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A statistical study of intense electric fields at 4–7 R_E geocentric distance using Cluster

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Abstract. Intense high-latitude electric fields (>150 mV/m mapped to ionospheric altitude) at 4–7 R_E geocentric distance have been investigated in a statistical study, using data from the Cluster satellites. The orbit of the Cluster satellites limits the data collection at these altitudes to high latitudes, including the poleward part of the auroral oval. The occurrence and distribution of the selected events have been used to characterize the intense electric fields and to investigate their dependance on parameters such as MLT, CGLat, altitude, and also K_p. Peaks in the local time distribution are found in the evening to morning sectors but also in the noon sector, corresponding to cusp events. The electric field intensities decrease with increasing latitude in the region investigated (above 60 CGLat). A dependence on geomagnetic activity is indicated since the probability of finding an event increases up to K_p=5–6. The scales sizes are in the range up to 10 km (mapped to ionospheric altitude) with a maximum around 4–5 km, consistent with earlier findings at lower altitudes and Cluster event studies. The magnitudes of the electric fields are inversely proportional to the scale sizes. The type of electric field structure (convergent or divergent) is consistent with the FAC direction for a subset of events with electric field intensities in the range 500–1000 mV/m and with clear bipolar signatures. The FAC directions are also consistent with the Region 1 and NBZ current systems, the latter of which prevail only during northward IMF conditions. For scale sizes less than 2 km the majority of the events were divergent electric field structures. Both converging and diverging electric fields were found throughout the investigated altitude range (4–7 R_E geocentric distance).

Keywords. Magnetospheric physics (Electric fields; Auroral phenomena; Magnetosphere-ionosphere interactions)

1 Introduction

Converging electric fields associated with negative U-shaped potential structures, accelerating electrons downwards in the upward field-aligned current (FAC) region, have been observed by numerous satellites such as S3-3, Dynamics Explorer 1, Viking, Polar, above the primary acceleration region. Diverging electric fields associated with positive U-shaped potential structures accelerating electrons upward in the auroral return current region were first observed by the Freja and FAST satellites at low altitudes (e.g. Freja at altitudes of 1400–1770 km, Karlsson and Marklund, 1996, and FAST at altitudes of 350–4175 km, McFadden et al., 1999). These acceleration structures are associated with intense electric fields, converging in the upward current region and diverging in the return current region. The statistical study by Karlsson and Marklund (1996) showed that the intense events (>200 mV/m) were fine structured (less than 5 km); the more intense the electric field, the smaller the scale sizes. They were generally confined to the auroral oval, with peaks in the midnight and early morning sectors. The events were likely to correspond mostly to diverging electric fields in the return current regions. Observations of intense electric fields have also been made by the Dynamics Explorer 1 satellite (Weimer and Gurnett, 1993). They found from observations in the range of 1.1–4.6 R_E geocentric distance that the average mapped electric field values increased with increasing altitudes, indicating a magnetic field-aligned electric field. From a study on Polar data at higher altitudes (above 4 R_E altitude), a lack of intense converging electric fields has been reported (Janhunen et al., 1999). To explain this observation, a new model of the auroral acceleration combining an O-potential structure with wave activity at the high-altitude end of the structure, was proposed by Janhunen and Olsson (2000). More recently, Janhunen et al. (2004) have conducted a statistical study on auroral potential structures calculated from the electric field measurements by Polar. That study covers the range of 1.5–6 R_E geocentric distance and looked only for signatures of converging electric fields. Janhunen et al. (2004) reported few encountered events at 3–4 R_E geocentric distance but they found events more frequent above 4 R_E and below 3 R_E. The interpretation given by Janhunen et al. (2004) was that there are two classes of events, one low-altitude class related to inverted-Vs, and one substorm-related high-latitude class, the latter one superposed above the O-potential structure proposed in Janhunen and Olsson (2000). However,

