Boundary-Oriented Electron Precipitation Model

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Abstract. A boundary-oriented model of the global configuration of electrons precipitating into the polar ionosphere is presented. It provides the differential energy flux of precipitating electrons from 32 eV to 30 keV for five different activity levels. Data from twelve years and eight DMSP spacecraft were incorporated into the model. The defining characteristic of this model is that only observations similarly located relative to auroral boundaries (e.g. observations just equatorward of the open–closed boundary) are averaged together. The model resulting from this approach more closely resembles instantaneous observations than previous efforts. There is a distinct polar cap surrounded by a narrow auroral zone, transitions between different regions are appropriately sharp, and model spectra are more realistic. This increased fidelity with observation is a significant advantage for the model, broadening its applicability. Also new, is the calculation of both mean and median model spectra. The mean is dominated by sporadic flux enhancements, where present, while the median resembles more commonly observed background fluxes, permitting both of these aspects to be addressed. Parameterization for activity is based on the degree of magnetotail stretching, as indicated by the latitude of the ion isotropy boundary. A variety of features can be discerned in the model. There is a large difference between the mean and median energy flux in regions where upward region 1 Birkeland currents are commonly observed. The smooth ~1-10 keV precipitation seen at most local times, in the equatorward portion of the oval, is nearly absent in much of the afternoon sector. Enhanced number fluxes are seen at the poleward edge of the oval near midnight, likely due to the frequent presence of field-aligned bursts. Structured precipitation dominates the energy flux at all local times except between dawn and noon, where the contribution from unstructured precipitation dominates. The total hemispheric energy flux due to mean spectra varies with activity from 6 to 38 GWatts, and exceeds the energy flux due to median spectra by a factor of approximately 4, regardless of activity.

1. Introduction

A model representing the spatial distribution and energy spectrum of electrons precipitating into the polar ionosphere can provide insights into the behavior of source populations at higher altitudes, and can be used to estimate the effect of such precipitation on ionospheric conductivity and the chemistry of the upper atmosphere. Elevated fluxes of electrons produce aurora, typically falling in an oval circling the Earth's magnetic poles. The auroral oval varies considerably in its size and in the intensity of its precipitation, both on a global scale and on smaller scales, where electron acceleration sporadically enhances local energy fluxes significantly. Models can attempt to capture the global character of precipitating electrons as the oval changes in size and breadth, with some hope of success. Accelerated electron fluxes can vary on small scales both spatially and temporally, precluding accurate representation except in an average sense.

At a given time, ionospheric precipitation can be ordered spatially into different regions of distinct character. Previous models [Hardy et al., 1985; Spiro et al., 1982; McDiarmid et al., 1975] have binned electron precipitation observations spatially by corrected magnetic latitude (MLAT) and local time (MLT). Since different precipitation regions move about continually, averaging precipitation at fixed MLAT and MLT mixes different types of precipitation together depending on the occurrence frequency for each type at each location. Here an alternate approach is used, we order precipitation for each satellite pass over the polar ionosphere, relative to various auroral boundaries. For example, electron fluxes at the equatorward edge of the auroral oval are averaged together only with similarly located fluxes.

By ordering observations relative to auroral boundaries a distinct representation is obtained for each precipitation region, even though a given geomagnetic location will see precipitation from different regions.
over time. For regions where electron acceleration is common the mean energy spectrum will be dominated by the intermittent presence of auroral arcs, since unaccelerated fluxes are meager in comparison. For regions where electron acceleration is rare, model representations can achieve greater fidelity with observations. Since latitudinal location is specified only relative to various auroral boundaries, we need to specify the location of these boundaries in order position the model spatially. Here, we use the average location of the boundaries for each activity level. Such an approach lends itself to future generalization, in order to achieve greater accuracy for a particular instant in time, one could adjust these average boundary shapes to fit available observations.

Previous electron precipitation models [Hardy et al., 1985; Spiro et al., 1982; McDiarmid et al., 1975] have organized observations by using magnetic activity indices (AE and/or Kp). The model presented here is self organized, in that observations are organized by the degree of magnetotail stretching as inferred from concurrent ion precipitation [Newell et al., 1998]. A previous example of a model based on self organized data is provided by Fuller-Rowell and Evans [1987]. Their model of ionospheric conductivity organized TIROS/NOAA electron precipitation observations using an estimate of the hemispherical power input into the atmosphere derived those same observations. A brief description of the three referenced electron precipitation models follows.

