do not suggest that they represent a unique answer for the observed nitric oxide density. A longer period of electron precipitation with a lower flux or a shorter period with a higher flux both would produce the same nitric oxide density. The important result presented here is the seasonal dependence of the electron precipitation.

4. Discussion

[12] In an earlier paper [*Baker et al.*, 2001], we showed the average density of nitric oxide measured by SNOE at 106 km altitude for the same two and a half year period shown in this paper (i.e., DOY 079 of 1998 to DOY 266 of 2000). We used data for the geomagnetic latitude range 60°−70° north and 60°−70° south. A ratio of the south/north nitric oxide density showed the kind of seasonal trend described here (see Figure 5 of *Baker et al.* [2001]). The presence of higher nitric oxide density in the north during northern winter and in the south during southern winter was attributed to the longer lifetime of nitric oxide molecules when solar illumination (and subsequent photodissociation) is reduced in the winter hemisphere. However, we also noted that the seasonal hemispheric asymmetry of the nitric oxide density could be due to the summer/winter differences that have been clearly documented to exist in the auroral electron precipitation [see *Newell et al.*, 2001] and the references therein). This seasonal dependence is attributed to the suppression of intense auroral arcs due to high ionospheric conductivity in the solar-illuminated summer hemisphere. In this scenario, primarily the winter hemisphere would have very intense precipitation of multi-keV auroral electrons and, thus, that winter hemisphere should dominantly see a strong production of associated nitric oxide.

[13] The results of our model calculations in this paper tend to confirm this interpretation. That is, our results in Figures 1 and 2 are consistent with the idea that a much stronger source of electrons must be present in the winter hemisphere than in the concurrent summer hemisphere. Since our model calculations take into account the nitric oxide photodissociation loss process in detail, we conclude
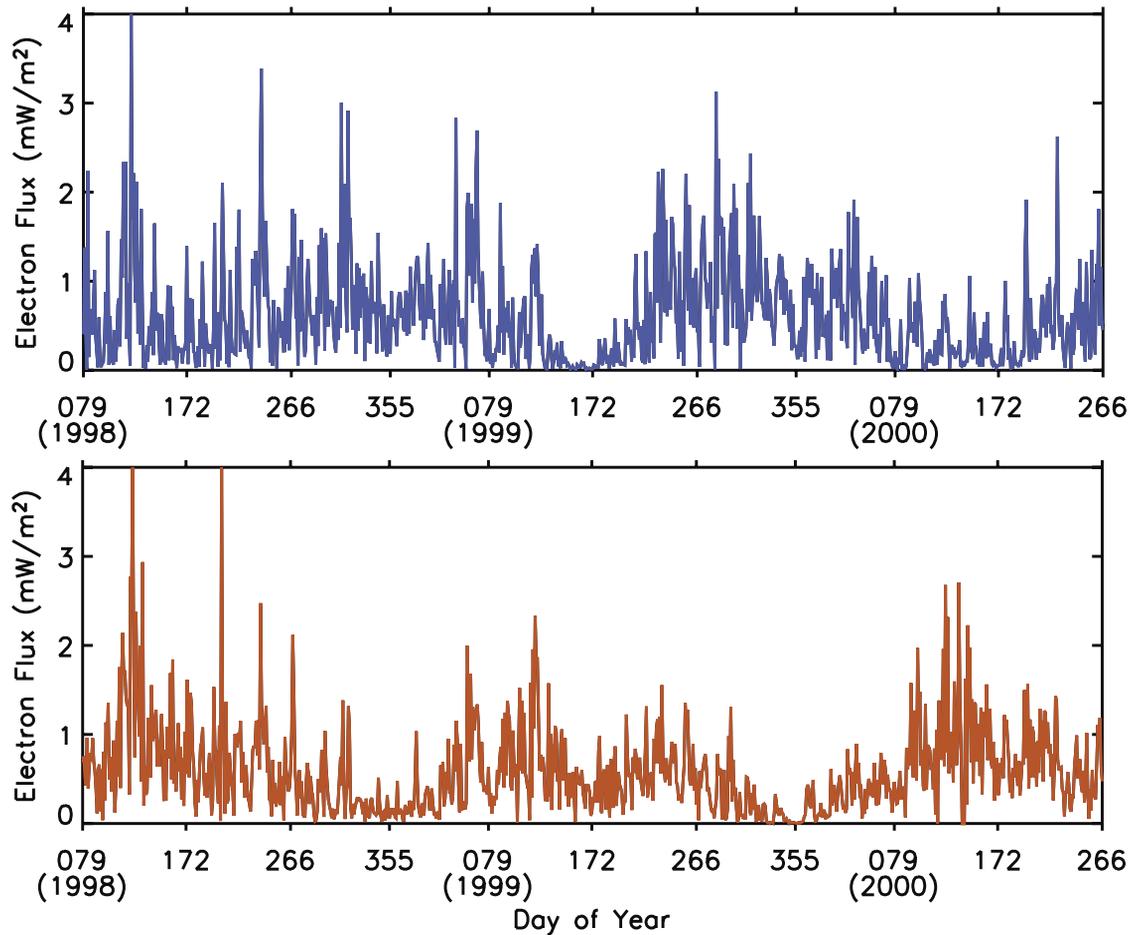
Figure 1. Daily average flux of auroral electrons in the northern auroral region (top, blue line) and the southern auroral region (bottom, red line) as deduced from observations of the nitric oxide density at 110 km for a two and a half year period, March, 1998–September, 2000. Seasonal dates are indicated on the x-axis; 079, Spring/Fall equinox; 172, Summer/Winter solstice; 266, Fall/Spring equinox; and 355, Winter/Summer solstice, (northern/southern hemispheres).
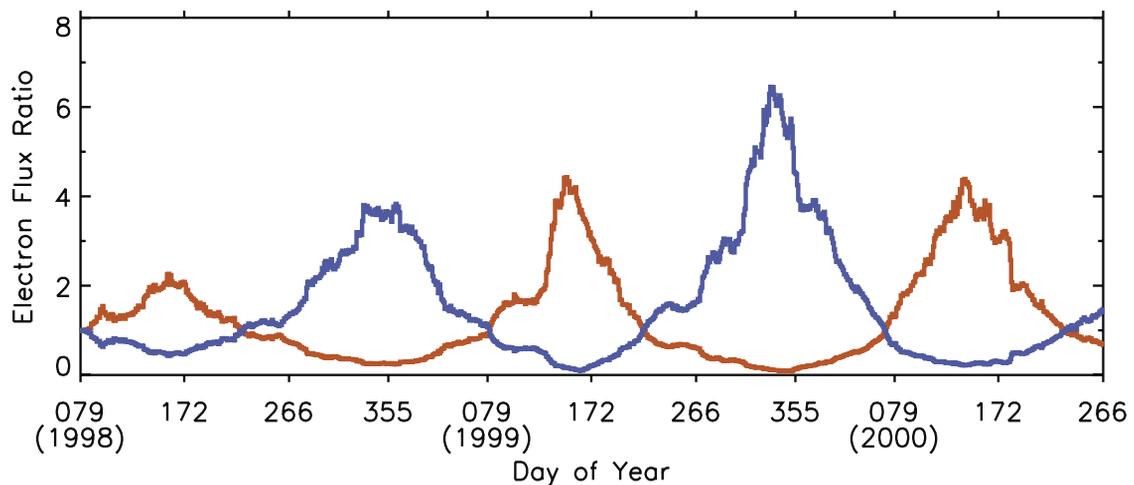