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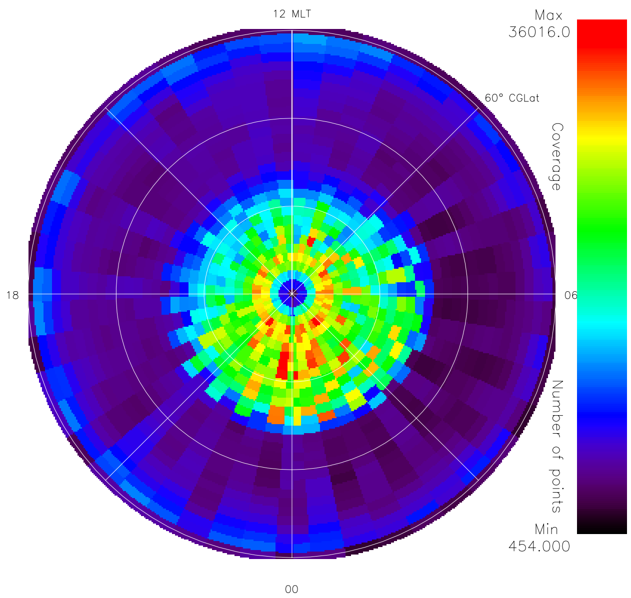

Fig. 1. A polar plot of the coverage of the Cluster satellites when they are within 7 R_E. The coverage is roughly limited to latitudes greater than 75° CGLat.

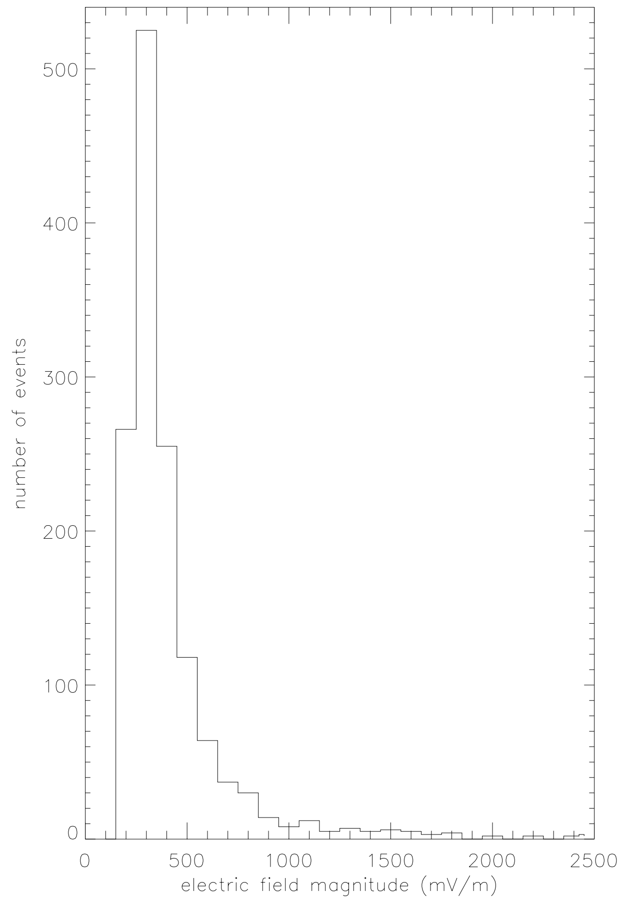

Fig. 2. The number of events versus electric field intensities are plotted in a histogram with bins of 100 mV/m.

intense diverging and converging electric fields have been observed by Cluster at high altitudes. Marklund et al. (2001) reported on the first Cluster observations in the return current region of the growth and decay of a diverging electric field structure at 4.3 R_E geocentric distance. Vaivads et al. (2003) concluded from magnetic conjugate observations by Cluster and DMSP in the upward current region that the U-shaped, quasi-stationary potential structure reached Cluster at 4.7 R_E geocentric distance. Figueiredo et al. (2005) reported on two Cluster converging electric field events. One of those events was in conjunction with observations by the ground-based South Pole All Sky-Imager, showing that the intense electric field variations were observed when Cluster crossed above an auroral arc structure at a geocentric distance of approximately 4.6 R_E. Cluster observations of intense electric fields with monopolar signatures (indicating S-shaped potential structures) in the return current region at 5.0 R_E geocentric distance were reported by Johansson et al. (2004). In that study, the temporal and spatial variations were described and investigated. The quasi-static electric fields were concluded to dominate the upward electron acceleration, since the most intense electric field variations were quasi-static, while regions of temporal variations (downward travelling Alfvén waves) were less intense (Karlsson et al., 2004). Marklund et al. (2004) discussed the properties of four events of intense electric fields at Cluster altitudes, the results supporting the existence of quasi-static positive U-shaped and S-shaped potential structures in the return current region. To summarize, Cluster observations, published to date include both converging and diverging electric fields, but also monopolar electric field structures, indicating that the perpendicular electric field structures directly associated with particle acceleration map out to high altitudes. These event studies have provided much insight into the temporal and spatial variations of the electric field structures. Support has been found that quasi-static electric field acceleration plays a major role in the acceleration of auroral particles and that the process is more or less always accompanied by Alfvén waves. Further, Keiling et al. (2001) have reported on Polar electric field observations in the primary current region that are consistent with both Alfvén wave activity and quasi-static structures. Most of their events, of which a large fraction were interpreted to be Alfvénic, occurred in the poleward part of the plasma sheet boundary layer (PSBL). As shown by Johansson et al. (2004) intense quasi-static electric field structures were also found in that region.