McDiarmid et al. [1975] constructed a model from Isis 2 observations of electrons at 1400 km altitude, using data from about 1100 passes selected from the interval March 1971 to August 1972. The detector energy range extended from 150 eV to 10 keV in eight channels, and two additional detectors provided $E > 22$ keV and $E > 210$ keV fluxes. Only lower activity (Kp $\leq 3$) data were used. The data were located on a grid spaced 1° in MLAT and 2 hours in MLT, then averaged. Contour plots of average energy, and energy fluxes at five different energies, were provided. Local minima of the average energy were found post-noon and post-midnight.

Spiro et al. [1982] constructed a model of precipitating electrons from AE–C and AE–D observations acquired during the years 1974-1976. Precipitating electrons from 200eV to 27 keV were observed in 16 separate energy channels. Over 30,000 15–second observations of the energy flux and characteristic energy were separated into bins, 1 hour in MLT by 1° to 2° in MLAT (1° between 60° and 80°, 2° elsewhere). Two different schemes were used to separate the data according to activity, binning by Kp and binning by AE; AE was found to better separate the data. A smoothing procedure was applied and conductivity patterns were derived.

Hardy et al. [1985] constructed a model of precipitating electrons using DMSP F2, F4 and STP P78-1 observations acquired during the years 1977-1980. Precipitating electrons from 50 eV to 20 keV were observed across 16 energy channels. Fourteen million 1–second spectra from 29,000 passes were assembled from the years 1977-1980 and assigned to bins 0.5 hours in MLT by 1° to 2° in MLAT (1° between 60° and 80°, 2° elsewhere). The data were separated by activity using the Kp index. Average differential number fluxes for each energy, in each spatial bin, and for each level of activity, were calculated. Representative energy spectra were provided, as well as smoothed maps of number flux, energy flux and average energy. Hardy et al. [1987] calculated ionospheric conductivity patterns using the Hardy et al. [1985] model.

The model presented here makes use of 50 million electron energy spectra acquired during the years 1983-1995 by DMSP F6-F13. The DMSP spacecraft are in polar orbits at ~840 km altitude and carry the SSJ/4 detector [Hardy et al., 1984]. The SSJ/4 measures downward fluxes of field aligned (within ~3° of vertical) ions and electrons from 32 eV to 30 keV in 19 channels, once per second. These 50 million electron energy spectra were assigned to bins extending 20 minutes in MLT (5°) and across 15 (day) or 25 (night) steps in latitude, from the equatorward edge of the auroral oval to the pole, and were separated into five different activity levels using inferred magnetotail stretching. The next section describes the auroral boundaries used to frame and control the model. It is followed by a description of the model calculation and presentation of the model results. Finally, a global perspective precedes our summary and conclusions.

2. **Auroral boundaries**

Before discussing the construction of the model we describe the automated auroral boundary identification schemes that are its underpinning. The results of these automated identifications for both the dayside and the nightside are available to the community at http://sd-www.jhuapl.edu/Aurora. First, we review the
b2i boundary, a proxy for the ion isotropy boundary, used to infer magnetotail stretching. Then, we review the nightside boundary identifications used to order the nightside data latitudinally. This is followed by a review of the dayside boundaries used to order the dayside data.

2.1 The ion isotropy boundary and magnetotail stretching

An indicator of magnetotail stretching can be obtained from consideration of the latitude at which a loss cone appears in the pitch angle distribution of ions impinging on the ionosphere. Ions on dipolar field lines bounce back and forth between hemispheres mirroring at each end. Field aligned ions whose mirror point lies below ~100 km in altitude will usually interact with the upper atmosphere and be lost, resulting in empty loss cones. Ions on stretched field lines are prone to pitch angle scattering as they navigate the hairpin turn at the neutral sheet, maintaining filled loss cones in spite of losses to the atmosphere. The latitude at which the transition between filled and unfilled loss cones occurs (a weak function of species and energy) is a good indication of how stretched the magnetotail is [Sergeev and Gvozdevsky, 1995; Sergeev et al., 1993, 1983].

Directly determining the isotropy boundary for a particular species and energy requires pitch angle information. Newell et al. [1998] found that the b2i boundary (the peak precipitating energy flux of 3–30 keV ions) was well correlated with both the location of the isotropy boundary for 30–80 keV ions and with the degree of magnetotail stretching observed at geosynchronous orbit. The reason is that the energy flux of 3–30 keV ions generally increases with decreasing absolute latitude, until the appearance of empty loss cones causes it to fall off.

