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Spatial distribution of the eddy diffusion coefficients in the plasma sheet during quiet time and substorms from THEMIS satellite data

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[1] During the last decade, a number of studies have shown that turbulent processes in the plasma sheet are very important for the analysis of the formation of quasi-stable plasma sheet configurations. The existence of this turbulence provides a self-consistent approach to study the dynamics of the Earth's magnetosphere, including the plasma sheet stability. The turbulence can also be very important for an understanding of the location of an isolated substorm expansion phase onset. In this study the level of turbulence has been evaluated by calculating the eddy diffusion coefficients using the Time History of Events and Macroscale Interactions during Substorms satellite data. It was found that the value of the eddy diffusion coefficients may vary by at least 3 orders of magnitude, generally ranging from 10^3 to 10^6 km^2/s, increasing with the distance from the Earth. The area of low eddy diffusion coefficients, less than 10^4 km^2/s, is situated at distances below 12 R_E in the tail where we found the transition region between the dipole and the tail-like geomagnetic field configuration. This region is consistent with the location of isolated substorms, as indicated by the first auroral arc brightening situated at the equatorial edge of the auroral oval.

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1. Introduction

[2] There is mounting evidence that plasmas can demonstrate very complex behavior, that include multiscale dynamics, emergence and self organization, phase transitions, turbulence, spatiotemporal chaos, etc. [*Lu*, 1995; *Carreras et al.*, 1996; *Valdivia et al.*, 1996, 2003, 2005, 2006; *Biskamp*, 2000; *Klimas et al.*, 2000, 2010; *Uritsky et al.*, 2007].

[3] The magnetosphere is formed as a result of the interaction between the solar wind supersonic and super-Alfvenic turbulent flow and the geomagnetic field. Hence, it is natural to expect that existence of turbulence in various regions of the magnetosphere, and in particular in its tail. Nevertheless, there is a significant difference between a fluid turbulent wake behind an ordinary obstacle and the geomagnetic tail. The cross section radius of the ordinary wake is close to that of the obstacle, while the magnetotail is separated into the plasma sheet, and the tail lobes. A number of studies have shown that turbulent processes in the plasma sheet are very important for the understanding of its dynamics [*Antonova*, 1985; *Angelopoulos et al.*, 1992, 1993; *Borovsky et al.*, 1997; *Ohtani et al.*, 1998]. As evidences of turbulence in the plasma sheet, it is possible to mention the "sky images" of near-Earth space plasma, showing the presence of multiple structures moving with different, and sometimes very large, velocities [*Chamberlain*, 1961]; or the presence of strong fluctuations in the electric fields at the auroral field lines measured by Viking, Freja, Fast, and Interkosmos-Bulgaria-1300 satellites [*Maynard et al.*, 1982; *Mozer et al.*, 1980; *Weimer et al.*, 1985; *Stepanova et al.*, 2003a]. A clear manifestation of the existence of low-frequency magnetospheric turbulence was also obtained through analysis of fluctuations of geomagnetic indices [see *Takalo et al.*, 1993; *Consolini and De Michelis*, 1998; *Uritsky and Pudovkin*, 1998; *Hnat et al.*, 2002; *Stepanova et al.*, 2003b, 2005a; *Pulkkinen et al.*, 2006; *Wanliss and Uritsky*, 2010], auroral absorption [*Stepanova et al.*, 2005b, 2006], and Polar UVI images [*Uritsky et al.*, 2008]. Measurements of the particle fluxes inside the plasma sheet allowed to study the fluctuations in the plasma bulk velocity and show that these fluctuations exceed significantly their average values [see *Baumjohann et al.*, 1990; *Angelopoulos et al.*, 1992, 1993, 1996, 1999; *Borovsky et al.*, 1997, 1998; *Borovsky and Funsten*, 2003a, 2003b; *Borovsky and Gary*, 2009; *Ovchinnikov et al.*, 2000; *Troshichev et al.*, 2002; *Stepanova et al.*, 2005c, 2009]. Despite differences in time resolution, the behavior of different components of the bulk velocity fluctuations is very similar, except for the bursty bulk flow events (BBFs), which produce asymmetry in the probability

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density function of the X and Y components of the inner plasma sheet flows in the GSE/GSM coordinate system. According to *Baumjohann et al.* [1990], *Angelopoulos et al.* [1992, 1993, 1996, 1999], and *Borodkova* [2002], when BBFs are removed from the plasma sheet observational database, the plasma flow has an average convection that is small and a variance that is many times larger than its average.

