Statistical nature of the magnetotail current in the near-Earth region

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Abstract. ISEE 1 magnetic field data for 1978-1987 are examined to obtain the average distribution of the magnetotail current in the region -20 < X < -6 Re, |Y| < 7 Re. The whole data set is divided into three subsets according to different geomagnetic conditions, that is, AL > 50 nT, -200 < AL < 50 nT, and AL < -200 nT. Magnetic field values are averaged in each cell with a volume of 1 × 1 × 1 Re³, and the corresponding current densities are calculated from the average tail field. The radial distribution of the neutral sheet current for disturbed periods is characterized by intense currents near geostationary altitudes. In the midnight sector, it reaches as large as -140 mA/m², twice that for quiet periods. It is found that the neutral sheet current is maximized in the region 3 < X < 6 Re, exhibiting clear dawn-dusk asymmetry. There is no evident indication for the current disruption in the near-Earth magnetotail, except for a ~20 mA/m² depression in the current intensity for disturbed periods near the midnight meridian within X = -7 Re. Currents parallel to the average magnetic field are also derived. They are regarded as the average field-aligned currents (FACs) in this paper. It is shown that irrespective of variable geomagnetic activity, large-scale FACs are distributed in the conventional pattern, that is, region 1 and region 2 currents. The total intensity of FACs in the 2100-0300 MLT sector is found to increase rapidly with increasing X in the region X = 15 Re. This implies that the main source of FACs in the midnight sector is located in the near-Earth magnetotail. A new model of the magnetotail current system for disturbed periods is proposed on the basis of our findings.

Introduction

The configuration of the cross-field and field-aligned currents and their variability in the magnetotail has been a long-standing problem in magnetotail physics. Since Spieser and Ness [1967] first measured the intensity of the neutral sheet current, difficulties in separating unambiguously auroral and spatial variations in the magnetic field have preoccupied us from determining accurately the current distribution in the magnetotail. Using averaged magnetic field data from the satellites, ISEE 1 and 2, McComas et al. [1986] devised a technique to derive the structure of the neutral sheet current. They have successfully obtained three-dimensional profiles of the current density, which peaks at the center of the current sheet along with small-scale structures.

The neutral sheet current is connected to isoospheric currents via field-aligned currents (FACs hereinafter), forming the three-dimensional current system in the magnetosphere. FACs have less frequently been observed in the near-Earth tail region than at lower latitudes e.g., Aubry et al., 1972; Fairfield, 1973; Sagawa, 1975; Elphic et al., 1985). Ohnani et al. [1988] have shown that earthward and tailward currents are mostly observed in the midnight-morning sector and in the evening-midnight sector, respectively, as expected from the distribution of region 1 field-aligned currents. Tsyganenko et al. [1993] have shown that the total intensity of field-aligned currents decreases rapidly along the X axis down the tail. Earthward currents located poleward of tailward currents have been measured by geosynchronous spacecraft near the midnight meridian [Nagai et al., 1987; Fairfield and Zmester, 1989], corresponding to the well-established structure that dawnward region 1 currents are observed poleward of the region 1 currents in the premidnight sector [Sagawa and Itoh, 1976; Fujii et al., 1994].

Using magnetic field data acquired by AMPTE/CEM in the inner magnetosphere (4 < L < 8.8 Re), Sagawa et al. [1990] have

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studied the neutral sheet current for disturbed conditions, finding that the azimuthal currents exhibit a pronounced noon-midnight asymmetry with the nightside intensities being greater than the dayside intensities. In the nightside, the radial current flow tailward in the morning sector and flow earthward in the evening sector. They have inferred from the current distribution that equatorial currents converge in the morning sector and diverge in the evening sector, suggesting that the near-Earth equatorial currents are connected to the region 2 current system. The coupling between these two currents was first predicted theoretically by Schield et al. [1969] and was developed by Vasyliunas [1972] and by Jogi and Wolf [1973].

The generation mechanism of the region 1 currents has not been established yet. Somogyi [1980] has suggested that region 1 currents, at least in the dayside auroral oval, are generated in the low-latitude boundary layer driven viscously. The most intense region 1 currents are located at ~7 magnetic local time (MLT) and at ~15 MLT [Jimbo and Potemra, 1976], the origins of which are a controversial issue at present [e.g., Stern, 1992; and references therein]. Enhanced region 1 currents in the midnight sector are generally interpreted in terms of the formation of a substorm current wedge [Akesson, 1967; Hassell and McPherron, 1973; McPherron et al., 1973]. In the framework of MHD simulations, Heppner and Borm [1991] have shown that the substorm wedge current is associated with the magnetic field reconnection in the near-Earth magnetotail [Hones, 1979]. They have also suggested that the cross-tail current decreases largely in the vicinity of the near-Earth neutral line and that region 1 type currents are generated earthward of the neutral line because of a strong velocity shear in the plasma convection.

The present study focuses on the distribution of the neutral sheet current and field-aligned currents in the midnight portion of the near-Earth magnetotail. We first attempt to obtain the distribution of the neutral sheet current from a large data set of the ISEE 1 magnetic field for 1978-1987. The net neutral sheet current is calculated by integrating the current density along the Z axis. We closely examine the statistical characteristics of the net current distribution for disturbed periods by comparing them with those for quiet periods. Second, calculating the parallel component of tail currents with respect to the average magnetic field, the distribution of FACs is obtained. A close inspection of the spatial relationship between the neutral sheet currents and FACs provides us with useful information to discuss the current system in the near-Earth magnetotail.