The latitude of the b2i boundary \( \lambda_{b2i} \) is used to parameterize the observations from which our model is constructed. For nightside passes b2i is available from the pass itself. For dayside passes we use nightside b2i determinations from within 30 minutes, if available, otherwise the data is discarded. The observed latitude \( \lambda_{b2i} \) is projected to midnight to form a magnetotail stretching index analogous to the MT index of Sergeev and Gvozdevsky [1995] by using their functional form, fit to the b2i boundary by Newell et al. [1998].

\[
\text{MTd} = 90 - |\lambda_{b2i}| - 4.31(1 - \cos(\pi(\text{MLT} - 23.4)/12))
\]

Observations are separated into five bins by MTd, numbered #1 though #5 for least active to most active, respectively (Table 1). The five resulting models are correspondingly numbered. Observations for which MTd falls outside the range 59° to 71° are discarded.

2.2 Nightside electron boundaries

Automated nightside boundary identification algorithms are described by Newell et al. [1996a] wherein up to 10 different boundaries are identified for each pass through the oval. We use five of these boundaries in order to place each observed precipitating electron energy spectrum into one of the 25 latitudinal bins that span each local time sector on the nightside. From equatorward to poleward they are: b1e the zero energy electron boundary; b2e the start of the main plasma sheet; b4s the structured/unstructured boundary; b5e the poleward edge of the main oval; and b6 the poleward edge of the subvisual drizzle. Stretching between each adjacent pair are five equally spaced bins, with five more bins stretching between the b6 boundary and 90°MLAT.

The b1e (zero energy electron) boundary is located at the most equatorward appearance of low energy electrons. The b2e boundary is located where the frequently seen slow ramp up in energy flux plateaus. If there is no ramp then these two boundaries can coincide. The b4s boundary is identified on the basis of a transition in a running correlation coefficient between an electron energy spectra and the previous five spectra. As electron energy spectra are examined sequentially, moving poleward, the correlation coefficient makes a transition from high correlations to low correlations, locating the boundary. The b5e (poleward edge of main oval) boundary is identified by searching for a sharp drop to low energy fluxes. It may or may not coincide with the open–closed boundary since subvisual drizzle may lie poleward of b5e, and sometimes the open–closed boundary lies a little poleward of any precipitation [Sotirelis et al., 1999]. The b6 boundary lies at the poleward edge of any subvisual drizzle, if any, otherwise it coincides with the poleward-most of either b5e or b5i.

2.3 Dayside boundaries

Automated dayside region identification algorithms use the rules outlined in Section 4 of Newell
et al. [1991]. Since this identification scheme identifies regions and not boundaries, we must extract boundary information from it. Three boundaries are defined here: deq the equatorward boundary of the diffuse precipitation, analogous to b1e on the nightside; dds the diffuse/structured precipitation boundary, analogous to the b4s boundary; and doc the open–closed boundary, represented by the b6 boundary on the nightside. We use these three boundaries in order to place each observed electron energy spectrum into one of the 15 latitudinal bins that span each local time sector on the dayside. Stretching between each adjacent boundary pair are five equally spaces bins, with five more bins stretching between the open–closed boundary and 90° MLAT.

For deq, the equatorward boundary of the CPS, we look for an unambiguous transition between void and CPS. For dds, the diffuse/structured precipitation boundary, we look for an unambiguous transition from CPS to BPS and/or LLBL. For the open–closed boundary we look for an unambiguous transition between open and closed regions, where we take CPS, BPS, and LLBL to be closed, and cusp, mantle, open LLBL, polar rain and void are considered open. (Note that any void equatorward of any CPS, BPS or LLBL is considered to be closed). The three transitions described above may not always be clear since the automated processing can result in transitions from one region to another and back again, due to various ambiguities. If the transition is not clear then it is not used. To be clear we require it to be well located to within ~1.5°.

2.4 Average boundary shapes

Observations going into this model are parsed latitudinally according to boundaries determined from the data itself. The resulting model consists of 900 (~ = 25 \(\cup\) 36) bins on the nightside and 540 (~ = 15 \(\cup\) 36) bins on the dayside. We locate each of these bins relative to the average boundary locations for the corresponding degree of magnetotail stretching. Calculating average boundary shapes is fraught with peril, due to orbital biases that result in uneven coverage. For instance, a simple average over boundary determinations at fixed MLT would bias toward high latitudes at local times where the spacecraft rarely makes it to low latitudes.