[4] The existence of this turbulence provides a self-consistent approach to study the dynamics of the Earth's magnetosphere, including the plasma sheet stability and the location of the expansion onset of isolated substorms [e.g., *Antonova and Ovchinnikov*, 1996, 1999; *Antonova et al.*, 1998; *Stepanova et al.*, 2002, 2005c, 2009]. For example, on the average, the magnitude of the plasma bulk velocity in the magnetosphere of the Earth is generally smaller than the Alfven and sound speeds. So the condition of magnetostatic equilibrium (forces connected to the existence of plasma pressure gradients are compensated by the Ampere's force) is generally fulfilled. Nevertheless, the problem of the creation and support of this equilibrium remains a controversial issue.

[5] Along this line, *Antonova and Ovchinnikov* [1996, 1999, 2001] proposed that a stable turbulent plasma sheet can be formed when the regular plasma transport, produced by the dawn-dusk electric field across the plasma sheet, is compensated by the eddy diffusion turbulent transport across it. They consider that the plasma particle flux is equal to $\mathbf{S} = n\langle \mathbf{V} \rangle - D\nabla n$, where n is the average of the turbulent plasma particle density fluctuation, $\langle V \rangle$ is the averaged bulk velocity, and, D is an eddy diffusion coefficient. When the turbulent fluctuations act to expand the plasma sheet, the large-scale electrostatic dawn-dusk electric field tries to compress the sheet. When the expansion and compression compensate each other, a stationary structure can be formed. This assumption allows to predict the order of magnitude of the eddy diffusion coefficient in the Z direction 10^5 km^2/s, that is necessary to reproduce the observed plasma sheet thickness. This value agrees with the estimated eddy diffusion coefficients, obtained from measurements at the ISEE-2, Interball-Tail, and GEOTAIL satellites [*Borovsky et al.*, 1997, 1998; *Borovsky and Funsten*, 2003b; *Ovchinnikov et al.*, 2000; *Troshichev et al.*, 2002; *Stepanova et al.*, 2005c, 2009]. Furthermore, the eddy diffusion transport in the plasma sheet is affected by the location inside the plasma sheet, the geomagnetic activity, and the solar wind parameters [*Ovchinnikov et al.*, 2000; *Neagu et al.*, 2002, 2005; *Stepanova et al.*, 2005c, 2009; *Nagata et al.*, 2008; *Wang et al.*, 2010].

[6] To date, the nature of the observed turbulence is not clear, and probably there is a number of physical processes leading to the turbulence generation which depends on scale, both spatially and temporally. For example, *Antonova et al.* [1998], *Luizar et al.* [2000], and *Antonova* [2002], suggested that plasma pressure gradients are the most probable candidates for the generation of large- and medium-scale harmonics of the magnetospheric turbulence. There are also indications that the level of magnetic turbulence in the magnetotail correlates with the level of the velocity perturbations and particle beams, which dramatically increase with the flow velocity. Therefore, shear flows and particle beams are also premiere candidates for the generation of turbulence [*Bauer et al.*, 1995; *Vörös et al.*, 2004].

[7] Even though the plasma sheet appears to be a dynamic and turbulent region [*Borovsky et al.*, 1997; *Ohtani et al.*, 1998], the substorm cycle seems coherent and repeatable with identifiable distinct phases [*Baker et al.*, 1999] and predictable geomagnetic indices [*Vassiliadis et al.*, 1995; *Valdivia et al.*, 1996, 1999]. It has been suggested that the resolution to these seemingly contradicting observations should be through the understanding of the process of self organization in plasmas [*Chang*, 1999; *Uritsky and Pudovkin*, 1998; *Valdivia et al.*, 2005, 2006; *Uritsky et al.*, 2009a]. The possibility of an inverse turbulent cascade has been discussed by *Uritsky et al.* [2001] and *Rosa et al.* [1998]. Furthermore, the interaction between different harmonics of the magnetospheric turbulence is not well explored. A number of works indicate that the turbulence in the plasma sheet has an intermittent character [*Angelopoulos et al.*, 1999; *Consolini and De Michelis*, 1998; *Stepanova et al.*, 2003b, 2006; *Arancibia Riveros et al.*, 2008]. A very interesting approach to explain the processes leading to the formation of the spectrum of magnetospheric turbulence, including the self-consistent influence of geomagnetic substorms and storms, is the concept of the self-organized criticality [*Chang*, 1999; *Uritsky and Pudovkin*, 1998; *Klimas et al.*, 2000; *Valdivia et al.*, 2003, 2005, 2006; *Uritsky et al.*, 2007, 2009b].