This study presents a statistical investigation of intense electric fields observed by Cluster at geocentric distances of 4–7 R_E. Both diverging and converging electric field structures, corresponding to positive and negative U-shaped potential structures, are found at Cluster altitudes in a way consistent with downward and upward FACs.

2 Method

This statistical study used EFW electric field data (Gustavsson et al., 1997) from all four Cluster satellites from a 33-month period (1 January 2001, to 28 September, 2003). The data set was examined by searching for electric field peaks, using the duskward and sunward components of at least 150 mV/m, and then mapping to the ionospheric altitude using the dipole magnetic field approximation (Weimer and Gurnett, 1993). Further, the peaks should be observed when Cluster was located within 7 R_E geocentric distance, to avoid a more complicated mapping. For each part of the orbit where the satellites were approaching or receding from the north or south pole, the most intense peak meeting the selection criteria was recorded and used in the database (such an entry is called an event), where also MLT (Magnetic Local Time), CGLat (Corrected Geomagnetic Latitude), geocentric distance, L-value and scale size were recorded. The scale sizes were found by first determining the full-width half-maximum of the intense electric field events, giving a temporal scale which, together with the spacecraft velocity, give a spatial scale. For reference, the scale sizes were mapped to the ionosphere. No distinction has been made between events found by the different satellites. In order to obtain a good understanding of the occurrence of these events, the coverage of the Cluster satellites was also recorded. This is important since the orbit of the Cluster satellites gives the highest coverage at high latitudes. The K_p-index has been used to investigate the relation of the intense electric fields to the geomagnetic activity. As will be discussed later, FACs were also calculated for some of the events. This was done by assuming current sheets and using the magnetic field measured by the FGM instrument (Balogh et al., 1997) from each single satellite, to which a polynomial function was fitted in a large-time window and inspected manually, after which the background magnetic field was subtracted.

3 Observations

The occurrence, distribution and relation of the selected intense electric fields to MLT, CGLat, geocentric distance, scale size and K_p will be presented in this section. A subset of events, with intensities in the range 500–1000 mV/m (mapped to ionospheric altitude), were further examined to identify whether the electric field structure was divergent or convergent and to determine the direction of the associated FAC.

Due to the orbits of the four Cluster satellites, the coverage is much better at high latitudes and there is also a close coupling between altitude and latitude, which has to be kept in mind when interpreting the statistical results. Figure 1 shows the total number of measurement points recorded by Cluster (at geocentric distances less than 7 R_E) in each bin (1° in CGLat and 0.5 h in MLT) during the investigated period. The plot clearly illustrates that a majority of the possible recorded points are confined to high latitudes where the coverage is