A procedure was devised that tracked each boundary determination back along the spacecraft trajectory to a candidate boundary shape. An average absolute deviation from this candidate boundary shape was calculated from the sum of these distances. This absolute deviation was minimized by varying the boundary shape. There were not enough boundary determinations at all local times to perform the fit everywhere. The boundary shapes were interpolated across these problem areas. Of the 40 boundary fits (~ = 5 \(\times\) (5 + 3)), 17 needed no interpolation, the rest required a single interpolation in the vicinity of either 01 MLT (nightside) or 14 MLT (dayside). Of the 23 boundary shapes requiring interpolation, 7, 9, 4, 2 and 1 of them required interpolation across 1, 2, 3, 4 and 5 hours of local time respectively. The results are presented in Figure 1, where each individual bin is shown. An overview, showing the average location of structured, diffuse and subvisual precipitation is presented in Figure 2.

These boundary shapes are less reliable in areas where observational coverage is thin and where spacecraft trajectories are not aligned meridionally. Of course even where coverage is good and trajectories meridional there will be variation of individual boundary determinations about the average for each MTd bin. The mean absolute deviation of the individual determinations from the shapes that resulted from the fit ranged from ~1 to ~3 degrees. The mean absolute deviation for b5e, b6 and doc ranged from ~2 to ~3 degrees over the different degrees of tail stretching, for the other boundaries it fell between ~1 and ~2 degrees.

3. Electron precipitation model

Nineteen-point energy spectra (32 eV to 30 keV) from December 1983 through December 1995, from DMSP F6 through F13, were separated into 1440 bins spatially and into 5 bins for activity. Both hemispheres are combined. The average locations of these bins are shown in Figure 1. The spectra are in the form of directional differential energy fluxes in units of 1/s-\text{sr}-\text{cm}^2. For each bin and at each energy, average (mean and median) directional differential energy fluxes are calculated. All locations are in altitude adjusted corrected geomagnetic coordinates (AACGM) [Baker and Wing, 1989].

Plate 1 depicts the number of observations by spatial location and activity level. Since most DMSP spacecraft are in sun-synchronous orbits, either dawn–dusk or prenoon–premidnight, there are few observations in the vicinity of 01 and 14 MLT. Since the number of measurements is not normalized to the size of the bin, larger bins such as those in the polar cap contain...
more observations. Not all regions are present in every pass (e.g. b5e and b6 are frequently coincident near midnight), reducing the number of observations in the affected bins and drawing the average shape of the two sometimes coincident boundaries together there.

For each bin, the mean and the median directional differential energy fluxes at each energy are calculated. The median is the value located such that half the measured fluxes fall above it and half below it. It is insensitive to outliers and skew, whether due to instrument noise, electron acceleration, region misidentification, or any other effect. As such, it is a useful estimate of the most likely (i.e. background) flux. The mean is, however, sensitive to all these effects. It provides an estimate of the average flux of electrons, including the occasional presence of intense fluxes of accelerated electrons, but is also susceptible to various sources of noise.

In the polar cap (a region of very low fluxes), outliers have an effect on the mean, occasionally producing small fluxes near ~1 keV and in the very highest energy channel (30 keV). These are likely due to infrequent misidentification of the b6 boundary in the first case, and the occasional presence of high energy solar electrons in the second case. These small defects can affect the calculation of average electron energy in the polar cap where the legitimate electron flux signal is small compared to such noise. Hence, a small correction is applied to the mean flux through the subtraction of an offset, set at approximately the one-count level.

Plate 2 depicts our results at four local times and for the highest and lowest activity levels. Both the mean and median spectra are shown. The median spectra tend to fall below the mean spectra indicating that the distribution of electron fluxes is skewed toward the high end. This is especially true where electron acceleration is most common, between b4s and b5e on the nightside and between dds and doc on the dayside. This model has an explicit polar cap. Therefore, it does not well represent the high latitude regions in those rare instances when the polar cap is completely closed, or nearly so. Also, transient polar cap phenomena such as theta aurora are excluded.

4. Global Character

The global character of the model is illustrated with plots of the energy flux, the number flux and the average energy. Specifically, we provide: the directional energy flux $J_E$ (eV/s-sr-cm²) for the mean spectra in Plate 3, and for the median spectra in Plate 4; the directional number flux $J_N$ (1/s-sr-cm²) for the mean spectra in Plate 5, and for the median spectra in Plate 6; the average energy $<E> = J_E / J_N$ for the mean spectra in Plate 7, and for the median spectra in Plate 8. Sparsely populated spatial bins ($n < ~100$) were combined with neighbor(s) at adjacent local times (see Figure 1). Also, a slight smoothing was applied. The most notable data gap is just after midnight in model #5. Here, the procedure for combining sparsely populated bins has the effect of continuing the model inwards from the edges, resulting in a discontinuity where the extended bins meet at 0120 MLT. The reader should refer to Plate 1 and Figure 1 when interpreting the model, giving consideration to the number and location of contributing observations in order to judge the reliability of various features.