[8] In this paper we analyze the spatial distribution of the eddy diffusion coefficients using Time History of Events and Macroscale Interactions during Substorms (THEMIS) satellite data, for the different phases of isolated magnetospheric substorms. The manuscript is organized as follows. In section 2, we describe the data and its analysis. In section 3, we discuss the results.

2. Instrumentation and Data Analysis

[9] For this study we used THEMIS satellite data that was acquired in the plasma sheet. To select the time intervals we used the moments of the ion distribution functions obtained from the onboard moments calculations of the Electrostatic Analyzer (ESA) in the energy range from 25 eV to 25 KeV and Solid State Telescopes in the energy range from 25 keV to 6 MeV [*McFadden et al.*, 2008; *Angelopoulos*, 2008]. The geomagnetic field measurements were provided by the fluxgate magnetometer (FGM) [*Auster et al.*, 2008], which were used for the calculation of the plasma β parameter. In order to compare the previous results of *Stepanova et al.* [2009], using the Interball-Tail satellite, we select intervals with number density $n \geq 0.1$ cm^{-3}, and ion temperature $T \geq$ 1 keV. We enforce that the satellite Z coordinate is between -8 R_E and 8 R_E, with $\beta \geq 1$, to ensure that the satellite is located in the plasma sheet. The X and Y coordinate of the satellites are shown in Figure 3.

[10] Figure 1 shows an example of the data from THEMIS C satellite on 26 February 2008. It can be seen, that the satellite not always was located inside the plasma sheet, and the combination of criteria $n \geq 0.1$ cm^{-3} (not shown in Figure 1), $T \geq 1$ keV, and $\beta \geq 1$ is sufficiently robust to ensure the location of the satellite inside the plasma sheet Figure 2.