Data

Data used in the present study have been sampled from the measurements by the University of California, Los Angeles, fluxgate magnetometers on ISEE 1 [Russell, 1978] for 1978-1987. The ISEE 1 satellite had an initial orbit with an apogee of 226.6 RE and a perigee altitude of 280 km. In the annual "precession" of the orbit relative to the Sun-Earth line, the satellite went through the magnetotail during the first half of each year. Our primary interest in this study is confined to the region defined by -9.5< L <9.5, -22.5< b< 3.5, and -9.5< Z< 9.5 in geomagnetic solar-magnetospheric coordinates. Here ZL denotes the distance from the average position of the neutral sheet. To predict the position of the neutral sheet, an empirical formula has been derived from our ISEE 1 magnetic field database. This formula is equivalent to Cowley et al.'s [1986] in the region beyond X< -10 RE except near the tail flanks and agrees well with Loper [1990] in the near-Earth region. See appendix for details. BIEE magnetic field data (5-min values) have been classified into three groups, depending on the values of the Al index. We define the "quiet conditions" as Al< -50 nT, "the moderately disturbed conditions" as -20< Al< -50 nT, and "the disturbed conditions" as Al> -200 nT. The three components of the magnetic field have been accumulated for each cell with a volume of 1x1x1k RE. Since the magnetic field contribution from the Earth's magnetic dipole has a large gradient in the near-Earth region, the values of the Earth's dipole field have been subtracted from 5-min values to reduce the deviation in each cell. Then, the remnant values are mainly contributed from external sources.

Our data set has 60,890 data points (5-min values) for quiet periods, 55,339 points for moderately disturbed periods, and 40,692 points for disturbed periods. The average numbers of data points in the 1x1x1k cells are 14.1, 11.5, and 10.1 for quiet, moderate, and disturbed periods, respectively. Unfortunately, these values are not enough to eliminate temporal fluctuations in the values of the magnetic field components. To smooth out the fluctuations, we use the following three-dimensional filter:

Average values of the magnetic field at each cell are designated by the suffixes i, j, and k, which represent the X, Y, and Z coordinates, respectively. The Z component of the magnetic field, BZ (or i, j, k) at (x, y, z) is obtained from

\[ B_z^2 = \sum_{-1}^{+1} B_z^2 \sum_{-1}^{+1} B_x^2 \sum_{-1}^{+1} B_y^2 \]

Here N is the number of data in each cell, and \( B_i \) is the weight, which is defined as

\[ W = \frac{1}{2} (V + U - \sum_{-1}^{+1} B_x \sum_{-1}^{+1} B_y - B_z) \]

The cells in which the sum of the weights is less than 16 are not used as data points in our statistical study.

Calculation of the Current Density

Ampere's law enables us to calculate the three components of the neutral sheet current from \( B_x, B_y, \) and \( B_z \). For example, the Y component of the current density \( j_y \) is derived by integrating the magnetic field along the \( 1-R_y \) segments of the square. The magnetic field along one segment of the path is
represented by the average field in the two cubic cells on both sides of the segment. The two other components, \( i_y \) and \( i_z \), are also calculated in the same way as \( i_x \).

Table 1 shows an example of the components of the current density at \((8, 0, 0)\) \( R_e \) for disturbed periods. The column denoted as \( X, Y, \) or \( Z \) shows the contribution from \( i_x, i_y, \) or \( i_z \), respectively. It should be noted that the contribution from \( i_x \) to \( i_x \) is as strong as that from \( i_z \) at this point. The ratio of the contribution from \( i_x \) to that from \( i_z \) decreases with increasing the distance from the Earth in the \( X \) range dealt with in the present study.

As an example, Figure 1 shows the \( Z \) dependence of the current density \( i_x \) at \((X, Y) = (-6, 0)\) \( R_e \). The solid circles (or triangles) are for disturbed (or quiet) periods. Vertical bars are attached to data points for disturbed periods to show the probable errors of the mean. The thickness of the neutral sheet current is \(-6 R_e \) for both geomagnetic conditions. The distributions are found to be nearly symmetric with respect to their peaks, which are about 5 and 3 \( nA/\text{m}^2 \) for disturbed and quiet periods, respectively. However, the maximum of \( i_x \) does not seem to be placed at zero, resulting from the fact that the slope of the magnetic field magnitude versus \( Z \) is steeper in the southern hemisphere than in the northern hemisphere. This asymmetry probably can be accounted for by considering that the northern and southern data were obtained at different times under different solar wind conditions.

Iyoma et al. (1990) have found that during prolonged disturbed periods the azimuthal current flowing in the \( L \) shell between 7.2 and 8.8 in the midnight sector amounts to 40 A per 1 km thickness (\( \sim 3.9 \text{ nA/m}^2 \)). Lui and Hamilton (1992) have used measurements of the magnetic field strength and plasma for quiet conditions, showing that the average value of the current density is 1 to 4 \( nA/\text{m}^2 \) at \( L \) shells between 3.5 and 9. These two studies are consistent with our results. However, the three examples of the neutral sheet current measured by McComas et al. (1986) were 0.5-2 \( R_e \) thick, which shows that the neutral sheet current can be much thinner than those shown in Figure 1. The reasons for this discrepancy are probably twofold. First, they have chosen very fast crossings of the neutral sheet in order to minimize the effect of temporal varia-
tions of the neutral sheet current. This requirement might have led them to choose the crossings with relatively thin current sheets. Second, the flapping motions of the neutral sheet can make the average current sheet thick in statistical studies.