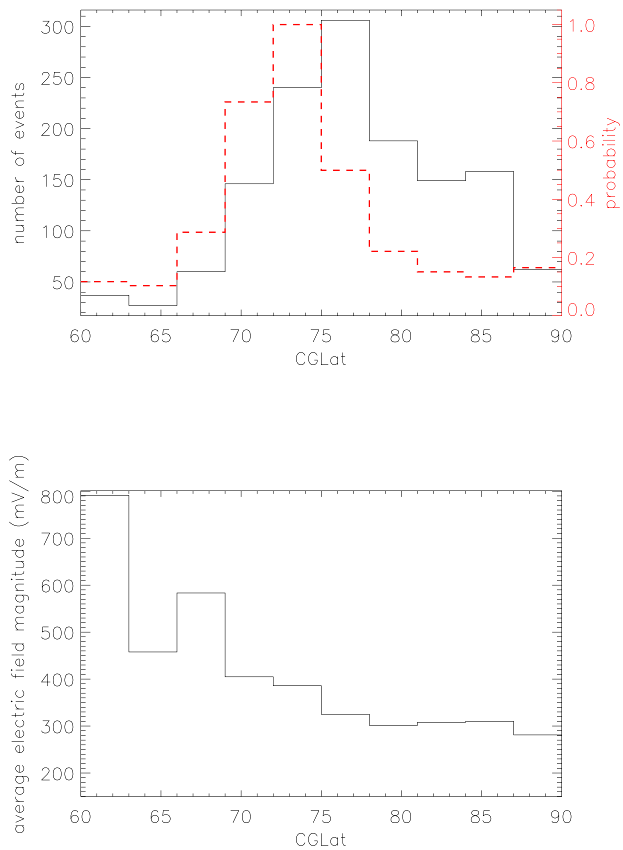

Fig. 3. The number of events versus CGLat in a histogram with bins of three degrees (black line) and the probability of finding an event (dashed red line) are plotted in panel 1. Panel 2 displays the average electric fields in each bin. Each bin is three degrees wide.

high and that the most equatorward of those points corresponds to the poleward part of the auroral oval. The average geocentric distance when the Cluster satellites were at geocentric distances below 7 R_E has been calculated and it was found that the altitudes, on average, are higher at higher latitudes.

A total number of 1373 events have been found. Very few events have mapped intensities exceeding 800 mV/m, and the majority of the events are found in the range 250–350 mV/m. This can be seen in the histogram in Fig. 2, showing the number of events for bins of electric field intensity.

3.1 Location

The distribution of the events as a function of MLT, CGLat, altitude and season has been investigated. A separation between high-latitude and low-latitude events has been made to investigate possible differences. The upper panel in Fig. 3 displays the CGLat distribution in the form of a histogram of the number of events (solid black line). Overlaid with a dashed red line is the number of events divided by the number of Cluster passages in each bin, normalized to the maximum value, i.e. there is a probability of finding an event for

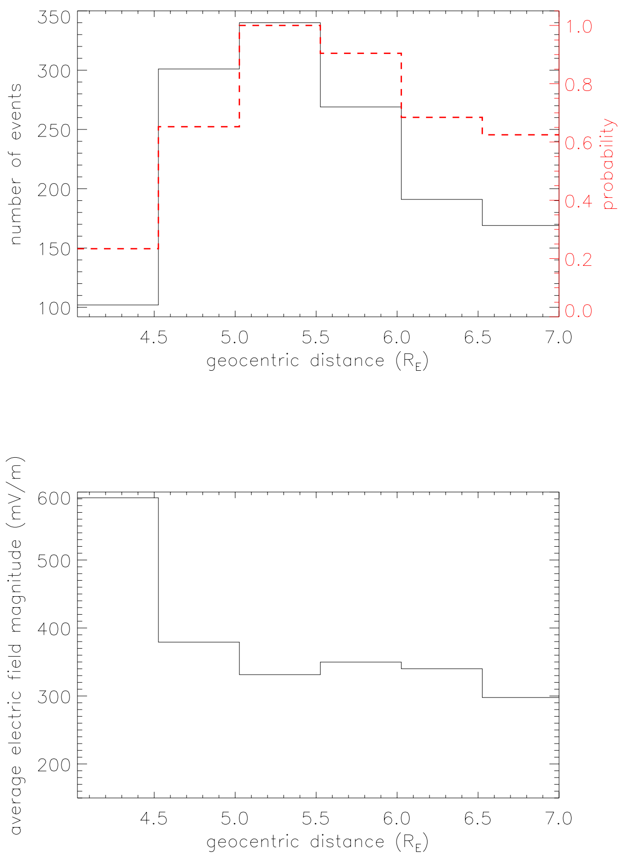

Fig. 4. Similar plot as in Fig. 3 but this time the geocentric distance is plotted on the x-axis. Each bin is 0.5 R_E wide.