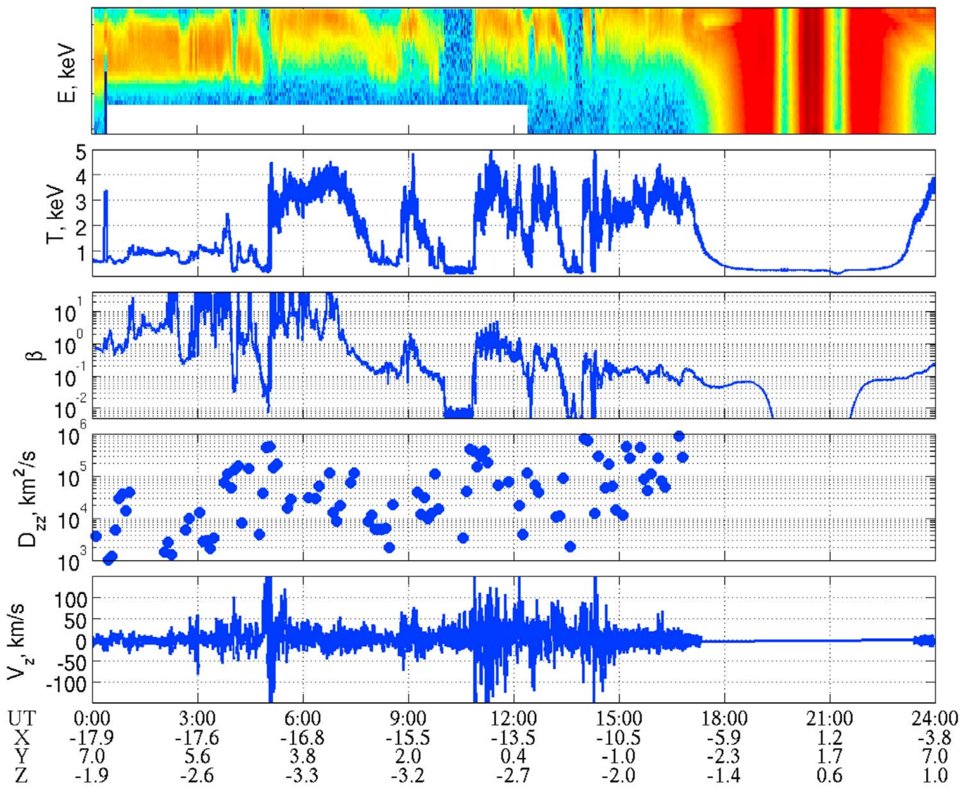

Figure 1. From top to bottom: (a) Ion spectrogram, (b) ion temperature, (c) plasma β parameter, (d) eddy diffusion coefficient, and (e) Z component of the bulk velocity and corresponding eddy diffusion coefficient obtained from the onboard moments of the ion distribution function measured by the THEMIS C on 26 February 2008.

[11] To evaluate the level of the turbulent transport it is convenient to determine the eddy diffusion coefficient tensor D which is the most suitable for the description of the plasma transport produced by the turbulent convection vortexes in the diffusion approximation. It is not the only parameter that describes the turbulent transport, but it is a robust measure of the intensity of turbulent transport. Furthermore, as we mentioned above, this quantity is very important for the understanding of the plasma sheet stability through the relation $\mathbf{S} = n\langle \mathbf{V} \rangle - D\nabla n$.

[12] For THEMIS, we can construct three components of the bulk velocity $V_\alpha(i)$ in the GSM coordinate system with a time resolution of 3 seconds according to the probe spin time. If we take two of such components, for example α and β, we can calculate the autocorrelation function

$$A_{\alpha\beta}(\tau) = \frac{\sum (V_\alpha(i) - \langle V_\alpha \rangle)\left(V_\beta(i+\tau) - \langle V_\beta \rangle\right)}{\sqrt{\sum (V_\alpha(i) - \langle V_\alpha \rangle)^2}\sqrt{\sum \left(V_\beta(i) - \langle V_\beta \rangle\right)^2}}, \qquad (1)$$

where the mean velocity for N data points is defined as

$$\langle V_\alpha \rangle = \frac{1}{N}\sum_{i=1}^{N} V_\alpha(i). \qquad (2)$$

The data were separated into 12 min intervals, that contain $N = 240$ bulk velocity data points. Adjacent intervals overlap for half of their length (6 min), and we use the center of the interval to mark the time. The autocorrelation time ($\tau_{\alpha\beta}$) was determined as the best fit to the natural logarithm of the autocorrelation function

$$A_{\alpha\beta}(\tau) = \exp\left(-\tau/\tau_{\alpha\beta}\right) \qquad (3)$$

by the linear expression $y = 1 - ax$, using only one parameter of fitting. Figure 2 shows an example of the bulk velocity V_z and the corresponding autocorrelation function with the respective fit. We have used three methods to estimate the autocorrelation time. In the first method, we find the value τ_0 at which the logarithm of the autocorrelation function goes through zero. Then we do a number of fits to the value of $\tau_{\alpha\beta}$ using a decreasing number of points between $3 \leq \tau \leq \tau_0$, and select the value of $\tau_{\alpha\beta}$ with the smallest average error. In the second method, we find the value $\tau_{\min}$ where the autocorrelation function has its first minimum, and fit the value of $\tau_{\alpha\beta}$ using all the points between $0 \leq \tau \leq \tau_{\min}$. In the third method, we find the value τ_e where the autocorrelation function goes below e^{-1}, and fit $\tau_{\alpha\beta}$ using all the points between $0 \leq \tau \leq \tau_e$. With these three values of $\tau_{\alpha\beta}$, we can estimate an average value of $\tau_{\alpha\beta}$.