The energy and number fluxes calculated from the median spectra are usually lower than those calculated from the mean spectra (> 99% of the bins), indicating that their statistical distributions are skewed toward the high side. This is as expected for phenomena which are ordinarily quiescent but exhibit sporadic intensification. Since auroral fluxes vary over several orders of magnitude one might consider averaging the log of the flux, providing the geometric mean. This was done for a preliminary version of the model; the geometric mean and the median fluxes were found to be quite similar to each other, but the median is preferable since it is less sensitive to outliers.

Many interesting features are apparent from this global perspective. The greatest difference between the energy fluxes due to the mean and median spectra coincides with the expected location of upward region 1 current, azimuthally from 1400 MLT through dusk and midnight to 0200 MLT, and latitudinally in the region of structured precipitation (between b4s and b5 on the nightside and between dds and doc on the dayside). We interpret this enhanced difference between the energy flux for the mean and median spectra as being due to the frequent presence of electron acceleration that can coincide with upward currents, and can raise energy fluxes by orders of magnitude. Such indications of electron acceleration are present near midnight and near 1500 MLT for all five activity levels. For low activity (models #1 and #2) the afternoon enhancement stands by itself. As tail stretching increases, the enhancement near midnight extends toward the afternoon sector until the two regions are joined (models #3, #4 and #5). This
behavior has been seen previously in particle data [Evans, 1985; Newell et al., 1996b] and in auroral imagery [Murphree et al., 1981].

A distinguishing characteristic of the median energy flux (Plate 4) is the relative absence of precipitation in the afternoon sector between deq and dds. This reflects a scarcity of the diffuse ~1-10 keV CPS precipitation seen at other local times. It is likely due to the combined effect of convection and gradient B drift, which taken together bring few electrons to this region. As electrons convect earthward into an increasing magnetic field strength they are deflected dawnward. Most are lost to the dayside magnetopause before reaching 1500 MLT (e.g. Figure 4.24 of Lyons and Williams [1984]).

On the nightside, the b4s boundary serves to mark the equatorward-most extent of structure in precipitating electrons. Large background (i.e. median) energy fluxes seem to be confined mostly to the unstructured portion of the oval for low activity, but migrate into the structured region for higher activity. Examination of individual cases reveals smooth 0.5–10 keV electron precipitation (typically seen in the unstructured region for low activity) supplying the large median flux, overlapping with structured lower energy electrons (up to ~1 keV).

There are many effects contributing to the spatial distribution of 0.5–10 keV electron fluxes. Once plasma sheet electrons convect sufficiently earthward to begin appreciable gradient B drift, each energy's bounce averaged guiding center will follow a separate path. Electrons at the same energy but different equatorial pitch angle will also follow different paths in order to conserve their second adiabatic invariant as they encounter different degrees of magnetic field stretching at different local times. Combine these effects with the pitch angle diffusion thought to be caused by electrostatic waves near the electron cyclotron frequency [Kennel, 1970] and it is easy to see how the resulting precipitation would become smooth, even if the original population were not. If we associate the structure usually seen in the poleward part of the oval with turbulent magnetotail convection, it would not be surprising to see such structure overlap with precipitation typical of the near tail, as activity increases and sunward convection penetrates Earthward.

Plate 5, which shows the mean number flux, exhibits two features of note. First, there are large number fluxes contributing at the poleward edge of the auroral zone near midnight. These reflect the frequent presence of flux enhancements that span most energies, sometimes called "suprathermal bursts" or "field-aligned bursts" [Johnstone and Winningham, 1982], in contrast with the monoenergetic enhancements more common equatorward of this. This feature might seem less intense for higher activity because of the large latitudinal size of the relevant bins, which may dilute the signal. A second feature of note is the large number flux that appears on open field lines near noon. This is likely due to the enhanced low energy electron fluxes associated with cusp and mantle precipitation. There is a marked dawn–dusk asymmetry to this feature, largest at low activity, for which the explanation is not clear.