### Distribution of the Neutral Sheet Current

In the following analysis, we assume that the magnetic field configuration is symmetric with respect to the imaginary plane \( X=0 \). We have folded data in the southern hemisphere into the northern hemisphere. At that time, we have substituted \( i_y \) and \( i_z \) with \( -i_y \) and \( -i_z \), respectively. Then, we have unfolded the data back to the southern hemisphere.

By integrating the current density along the \( Z \) axis from \( Z\text{min} = 4.5 R_e \) to \( 4.5 R_e \), we deduce the net neutral sheet current \( I(NS)^2 \cdot L(2\pi)J \), where \( L \) and \( J \) denote the integrated values of \( i_x \) and \( i_y \), respectively. In Figure 2, the net current at \( X=6 \), \(-10\), and \(-18 R_e \) is plotted as functions of \( Y \). The standard errors of averages are shown for disturbed periods in the left upper graph. For simplicity in the other three graphs, the error bars are attached at only one data point. The standard errors for moderately disturbed and quiet periods are, in general, smaller than those for disturbed periods. It is shown that the current intensity increases evidently with increasing geomagnetic activity at \( X=6 \). The currents for disturbed periods are enhanced particularly in the region \( 3 < \text{TM} < 6 \), resulting in the dawn-dusk asymmetry in the current intensity. There seems to be a least minimum at \( Y = 0 \) for disturbed periods, although the degree of the depression is smaller than the statistical error. (Grouping our data into two subsets for the first half (1978-1982) and the second half (1983-1987) of the satellite observations, we have confirmed that both data sets exhibit such a depression in the midnight sector near the geocen- tric orbits.) It should also be noted that the differences between disturbed and quiet conditions at \( X=14 \) and \( -18 R_e \), respectively, are much smaller than those at \( X=6 \) and \(-10 R_e \).

The \( X \) dependence of the current intensity in the midnight meridian is shown in Figure 3. For quiet periods, the current intensity increases almost constantly by \(-2.5 \text{ nA/m}^2 \) every \( 1 R_e \) from \( X=20 R_e \) to \( X=6 R_e \). On the other hand, for disturbed

Table 1. Current Densities at \((8, 0, 0)\) \( R_e \) for Disturbed Periods

<table>
<thead>
<tr>
<th>( X )</th>
<th>( Y )</th>
<th>( Z )</th>
<th>Total, ( nA/\text{m}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i_x )</td>
<td>0</td>
<td>-0.12</td>
<td>-0.29</td>
</tr>
<tr>
<td>( i_y )</td>
<td>3.16</td>
<td>0</td>
<td>1.80</td>
</tr>
<tr>
<td>( i_z )</td>
<td>-0.55</td>
<td>0.12</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 2: The \( f \) dependence of the net intensity of the neutral sheet current for four different \( X \) distances at (a) \( X = -6 \) \( R_E \), (b) \( X = -10 \) \( R_E \), (c) \( X = -14 \) \( R_E \), and (d) \( X = -18 \) \( R_E \). In each of them the solid and open circles and the triangles denote the net current for disturbed, moderately disturbed, and quiet periods, respectively.

Figure 3: The \( X \) dependence of the net neutral sheet current with the same symbols as Figure 2.

Midlatitude. For example, the differences at \( X = -6 \) and \( -18 \) \( R_E \) are found to be 66.6 mAm and 13.9 mAm, respectively.

Vectors of the net current are plotted on the XY plane in Figures 4a and 4b for disturbed and quiet periods, respectively. iso-intensity contours of the current intensity are also shown. Figure 4a demonstrates that there is a marked dawn-dusk asymmetry in the net current distribution in the region \(-9 \leq X \leq 6 \) \( R_E \). A similar but less drastic asymmetry is seen in the contours for quiet periods in Figure 4b. The current depression, shown in Figure 2 at \( X = -6 \) \( R_E \), appears in the region \( X = -7 \) \( R_E \). However, except for this small depression, there is no clear indication that shows the occurrence of the current disruption, that is, a V-shaped current distribution with a minimum at midnight or premidnight.

In Figure 5, the current density at the equatorial plane \( \left( \Phi = 0 \right) \) for disturbed periods is plotted by arrows along with the contours. This plot also indicates a dawn-dusk asymmetry in the near-Earth region with higher densities in the premidnight sector, implying that this asymmetry results from the distribution of the ion pressure. Assuming isotropic plasma \( \left( \text{Slye et al., 1978; Easter et al., 1992} \right) \), the pressure gradient in the equatorial plane is represented by

\[ \mathbf{P_L} = I \times B \]