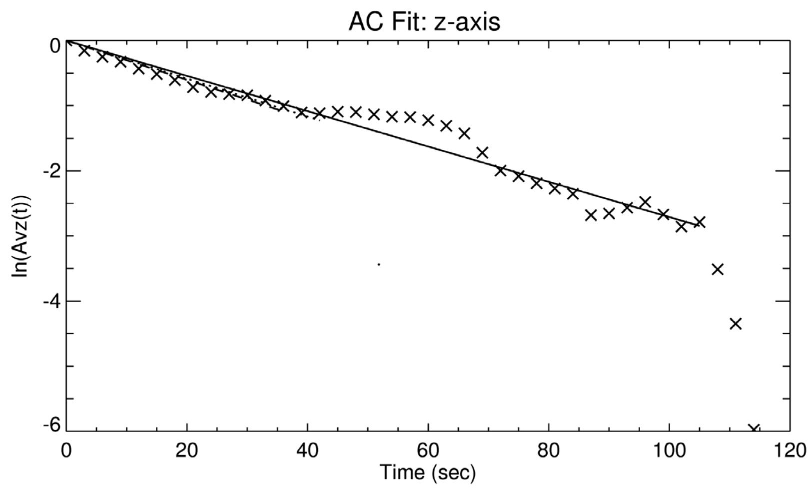

Figure 2. The autocorrelation function will all three fits, obtained from the THEMIS C satellite data on 26 February 2008 at 0509 UT.

[13] Similarly, the mean square (rms) speed during the chosen time interval is determined from

$$V^2_{rms,\alpha\beta} = \frac{1}{N}\sum\left(V_\alpha(i) - \langle V_\alpha\rangle\right)\left(V_\beta(i) - \langle V_\beta\rangle\right). \qquad (4)$$

Finally, the eddy diffusion coefficient is obtained from

$$D_{\alpha\beta} = \frac{V^2_{rms,\alpha\beta}\tau_{\alpha\beta}}{2}. \qquad (5)$$

[14] Let us note that following this procedure makes it possible to estimate all components of the eddy diffusion coefficient tensor in the GSM basis, but for the purpose of the present manuscript we will only analyze the diagonal terms D_{xx}, D_{yy} and D_{zz}.

[15] With the three values for τ, we can also estimate a deviation σ_τ, defined by half the difference between their minimum and maximum values. If this deviation is larger than 50% of the average value of τ, we do not consider the interval in our analysis. It is important to mention that we also eliminate from the analysis the intervals that have small autocorrelation time (τ < 10 s) and large autocorrelation time (τ > 300 s). Exclusion large autocorrelation times partially removes the coherent flows.

[16] To determine whether the eddy diffusion coefficient is taken during the quiet time, expansion, or recovery phase of the substorm, we perform an analysis of the 1 min resolution Auroral Low (AL) index. The interval was considered as quiet when $AL \geq -100$ nT and the absolute value of the slope s of the AL index was $|s| \leq 1/2$ nT/min for 40 min before and after the middle of the interval. The interval was considered as expansion when $AL < -100$ nT and the value of the slope of the AL index was $s \leq -1/2$ nT/min for 5 min with respect to the middle point of the interval, and $s < 0$ for 20 min with respect to the middle point of the interval. The interval was considered as recovery when $AL < -100$ nT and the value of the slope of the AL index was $s \geq 1/2$ nT/min for 5 min with respect to the middle point of the interval, and $s > 0$ for 20 min with respect to the middle point of the interval. In this study we could not distinguish the data corresponding to the growth phase, as it was difficult to establish a clear criterion for automatic data extraction. Therefore, the majority of eddy diffusion values corresponding to the growth phase have been included into the quiet time data set.

[17] To analyze the spatial distribution of the eddy diffusion coefficients, we partition the *X-Y* GSM plane into 30 overlapping bins between 6 and 30 R_E into the tail, and between $-\pi/4$ and $\pi/4$, having midnight as 0, in the azimuthal direction. Each bin has an extension of 6 R_E in the radial direction and $\pi/12$ in the azimuthal direction. Each next bin overlaps with the previous one for half step size (3 R_E and $\pi/24$). This was done to improve the statistics so that each bin has at least 10 measurements of the eddy diffusion coefficients, which permits a smooth final distribution. The number of eddy diffusion coefficients measurements found in each bin is shown in Figure 3d, for each of the three different phases of isolated substorms.