The average energy for both the mean and median spectra, Plates 7 and 8, both exhibit similar features. Higher average energies are seen equatorward of b4s on the nightside and dds on the dayside. This delineation can become unclear or absent at higher activity levels, premidnight, due to the aforementioned overlap between smooth higher energy precipitation and structured lower energy precipitation. Average energy equatorward of b4s and dds (diffuse/structured boundaries) tends to increase with local time, from a minimum just after noon, to a maximum near noon. The step down, from maximum to minimum around 1330 MLT, is rather abrupt. Precipitation of ~0.5 to ~10 keV electrons after this drop around is quite weak. The sharp decrease in average energy occurs in the vicinity of thin observational coverage, particularly for model #1, so there is some degree of noise present. Nonetheless, there are more than 100 measurements in almost every bin of this region for models #2-5, and so the feature seems robust.

In Plates 3 through 8, the eye is drawn to the seam between the dayside and the nightside models. In areas where the flux is weak, a mismatch is not very significant since the underlying phenomenon does not represent a very strong signal. As is evident in Plates 3 and 4 there is a clear mismatch of large flux levels at dawn, where the dayside flux is equatorward of the nightside, for low activity, and poleward for high activity. This is probably due to the models parameterization. Since the nightside is parameterized by a b2i boundary crossing from that very pass, and the dayside is parameterized by a nightside boundary crossing from within 30 minutes (possibly the other side of the same pass), the nightside model is better controlled. In other words, the nightside model is farther
poleward for low activity and farther equatorward for high activity because nightside data are better separated for activity. This explanation also agrees with the sense of the largest disagreement at dusk, in model #5. Other disagreements at dusk are neither large nor well ordered.

Plate 9 depicts the fluctuations in the data from which the model is constructed. Plate 9 features model #4 which exhibits similar fluctuation features to the other activity levels. Each part of Plate 9 depicts either the energy or number fluxes implied by a fluctuation spectra. Each channel of the fluctuation spectra is set to either the standard deviation or the mean absolute deviation of the data from the mean or median flux in that channel. We present fluxes using the standard deviation of the observations from the mean model in parts (a) and (c). Since we formed the median models in order to minimize the effect of outliers and skew, in (b) and (d) we present fluxes calculated from the mean absolute deviation, which also minimizes these effects. Fluxes for the standard deviation from the median model appear identical to those presented for the mean model. Fluxes calculated using the mean absolute deviation from a mean model appear only slightly larger than for a median model (compare Parts (b) and (e)). Regardless, fluxes calculated from both the standard and absolute deviations appear to be of the same order as the mean model fluxes, indicative of the great degree of variation present, except in low flux areas where variations can be an order of magnitude higher. The appreciably greater smoothness of the mean absolute deviation plots indicates that the speckling in the standard deviation plots is due to extreme elements of the relevant distributions, possibly due to occasional flaws in the data, algorithms and/or coding, as well as contributions from unusual events.

Figure 3 presents contributions to the integrated energy flux for model #5 as a function of local time. There are points every 20 minutes (5°) of magnetic local time. The contributions are broken out by region as well. There are several features of note. The region of structured precipitation dominates the other regions except between roughly dawn and noon, where the unstructured region dominates. The dayside and nightside models match fairly well except for the mean model in the polar cap region, where there is a mismatch of roughly a factor of ten. There are often small regions of weak precipitation near dawn and dusk at the open–closed boundary, that are difficult to classify either automatically or by eye. On the nightside this flux is usually classified as closed. On the dayside it might be classified as mantle, and thus open. This is the likely cause for the discontinuity in the latitudinally integrated polar cap energy flux at dawn and dusk. This explanation is supported by the presence of larger fluxes in equatorward versus poleward polar cap bins, at dawn and dusk on the dayside (not shown).

Figure 4 presents the contributions to the integrated energy flux as a function of local time for all five activity levels. The magnetotail stretching index MTd appears to control energy flux fairly well. One exception is that the separation by activity breaks down in the vicinity of 13 to 14 MLT. Also, the separation between the two least active models (#1 and #2) is small. The large-scale local time structure of the energy flux is that of a broad maximum centered shortly after midnight, descending to a minimum near 13 MLT. Superimposed on this pattern appears to be a bipolar signature near midnight, of the proper sense for an association with region 1 current. However, the dip at 02 MLT is also located in a problem area for the model, where the coverage is thin, and more importantly, the spacecraft trajectories are oblique. Since the algorithms used to construct the model work best for meridionally organized data, this feature could be due to a systematic effect.

Figure 5 presents the contributions to the integrated number flux at each local time. The number flux exhibits less variation with both activity and local time than the energy flux. It is maximum near midnight and reaches its minimum sometime in the morning hours. The minimum number flux in the median models migrates from noon for high activity to dusk for low activity.