Figures 6a and 6b show the vector diagram of the radial and azimuthal components of the pressure gradient, respectively.
The radial gradient increases generally with decreasing the distance from the Earth, as suggested theoretically by Cowley and Ashour-Abdalla [1975] and in observations by Watanabe and Fujima [1993]. The latter have confirmed the existence of $\Psi_{\phi}$ in the plasma sheet from the observations of precipitating ions. Figure 6a also indicates that the $\Psi_{\phi}$ magnitude tends to increase rapidly with increasing $X$ in the region $X<10 R_E$. This situation can be seen more evidently in Figure 7, where the pressure gradient in the midnight meridian is plotted as a function of $X$ for disturbed and quiet periods. The thick line denoted by K in Figure 7 comes from the observations of the ion pressure by Kaiser et al. [1992] for periods just after the onset of substorms. Their values are considerably smaller than what our estimate indicates, particularly, in the region $X<10 R_E$. Lui and Hamilton [1992] have obtained the radial profiles of the ion pressure for intervals of the low $D$Index (Daytime $-15 < nT$), which can be categorized as quiet periods in our terminology. The pressure gradient in Figure 7 from Lui and Hamilton is shown by the thick line denoted by LH in Figure 7. Our estimates for quiet periods agree well with their observations. The steep gradient in the near-Earth region suggests the existence of the high ion pressure near the inner boundary of the plasma sheet. This is probably caused by an enhancement of the earthward plasma flow [Angelopoulos et al., 1994] and/or by injection events associated with the expansion onset of substorms [e.g., Kaiser et al., 1992].

Figure 6b shows a vector diagram for the azimuthal component of the pressure gradient for disturbed periods. The magnitude of the azimuthal component is generally much smaller than that of its radial component in the regime of the present paper. It is noticed that the arrows point duskward in the near-Earth midnight region. On the basis of values of the pressure gradient, the $Y$ dependence of the ion pressure for disturbed periods has been derived. The result is shown in Figure 8. The ion pressure is normalized at $\Psi=0$. It is evident that the ion pressure is asymmetric with respect to the midnight meridian with a higher pressure in the evening sector. For example, the ratio of the ion pressure at $\Psi=5 R_E$ to that at $\Psi=-5 R_E$ is 1.48. This asymmetry is probably caused by the westward drift of ions, which occurs while ions convect earthward through the central plasma sheet. Therefore it may well be that the dawn-dusk asymmetry in the neutral sheet current results from the duskward concentration of plasma sheet ions [Fairfield, 1986]. This effect results in larger equatorward averaged at postmidnight compared with those at premidnight; for example, $B_e=108.5 \pm 1.9 nT$ and $94.6 \pm 2.2 nT$ at $(X,T)=(-5,-3)$ and $(5,3)$, respectively.

**Field-Aligned Component of the Tail Currents**

The current density at each point can be divided into the field-aligned and cross-field components with respect to the average magnetic field. The cross-field current is defined as

$$\mathbf{I}_{FA} = (\mathbf{i} \cdot \mathbf{B}) \mathbf{B}$$

where the suffix $FA$ denotes the "field-aligned" component of the tail current and $B$ is the average magnetic field at each $1 \times 1 \times 1 R_E$ cell. We assume that this component represents the
Figure 6. (a) The radial component and (b) the azimuthal component of the pressure gradient derived from equation (3) for disturbed periods.

Figure 7. The X dependence of the pressure gradient at Y=0. The solid and dashed thin lines indicate the pressure gradients for disturbed and quiet periods, respectively. The thick lines, denoted as K and LH, show the pressure gradients which are derived from measurements by Kistler et al. [1992] and Lui and Hamilton [1992], respectively.

Figure 8. The Y dependence of the ion pressure at X=6 Re. The values of the ion pressure, which are normalized at Y=0, are derived from equation (3).

average values of field-aligned currents (FACs). For example, the intensity of FACs is 1.09 ± 0.28 nA/m² at (-6, 4, 3) Re. Although the standard errors for FACs are not small, we believe that it is possible to disclose the statistical nature of the FAC distribution.

Figures 9a and 9b shows the vector diagrams of FACs for disturbed periods in the postmidnight and premidnight sectors, respectively. The origin of current vectors are shown by dots. For this special way of displaying a number of vectors, the dots for the points at Y=0 are plotted correctly on the XZ plane, while those at Y≠0 (or at Y=0) are displaced right upward (or left downward) from their original positions. Earthward directed FACs are dominant in the postmidnight sector, while tailward FACs are dominant in the premidnight sector. This pattern implies region 1 type FACs.

It is noticed in these diagrams that region 1 type currents flow at relatively high latitudes, Z=3 - 5 Re, within X=−8 Re. This is consistent with Kelly et al. [1984] and Wu and Stanford [1991], who have observed that region 1 type currents flow near the outer edge of the plasma sheet in the near-Earth region. To demonstrate the Z dependence of the tail currents, the vector diagrams of the current density at (X, Y)=(−6, −3) Re and (−6, 4) Re for disturbed periods are shown in Figures 10a and 10b, respectively. The numbers attached to arrows show the Z coordinates in Earth radii of each current vector. It is noted that the current vectors change spirally along the Z axis; that is, currents tend to flow westward at lower latitudes, while...
they flow radially earthward (or tailward) at higher latitudes in the postmidnight sector (or in the premidnight sector). This indicates that the ratio of the field-aligned component to the cross-field component increases with increasing Z from the equatorial plane up to Z=5 or 6 R_E.