[18] Figure 3 shows the spatial distribution of diagonal terms of the eddy diffusion coefficient tensor in GSM coordinate system during the three different phases of isolated substorms considered in the analysis. We can see that even under quiet geomagnetic conditions, the value of the coefficients vary significantly. However, we found that on average all the diagonal terms of the eddy diffusion coefficient tensor increase with distance in the tail under all geomagnetic conditions. Furthermore, we have in general $D_{xx} > D_{yy}$, D_{zz}, as can be seen by comparing Figures 3 (left), 3 (middle), and 3 (right), as the eddy diffusion in *X* direction could be affected by the propagation of the bursty bulk flows (BBFs) studied by *Baumjohann et al.* [1990] and *Angelopoulos et al.* [1992]. Let us note that the values of the eddy diffusion coefficients obtained here are similar to the typically values reported for the plasma sheet [see, e.g.,

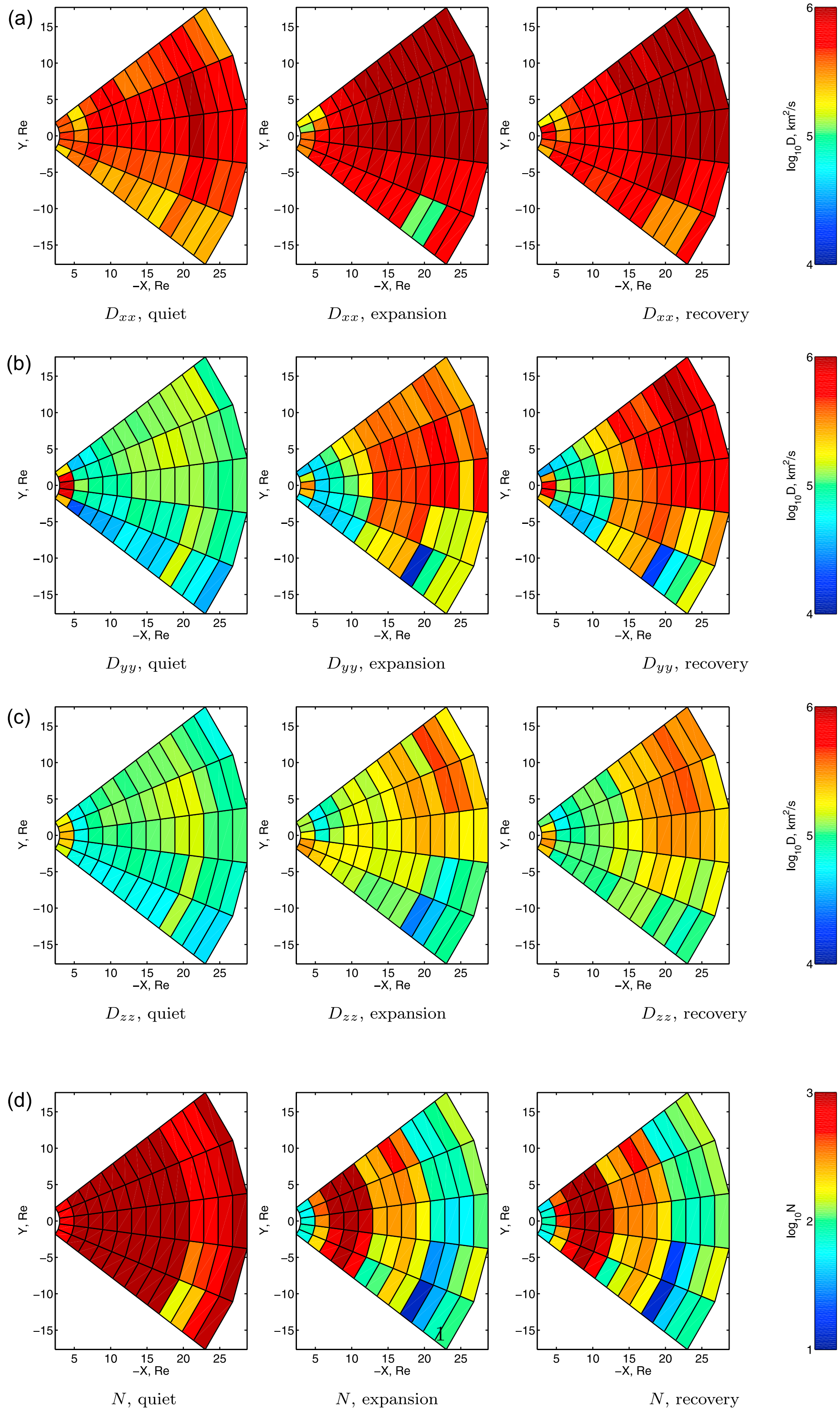

Figure 3. Estimations of the spatial profile of diagonal terms of the eddy diffusion coefficients ((a) D_{xx}, (b) D_{yy}, and (c) D_{zz}) during the three different phases of isolated substorms considered in the analysis: (left) quiet phase, (middle) expansion phase, and (right) recovery phase. (d) The number of eddy diffusion measurements N in each bin for the three different phases of isolated substorms is also given. The color bar is used for D and N values.