Table 2 presents the log of the total hemispheric energy flux Gwatts. It is calculated by summing the contributions from different local times presented in Figure 4 and integrating over solid angle, assuming isotropy within the loss cone (effectively, multiplying by π). The total energy flux is provided for each of the five activity levels of the model, for both the mean and median formulations, and is also broken into dayside and nightside contributions. The nightside contribution is always larger than the corresponding dayside contribution. For both the mean and median formulations the energy flux, as well as the ratio of dayside to nightside energy flux, increase monotonically with activity. The energy flux due to mean spectra is
larger than that due to median spectra by a factor of approximately 4.

5. Summary and conclusions

A model of precipitating electrons has been presented here. The data from which the model is formulated, are ordered latitudinally relative to contemporaneous auroral boundaries. The resulting model spectra are ordered latitudinally, relative to average auroral boundaries. The result more closely resembles observed precipitation patterns in that there are distinct regions: a polar cap, a region of cooler structured precipitation (though such small scale structure washes out in averaging), a region of smooth hotter precipitation, etc. Five separate activity levels are defined, based on magnetotail stretching as inferred from observations of precipitating ions. Both mean and median spectra are provided across 19 channels ranging from 32 eV to 30 keV in energy. The median spectra resemble the more commonly observed background precipitation in which sporadic enhanced fluxes embed themselves. In regions where electron acceleration is common, the mean spectra are dominated by contributions from the occasional presence of enhanced fluxes, and the difference between the mean and median model fluxes becomes large.

This model offers several advantages to the user. Without a boundary oriented approach the model auroral zone would be much thicker latitudinally, exhibiting only a gradual transition to the rarified precipitation seen in the polar cap. Also, the model spectra would be very different, resulting from a mixture of differing contributions. Ionospheric and thermospheric models should benefit from this more realistic input, impacting the conclusions of studies that rely on them (e.g. [Sibeck et al., 1996]). Additionally, both mean and median model spectra are provided. This offers users the ability to consider both the most frequently seen background precipitation, and an average that includes the sporadic intensifications frequently present in the structured region, depending on their need.

We have noted several interesting features. The largest difference between the mean and median energy fluxes overlaps with the expected location of upward region 1 current, from 1400 MLT through dusk and midnight to 0200 MLT azimuthally, and in the region of structured precipitation latitudinally, interpreted here as being due to the frequent presence of electron acceleration. The lack of median energy flux in the afternoon sector in the equatorward-most region reflected a scarcity of the smooth ~1-10 keV CPS precipitation seen at other local times. A likely explanation is that few plasma sheet electrons are brought to this region from the magnetotail when the combined effect of convection and gradient B drift are considered. An equatorward penetration of structure near midnight, with increasing activity, was noted. Enhanced number fluxes at the poleward edge of the auroral zone near midnight were interpreted as being due to the frequent presence of field-aligned bursts there, and large number fluxes on open field lines near noon were interpreted as being due to cusp and mantle precipitation.

Latitudinally integrated energy and number fluxes were presented as a function of magnetic local time. They were well separated by magnetotail stretching. Structured precipitation was found to dominate the energy flux at all local times except between roughly dawn and noon, where the energy flux from the unstructured region dominates. The total hemispheric energy flux was tabulated for each of the five activity levels of the model. Fluxes increased monotonically with activity and the nightside always contributed more than the dayside. Total energy fluxes due to mean spectra (6-38 GWatts) exceeded those due to median spectra by a factor of approximately 4.

The model presented here separates precipitation into categories, revealing a variety of behaviors that would otherwise be difficult to distinguish. It more closely resembles instantaneous auroral configurations by providing sharp transitions seen in actual precipitation observations, such as the difference in energy flux between the polar cap and the auroral zone and the difference in characteristic energy between structured and unstructured precipitation on the dayside. It should also be possible to adjust the model into greater agreement with a given auroral configuration by locating the model precipitation relative to observed boundaries rather than average boundary locations. Since both mean and median energy spectra are provided, the behavior of sporadically enhanced precipitation can be distinguished from background precipitation. Both the model's flexibility and its fidelity with observed auroral configurations should permit a broader range of applications than previous models.

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References


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Table 1. Observations are separated into five different activity bins #1 through #5 (least through most active, respectively) using MTd as an indicator of magnetotail stretching.