Discussion

From an analysis of magnetic-field data from ISEE 1 for 1978-1987, an attempt has been made to deduce the average distribution of tail currents in the near-Earth and midmagnetotail regions for disturbed and quiet periods. On the basis of the results of the present analysis, the magnetotail current system for disturbed periods is discussed in this section.

"Current Disruption" in the Near-Earth Magnetotail

It has often been assumed that the so-called current disruption causes the magnetic field dipolarization in the near-Earth magnetotail, X~8 R_E [e.g., Lui, 1978; Takahashi et al., 1987; Gazey et al., 1995; Pulkkinen et al., 1992]. Using AMPTE/ACE magnetic field measurements for prolonged disturbed periods, Fujima et al. [1990] have shown that the azimuthal component of the equatorial tail current at L=5.6-8.8 has a local minimum near midnight. This is probably identical to the depression in the net current found at X ~ 6 R_E in Figures 2a and 4a. We refer to this signature as "the current trough" in the present paper. This is the only signature we have found which might signify the occurrence of the so-called current disruption in the distribution of the neutral sheet current. Here we discuss whether the current trough truly indicates the occurrence of the current disruption.

In Figure 11, the averages of the B_Z component in the midnight neutral sheet region, |B|<5 R_E and |L|<4-5 R_E, are plotted as a function of the radial distance from the Earth R. Only the magnetic field data with elevation angles greater than 45° were used in calculating these averages. The solid circles and triangles indicate the averages of B_Z during disturbed and quiet periods, respectively. It is interesting to note that the

Figure 9. (a) The vector diagram of field-aligned currents for disturbed periods in the postmidnight sector. Their origins for the points at Y=0 are plotted with dots on the ZX plane, while those for the points at Y=7 are displaced right upward from their original position in the ZX plane; the dot at the far lower left (or upper right) of each array denotes the point at Y=0 (or Y=7) R_E. (b) Same as Figure 9a, except for the premidnight sector. The dot at the far lower left (or upper right) of each array denotes the point at Y=7 (or Y=0) R_E.

Figure 10. Vectors of the current density (a) at (X, Y)=(−6, 3) R_E and (b) at (−6, 4) R_E. The number attached to the head of each arrow denotes the Z coordinate.
averages of $B_r$ for disturbed periods are higher than those for quiet periods beyond $R = 8.5$ R$_{E}$ and vice versa within $R = 8.5$ R$_{E}$. Fairfield et al. [1987] have found the same feature using AMPTE/CCE data. Figure 11 shows that the $B_r$ value increases monotonically with the decreasing $R$. However, the slope of $B_r$ has a clear depression in the vicinity of $R = 6$ R$_{E}$ during disturbed periods. This is probably the result of the strong neutral sheet current within $X = 10$ R$_{E}$.

The $B_r$ values observed by AMPTE/CCE just prior to the onset of the magnetic field dipolarization are also shown by crosses for comparison in Figure 11 [Lui et al., 1992]. The $B_r$ values with elevation angles greater than $45^\circ$ were shown. They were distributed in the local time sector from 2042 MLT to 0124 MLT. The crosses are placed lower than the values for quiet and disturbed periods, implying that the $B_r$ component in the neutral sheet during the growth phase of substorms decreases significantly from the quiet level and subsequently increases up to the disturbed level during the magnetic field dipolarization. It can be inferred that during the recovery phase of substorms the $B_r$ component increases in the near-Earth region and decreases in the midmagnetotail region.

The dipolarizations were primarily attributed to the current disruption in the near-Earth region, the main part of the disruption must occur beyond $R = 8$ R$_{E}$. However, the current trough is in fact located within $X = 7$ R$_{E}$, see Figure 4a. Therefore it is unlikely that the magnetic field dipolarization, at least observed at $X = 8$ R$_{E}$, is caused by the current trough.

As shown in Figures 9a and 9b, earthward and tailward FACs are prevalent in the postmidnight and premidnight sectors, respectively. These FACs might have reduced the total intensity of the neutral sheet current in the midnight sector.

However, the most intense earthward FACs at $X = -6$ R$_{E}$ are in region $-5 < X < -3$ R$_{E}$ rather than $-1 < X < 1$ R$_{E}$, which is the eastward half of the current trough (see Figure 2). The current density over these two regions must be examined further to assess the nature of the current trough.

Coupling Between the Neutral Sheet Current and Field-Aligned Currents

In Figure 12, the $X$ profile of the current intensity at the midnight meridian is compared to that of Tsyganenko's [1987] model (T87 model hereafter) for various $Kp$ values. Note that the $X$ dependence of the net current for quiet and for disturbed periods is well simulated by the model currents for $Kp = 1$ and 4, respectively. These magnetic field models are useful to discuss the distribution of FACs at geomagnetic altitudes in the following part of this subsection.