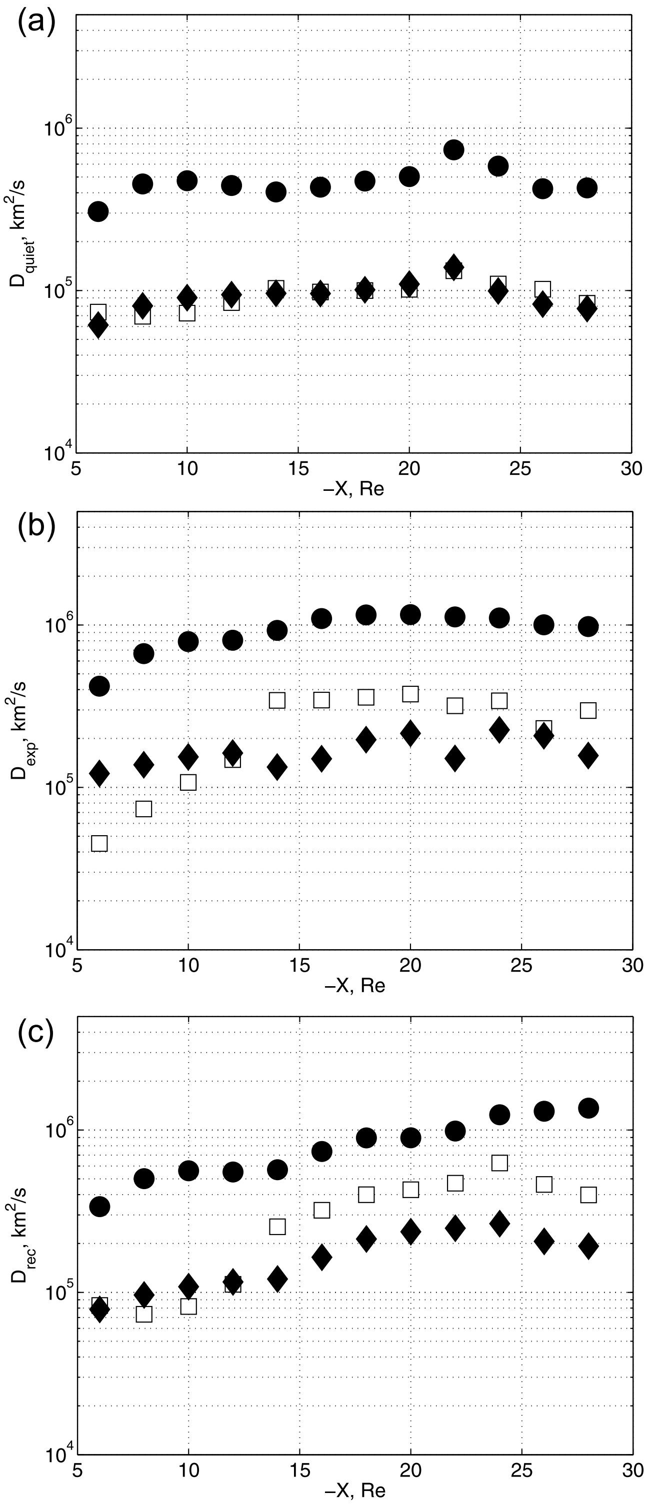

Figure 4. Variation of the eddy diffusion coefficients for (a) quiet, (b) expansion, and (c) recovery time intervals. D_{XX} (black circles), D_{YY} (white squares), and D_{ZZ} (black diamonds) are given.

Borovsky et al., 1998; *Borovsky and Funsten*, 2003b; *Ovchinnikov et al.*, 2000; *Troshichev et al.*, 2002; *Stepanova et al.*, 2005c, 2009].