<table>
<thead>
<tr>
<th>Model #</th>
<th>Min MTd</th>
<th>Max MTd</th>
</tr>
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<tbody>
<tr>
<td>#1</td>
<td>68°</td>
<td>71°</td>
</tr>
<tr>
<td>#2</td>
<td>66°</td>
<td>68°</td>
</tr>
<tr>
<td>#3</td>
<td>64°</td>
<td>66°</td>
</tr>
<tr>
<td>#4</td>
<td>62°</td>
<td>64°</td>
</tr>
<tr>
<td>#5</td>
<td>59°</td>
<td>62°</td>
</tr>
</tbody>
</table>

Table 2. The total energy flux deposited by the mean and median model spectra, per hemisphere, in gigawatts. The totals are broken into dayside and nightside contributions. Model #5 is the most active and #1 the least.

<table>
<thead>
<tr>
<th>Model #</th>
<th>Total Energy Flux (GWatts)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Spectra</td>
</tr>
<tr>
<td></td>
<td>Day</td>
</tr>
<tr>
<td>#5</td>
<td>5.8</td>
</tr>
<tr>
<td>#4</td>
<td>5.0</td>
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<tr>
<td>#3</td>
<td>3.3</td>
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<tr>
<td>#2</td>
<td>2.2</td>
</tr>
<tr>
<td>#1</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Plate 1. The log of the number of observed electron spectra in each spatial bin are shown for each activity level. Each observation is assigned to a bin, latitudinally, relative to contemporaneously determined auroral boundaries. The bins are depicted here, relative to the average position of the relevant auroral boundaries.
Plate 2. Example spectrograms are shown, as if a DMSP spacecraft were traversing from 55° to 90° MLAT through the model spectra. Traversals are shown at four local times and for the most and least active models. The log of the directional differential energy flux (1/s-sr-cm²) is shown for both the mean and median model spectra.
Plate 3. The global distribution of the log of the directional energy flux of electrons $J_E$ (eV/s-sr-cm$^2$) resulting from the mean model spectra is depicted for the five different activity levels of the model.
Plate 4. The log of the directional energy flux $J_E$ (eV/s-sr-cm$^2$) of electrons in the median model.
Plate 5. The log of the directional electron number flux $J_N$ (1/s-sr-cm$^2$) of the mean model.
Plate 6. The log of the directional electron number flux $J_N$ (1/s-sr-cm$^2$) of the median model.
Plate 7. The log of the characteristic electron energy $<E> = J_e/J_N$ (eV) in the mean model.
Plate 8. The log of the characteristic electron energy $<E> = J_e/J_N$ (eV) in the median model.
Plate 9. Energy and number fluxes of the standard and mean absolute deviations of the contributing data from the model spectra, for model #4, are presented. (a) The energy flux $J_E$ carried by the spectrum of standard deviations $\sigma$ about each energy channel's mean flux. (b) The energy flux carried by the spectrum of mean absolute deviations $\mu$ about each channel's median flux. (c) The number flux $J_N$ carried by the spectrum of standard deviations about each channel's mean flux. (d) The number flux carried by the spectrum of mean absolute deviations about each channel's median flux. (e) The energy flux carried by the spectrum of mean absolute deviations about each channel's mean flux.
Figure 1. The bins into which observations are separated spatially and by activity are shown with their latitudinal position given relative to the average location of the relevant auroral boundaries. Some of the bins have been combined with neighboring bins, in areas where coverage is thin or absent, in order to achieve a minimum of ~100 measurements per bin. Noon is at the top with dusk at the left. Concentric circles are drawn at 60°, 70° and 80° MLAT.
Figure 2. The average location of the various auroral regions are presented for the five different activity levels of the model. Noon is at the top with dusk at the left. Concentric circles are drawn at 60°, 70° and 80° MLAT.
Figure 3. Log contributions to the total directional energy flux by local time and region for model #5. Each point represents the contribution from a 20 minute (5°) MLT sector. The total from all regions is given by the heavy line. Contributions from different regions are given by various broken lines: the structured region lies between b4s and b5e on the nightside and dds and doc on the dayside; the unstructured region lies between b2e and b4s on the nightside and between deq and dds on the dayside; the equatorward edge lies between b1e and b2e on the nightside; the polar cap lies poleward of b6 on the nightside and doc on the dayside; and the subvisual drizzle lies between b5e and b6 on the nightside.
Figure 4. Log contributions to the total directional energy flux, by local time, for the five different models. Each point represents the contribution from a 20 minute (5°) MLT sector.
Figure 5. Log contributions to the total directional number flux, by local time, for the five different models. Each point represents the contribution from a 20 minute (5°) MLT sector.