Figure 2. Ratio of the electron flux in the northern auroral region to the electron flux in the southern auroral region (blue line) and the ratio of the southern auroral flux to the northern auroral flux (red line). Both the northern flux and the southern flux have been smoothed over 27 days before the ratio was calculated.

that only a season-dependent source strength for the auroral electrons can account for the strong hemispheric asymmetries shown in Figure 2.

[14] In another earlier paper [*Barth et al.*, 2002], we showed that the geographic asymmetry of the Earth's magnetic field also plays a strong role in controlling the average nitric oxide density observed by SNOE. Specifically, we showed that the pattern of electron precipitation in the lower thermosphere is most likely controlled by the South Atlantic Anomaly and the associated pattern of lowered magnetic mirror points for trapped magnetospheric electrons. This result was determined for conditions at the time of the spring and fall equinoxes. Not all auroral electrons, it must be noted, are immediately dumped into the atmosphere in the vicinity of auroral arcs. Thus, some of the quasitrapped electrons drift around the Earth and are preferentially precipitated near, and to the west of, the South Atlantic Anomaly.

[15] The present seasonal results suggest that it is not only the quasitrapped electrons whose eventual precipitation causes nitric oxide production. If in fact the strong seasonal variability illustrated in Figure 2 is the result of the suppression of discrete auroral arcs under sunlit conditions, then it is very much the case that the bulk of the energy deposition is associated with intense auroral arcs and these electrons cause the most dramatic nitric oxide increases.

5. Summary

[16] The analysis of two and a half years of global observations of nitric oxide with a thermospheric model has shown seasonal asymmetries. The flux of precipitating auroral electrons is less in the summer polar region than it is in the winter polar region. What is important about using nitric oxide abundance to determine the precipitating electron flux is that the production of nitric oxide is a measure of the amount of energy transported from the magnetosphere into the atmosphere. The model calculation allows us to take into account the nitric oxide loss processes from photodissociation and to calculate the production of nitric oxide from auroral electrons. The result of this analysis shows that there is less energy from the magnetosphere injected into the summer hemisphere than into the winter hemisphere. This seasonal dependence of precipitating auroral electrons supports the idea that auroral arcs are suppressed in the solar-illuminated hemisphere due to high ionospheric conductivity. This result is an example of the transport of energy from the Sun to the magnetosphere and, ultimately, into the upper atmosphere. This is a key "last leg" in the connected Sun-Earth system.

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