FACs in the near-Earth magnetotail are mapped to the ionospheric altitude along magnetic field lines. The T87 magnetic field model for $Kp = 4$ is used for the mapping because, as shown earlier, the $X$ dependence of the neutral sheet current of T87 model for $Kp = 4$ is approximated to that for disturbed periods. The results are plotted in Figure 13a, where only FACs with the intensity $>0.05$ nA/m$^2$ in the region $X = -15$ R$_{E}$ are mapped to the ionosphere. Different symbols are used to differentiate the intensity of FACs, and downward and upward FACs are shown separately. The dashed curve corresponds to the equatorial plane at $X = -6$ R$_{E}$, which is the equatorward boundary of the region concerned in the present study. As described in the previous section, Figure 13a shows that downward FACs range mostly from midnight to morning, and upward FACs within $X = -6$ R$_{E}$ is in the midnight. Downward currents extended from the dawnside prevail in the poleward half of the auroral oval in the premidnight sector, 2300-2400.
MLT (magnetic local time). The pattern of FACs illustrated by Iijima and Potemra [1976] has the same structure as the previous one in the premidnight sector. However, small, but
unnegligible upward FACs exist in the same region. The
coexistence of these FACs might imply that FACs in this region are not as stable as region 1 currents at other local times. Indeed, Nagai et al. [1987] and Fairfield and Zonetti [1989] have observed that the structure of FACs in the premidnight sector can vary drastically in association with the onset of substorms. On the basis of their low-altitude measurements, Watanabe and Iijima[1993] have marked this region as the region of multiple current sheets.

In Figure 13a, a small portion of region 2 type FACs can be seen at 2000-2100 MLT and at 0000-0400 MLT equatorward of region 1 type FACs. However, region 2 type currents are likely to be located mostly at latitudes lower than the equatorward boundary of our coverage shown by the dashed line. In Figure 4a, note that the current vectors cross the contours of the current density at $\nabla \nabla = 6 \, R_E$, $\nabla \nabla = 6 \to 2 \, R_E$, implying that region 2 type currents flow into the neutral sheet near and within $\nabla \nabla = 6 \, R_E$. It can be inferred that intense currents which flow azimuthally and radially outward near the center of the neutral sheet, located near $\nabla \nabla = 6 \, R_E$, are a result of the postmidnight sector (see Figure 10a) are coupled with these region 2 type currents.

The distribution of FACs for quiet periods is shown in Figure 13b in the same format as Figure 13a. The T87 model for $Kp=1$ has been used. Region 2 type currents are more clearly seen than in Figure 13a, indicating that the neutral sheet is contracted during quiet times. Perhaps region 0 type currents are identified poleward of region 1 type currents.

In Figure 13a, the intense FACs are located at 2000-2200 MLT and at 0100-0300 MLT. However, Iijima and Potemra [1976] have shown that the downward and upward region 1 current densities are maximized at 0700-0800 MLT and 1500-1600 MLT, respectively. It is unfortunately unclear whether the regions filled with intense FACs in Figure 13a are extended from the high-density regions in the morning and evening sectors or are jetted from them. Kamide et al. [1996] have recently demonstrated in their statistical study that the substorm current patterns over the entire polar region consist of two components: The first is related to the two-cell convection pattern, and the second is related to the westward electrojets in the dark sector, which is associated with the wedge current [Nakada and Koshikam, 1971]. Our intense FACs in Figure 13a seem to correspond to the second pattern of Kamide et al. [1996]. In fact, the FACs around 2100 MLT are tightly identical in local time with the westward traveling surge, which is a dominant feature of substorms. A number of FAC patterns have been proposed based on data from magnetometer arrays and radars at high latitudes [Bougerol et al., 1980, 1981; Oppenkae et al., 1980, Inutsuka et al., 1981]. These authors have contended that there are very localized and intense upward FACs at the head of the auroral surge and less intense downward FACs widely spread eastward of the auroral region. More recently, using data from DE 1 and 2 satellites, Hoffman et al. [1994] have suggested that upward region 1 currents spread wider both eastward and westward from the auroral surge than those obtained from radar and array data. The pattern of the intense upward FACs in Figure 13a extends longitudinally by about 2 hours consistent with Hoffman et al. [1994], although small-scale structures of the auroral surges tend to be smoothed out because of our statistical method.

Earthward (or tailward) FACs mapped to the ionosphere in the local time sector 0000-0300 MLT (or 2100-2400 MLT) are integrated in the ZF plane at $\nabla \nabla = 20 \to 6 \, R_E$. The net intensities of FACs for disturbed and quiet periods are plotted as a function of $\nabla \nabla$ in Figures 14a and 14b, respectively. Since the point $(-15, -7, 0) \, R_E$ is mapped to the ionosphere at $\nabla \nabla = -0300$ MLT along the T87 magnetic field line, the total intensity of
FACs beyond $X=15 R_E$ are underestimated because of the finite resolution of the magnetotail. The earthward and tailward total current amount to 2.5-3.5$10^{10}$ A at $X=6 R_E$, which can be compared with the following earlier studies. [Iijima and Potemra 1976] have estimated the amplitude of region I currents to be $1-2$ $\mu$A/m$^2$ in the midnight sector from 2100 MLT to 0300 MLT for relatively disturbed periods, $X$ $\approx$ $X_p$+$4$. Assuming a 2$^\circ$ width of region I currents in latitude, this yields a total current of $3.4$-$10^{10}$ A for the sectors, 2100-0000 MLT or 0000-0300 MLT. [Ohtani et al. 1988] have obtained the intensity of FACs of the order of 10 mA/m$^2$, examining step-like variations in the $R_s$ component in the near-Earth magnetotail region. If the width of the current sheet is assumed to be 5 $R_E$, the total earthward current in the postmidnight sector becomes $3.2$-$10^{10}$ A. Our estimate is consistent with [Iijima and Potemra 1976] and Ohtani et al. [1988]. More recently, Tsuganezako et al. [1993] evaluated the total field-aligned current at $X=10 R_E$ within $[7]_{20} R_E$ (in the sector from 1930 to 0430 MLT at geomagnetic latitudes). Their estimate for the total field-aligned current at $X=10 R_E$ is $5$-$7$-$10^{10}$ A, which is converted to the 3 hour local time values of 3.3-4.7$10^{10}$ A. While they have assumed no criterion on geomagnetic activity, their results are nevertheless somewhat greater than our results for disturbed periods. This discrepancy is probably, at least partly, the result of the several assumptions they have made about the magnetic field configurations.