[19] Figure 4 shows the variation of eddy diffusion coefficient with the distance from the Earth, obtained by averaging the bins showed in Figure 3 by the angle. We can see that in general all the diagonal components of the eddy diffusion coefficient tensor tend to increase with distance from the Earth, especially during the expansion and recovery phases of substorms. There seem to be a saturation at around 10–15 R_E, which could be related to the change from dipole to tail field. Unfortunately, the THEMIS mission does not account for a satellite at distances larger than 30 R_E, so that we can only assume that this saturation effect continues, but we cannot be certain.

[20] We note that during substorms all three diagonal components, D_{XX}, D_{YY}, and D_{ZZ}, experience a significant increase with respect to the quiet times. There is a local maximum at a distance of ~22 R_E, that deserves further study.

[21] There is a clear dawn-dusk asymmetry in all three diagonal elements of D, as can be seen in Figure 3. This effect occurs for all phases, but it is more significant during the recovery phase. It is also interesting to note that at around $X = -20\ R_E$ and $Y = -10\ R_E$ there is a local decrease in all three diagonal components, which may be related to the low statistics seen in Figure 3d.

3. Conclusions

[22] Analysis of bulk velocity fluctuations obtained from THEMIS satellite mission allowed to determine the spatial distribution of the values of eddy diffusion coefficients for different phases of geomagnetic substorms and during quiet time inside the plasma sheet for all components of the bulk velocity. Obtained D_{yy} and D_{zz} distributions are similar to ones reported by *Stepanova et al.* [2009] using the Interball-Tail data. Nevertheless, better sampling of the bulk velocity allowed to detect new features in the behavior and distribution of the eddy diffusion coefficients and, unlike the Interball-Tail satellite, to study the eddy diffusion in the X direction. It also allowed to improve the identification of quiet time intervals and intervals corresponding to expansion and recovery phases. Eddy diffusion coefficients obtained for quiet geomagnetic conditions are close to those obtained by *Nagata et al.* [2008] and *Wang et al.* [2010].

[23] In this study it was found that the values of eddy diffusion coefficients vary significantly, increasing on average in the tailward direction, especially during disturbed geomagnetic conditions. Furthermore, the values of the diagonal terms of the eddy diffusion coefficient tensor seem to saturate for large values of $-X$. This variation can reflect the transition from the region where the presence of the dipole geomagnetic field is still relevant, to the region where the geomagnetic field has a pure tail configuration.

[24] The values of the eddy diffusion coefficients in Z direction are very similar to those predicted by *Antonova and Ovchinnikov* [1996, 1999, 2001]. According to this approach, a compact and comparatively stable turbulent plasma sheet can be formed when the regular plasma

transport, produced by the dawn-dusk electric field across the plasma sheet, is compensated by the eddy diffusion turbulent transport. When the turbulent fluctuations act to expand the plasma sheet, the large-scale electrostatic dawn-dusk electric field counteracts to compress it, similarly to the case of the laboratory plasma pinch which is compressed by the induction electric field. When the expansion and compression compensate each other, a stationary structure is formed.

[25] It is necessary to stress that the existence of turbulence in the Earth's magnetosphere is quite natural, taking into consideration that the solar wind plasma flowing around the Earth has high fluid and magnetic Reynolds numbers. In such a case a turbulent wake is expected to be formed.

[26] The increase in the values of diffusion coefficients with the distance in the tailward direction also can help to explain why the substorm onset takes place deeply inside the magnetosphere, as confirmed by many authors [see, e.g., *Samson et al.*, 1992a, 1992b; *Frank and Sigwarth*, 2000; *Lyons et al.*, 2002; *Stepanova et al.*, 2002; *Yahnin et al.*, 2002; *Dubyagin et al.*, 2003; *Antonova et al.*, 2009], because only the region which was stable before the onset of the substorm expansion phase can become unstable.

[27] There is a broad spectrum of plasma instabilities which could lead to such a substorm development (see, for example, the discussion by *Stepanova et al.* [2002, 2004] and *Lui et al.* [2008] and *Antonova* [2004] for a review).

[28] Nevertheless, the interplay between the turbulent processes in the plasma sheet and the geomagnetic substorms is not clear. It is necessary to concentrate a significant effort in understanding the processes involved for different time and space scales.

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