Figure 1b demonstrates that the total intensity of FACs for disturbed periods increases with increasing $X$, particularly in the region $X=15 R_E$ [Tsuganezako et al., 1993]. Comparing Figure 1a with Figure 1b, it can be seen that the intensity of FACs becomes more sensitive to substorm activity in this region. This is consistent with the fact that intense FACs at disturbed times are preferably observed within $R<15 R_E$ [Ohtani et al. 1988]. These two features imply that the main source of FACs for disturbed periods is located in the region $R<15 R_E$ in the midnight sector.

It is noted in Figure 9a that there are intense FACs at $Z$-$4$-$5$ $R_E$ in the region $-8$-$6$-$8$-$6$ $R_E$. Each point $X=6 R_E$ above $Z=4$ $R_E$ is mapped downstream to the equatorial plane beyond $R=20 R_E$ along field lines of the T67 model for $K_p=4$. Nevertheless, Figure 9a clearly shows that FACs at high latitudes become weak in the region beyond $X=10 R_E$. A similar tendency can be seen in the premidnight sector (Figure 9b). For FACs at $Z<3 - 5 R_E$ this implies that FACs cannot originate from (or sink into) the outer plasma sheets, or perhaps the plasma sheet boundary layer, within $X=10 R_E$.

If we assume that the source region of FACs extends radially to 5 $R_E$ and the total current is $3.0$$10^{10}$ A in the postmidnight sector, the decrease in cross-field currents is estimated to be $-5$ $\mu$A/m$^2$. However, the net current increases in the region $X>10 R_E$ with the decreasing $J_l$ as shown in Figure 2a and 4a. Assuming that one of the origins of FACs exists at high latitudes within $R<10 R_E$, it is possible to infer that the current divergence is compensated by equatorial currents, which are probably reinforced by region 2 type currents in the morning sector. The coupling between FACs and the neutral sheet current has been discussed extensively, assuming that the thickness of the neutral sheet current is zero. However, this assumption is not well-grounded in observations or theoretically [Fujikawa, 1984]. The present study suggests that current models with a thin current sheet at the equatorial plane cannot describe adequately the three-dimensional structure of the magnetospheric current system.

Summary

The following points are the main findings regarding the average distribution of tail currents for disturbed periods. (1) The net current is very intense (-140 $\mu$A/m$^2$) in the near-Earth region. It decreases downstream rapidly in the transition region, $X=10 R_E$, and decreases gradually beyond $X=15 R_E$. (2) The current density at the neutral sheet also increases with the increasing $X$, implying the increase in the gradient of the ion pressure particularly in $X>10 R_E$. (3) The current intensity is maximized at premidnight near $X=8$-$6$ $R_E$, although there is a small current depression at $X=6$-$7 R_E$. (4) There is an azimuthal asymmetry in the current intensity with stronger currents in the premidnight sector than in the postmidnight sector. (5) The total intensity of region 1 type earthward (tailward) FACs, whose foot points on the ionosphere are in the
local time sector from 0000 MLT to 0300 MLT (from 2100 MLT to 0000 MLT), is about 2.5-3.5x10^{10} A at X=-6 R_E (6). In the midnight sector, FACs originating from the region X_E-15 R_E are dominant in the near-Earth region. (7) FACs are partly created in the outer plasma sheet or in the plasma sheet boundary layer within X_E=-10 R_E.

These findings are quite useful in providing restrictions to deduce a realistic model of the nightside magnetospheric current system for disturbed periods. Figure 15 presents a schematic pattern of three-dimensional current system connecting the magnetosphere to the ionosphere during a substorm. The region 1 and region 2 currents are drawn in the YZ plane for simplicity, although they are not necessarily symmetric with respect to the noon-midnight meridian. From the points 3 and 4, the current continuity requires that region 2 type currents converge on (or diverge from) the neutral sheet current in the postmidnight sector (or in the evening sector), forming the partial ring current [Pilippishina and Kamide, 1973, and references therein]. The narrow wedge current that flows into the ionosphere in the postmidnight sector and flows out from the ionosphere at premidnight is also depicted in Figure 15.

In this study, the data set have not been divided on the basis of substorm phases. Thus the subset with ΔV_YS=200 nT can involve the data obtained during the different phases of substorms. However, the generation of FACs in the midnight sector is supposed to occur during the expansion phase or (early recovery phase) of substorms. The relaxation of the extended magnetic field lines, which is associated with the decay of the lobe field, enhances earthward plasma flows in the midmagnetotail at the expansion phase of substorms [e.g., Bortnik et al., 1991]. Then, the wedge current is generated by the velocity shear along both sides of the enhanced plasma flow [Bortnik and Heppner, 1991]. In terms of this scenario, we statistical results for disturbed periods are thought to represent the current configurations for the expansion phase (or the early recovery phase) rather than those for the postmidnight phase of substorms.

The slowing down of the fast earthward flow due to the strong magnetic field in the inner magnetosphere results in the pile up of ions in the region X_E-10 R_E (the shaded region in Figure 15). The increase in the pressure gradient enhances the partial ring current, causing the magnetic field dipolarization in the near-Earth magnetotail [Nakai and Kamide, 1994, 1995]. The connection between the partial ring current and region 2 field-aligned currents can be expected from the requirement of current continuity. The enhanced partial ring current diverges partly at high latitudes, resulting in the reinforcement of the wedge current (the dashed lines in Figure 15). Although the causes of the current trough are not understood at present, the divergence of the partial ring current along field lines is probably one of the possible causes. It is important to note that this scenario implies the existence of the couplings between the large-scale region 1 and 2 currents and the substorm current wedge. Categorizing the magnetospheric current systems into the directly driven process (the large-scale region 1 and 2 current system) and the loading-unloading process (the substorm current wedge system) [e.g., Akasofu, 1991], our scenario suggests that the partial ring current can play an important role in coupling the directly driven process and the unloading process is solar wind-magnetosphere interactions.

Appendix

We have searched the OSEE 1 magnetic field data in the region X_E-10 R_E and Y=18 R_E for neutral sheet crossings. Crossings that were subsequently followed by a reconnection within a few tens of minutes have not been accepted in the present analysis, since they might result from temporal motions of the magnetotail. It has also been observed at times that the satellite crossed the neutral sheet repeatedly during a few hours. In such multiple-crossing events, only one crossing that occurred at about the center of the duration, has been included in our data set. The 333 crossings satisfying these conditions have been retained for the present statistical study.

The position of the average neutral sheet DZ_E (R_E) is estimated by using an equation,

$$DZ_E = H_0 \sin(\chi) \left[ 1 - \frac{(T - T_c)^2}{T_c^2} \right]$$  \hspace{1cm} (A1)

Here \chi denotes the tilt angle of the dipole axis, and T_c denotes the point at which the neutral sheet crosses the equatorial plane. The best fit for the data is found when H_0, T_c, and T_c are 5.5 R_E, 1.0 R_E, and 14.0 R_E, respectively, with a correlation coefficient of 0.83. The best choice value of T_c indicates that the aberration of the tail axis is -4 degrees on average. To predict the distance from the neutral sheet in the present study, we have replaced T_c with -5 tan \theta, where \theta is 4 degrees.

Figure 15. A schematic pattern of three-dimensional current system connecting the magnetosphere to the ionosphere during disturbed periods. The region 1 and region 2 currents, the partial ring currents, and the substorm current wedge are shown by solid lines with arrows. The solid thick arrow indicates the plasma convection enhanced in association with the onset of substorms. The shaded region shows the piling up of hot ions.
Figure A1. Distribution of neutral sheet crossings. The data are divided into five bins of the tilt angle with 7 degrees width. The solid lines indicate the model neutral sheet yield computed from equation (2).

In Figure A1, the neutral sheet crossings are plotted in each tilt angle bin with a width of 7 degrees. Assuming that the shape of the neutral sheet is symmetric to that in summer with respect to the solar-magnetospheric equatorial plane, the data points with the negative tilt angle have been mapped onto the opposite hemisphere. The solid lines in Figure A1 indicate (A1), which fits best to the data points. Figure A2 shows our neutral sheet model for χ=30° along with Gosling et al.'s [1986] model. Our prediction agrees quite well with Gosling et al. in the midnight sector but disagrees in the tail flank region.

The neutral sheet tends to bend toward the equatorial plane of the dipole field in the near-Earth tail region. The Z coordinate of the equatorial plane is given by $Z = -X \tan(\chi)$. To represent a smooth transition from the equator of the dipole field to the warped neutral sheet (A1), the following formula is constructed:

First, $X_0$ is defined as $DZ = -X_0 \tan(\chi)$. For $X < X_0$, the position of the neutral sheet $DZ$ is given by

$$ DZ = -X \tan(\chi) f $$

where

$$ f = \begin{cases} 
C_1 (X - X_0) + (1 - \delta) & \text{for } X < X_1 \\
1 & \text{for } X > X_1
\end{cases} $$

Here $X_1$ is defined as

$$ X_1 = X_H - \frac{\delta}{C_1} $$

Here $X_1$ is defined as

For $X > X_0$,

$$ DZ = DZ_0 \ g $$

where

$$ g = \begin{cases} 
C_1 C_2 (X_H - X) + (1 - \delta) & \text{for } X > X_2 \\
28-36 & \text{for } X = X_2
\end{cases} $$

Here $X_2$ is defined as

$$ X_2 = X_H - \frac{\delta}{C_1 C_2} $$

Figure A2. A model of the neutral sheet (solid line) along with Gosling et al.'s [1986] model (dashed line) for $\chi=30°$. 
In Figure A3, the position of the neutral sheet in the midnight meridian is shown as a function of X for five values of the tilt angle. The open squares indicate the neutral sheet position obtained by Lopez [1990], examining neutral sheet crossings of AMTE/CECE in the near-Earth region. Our empirical formula can very well predict their results, when $\delta$ is 0.25 and $C_1$ is 0.050.

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