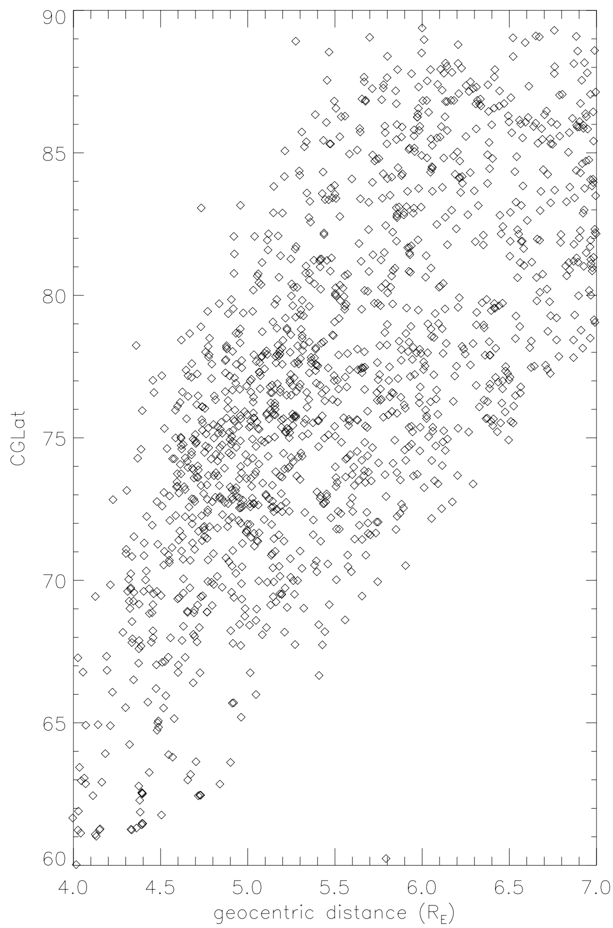

Fig. 5. CGLat versus geocentric distance, displaying the fact that the higher the altitude at which the event is found, the higher the latitude. Each diamond represent an event.

a given CGLat. The bottom panel in Fig. 3 displays the average electric field for each bin. The maximum number of events are found at 75° CGLat but when the coverage of the Cluster satellites is taken into account, one can seen that the probability of finding an event shifts to lower latitudes (72–75° CGLat). The average electric fields drops rapidly with increasing latitude, which also corresponds to the increasing altitude in this data set. It is expected that the intense electric fields are mostly associated with auroral acceleration structures and intense FACs (primary and return current) on auroral field lines, which correspond to the lower latitude range of this study, and this is consistent with the results seen in Fig. 3.

Figure 4 displays the dependence on geocentric distance. A surprising decrease in the number of events is found at high altitudes, above 5.5 R_E geocentric distance. These high altitudes correspond to high latitudes. The probability decreases in the same range and a decrease of the average electric field with increasing geocentric distance is also observed. The decrease is, however, supposedly more due to a latitude effect than to an altitude effect. The fewer and less intense electric field events found at higher altitudes corresponds to very high latitudes, due to the co-dependence between altitude and latitude, far from the main auroral oval and auroral activity. This can be seen in Fig. 5, which is a scatter plot of CGLat versus geocentric distance for all the events. No events below 70° CGLat have been found above 6 R_E and no events above 80° CGLat have been found below 4.5 R_E. Still, the observed trend could be due to variations with altitude. In Fig. 6, where the events have been divided into two latitudinal groups, one high-latitude group (>80° CGLat) and one low-latitude group (<70° CGLat), a clear difference in the average electric field can be observed. (The limits for high and low latitudes have been chosen to separate events found at higher latitudes from those within the auroral oval and to obtain a sample of events from within the auroral oval.) The low-latitude events have average electric fields of approximately 500 mV/m compared to approximately 300 mV/m for the events at high latitudes. Since the higher average electric field magnitudes for the low-latitudes overlap in geocentric distance with the lower average electric field magnitudes for the high latitudes, it can be concluded that a latitudinal variation has been identified. Further, the event probability increases for the low-latitude events all the way up to 6 R_E (above which no events are found), while the altitude

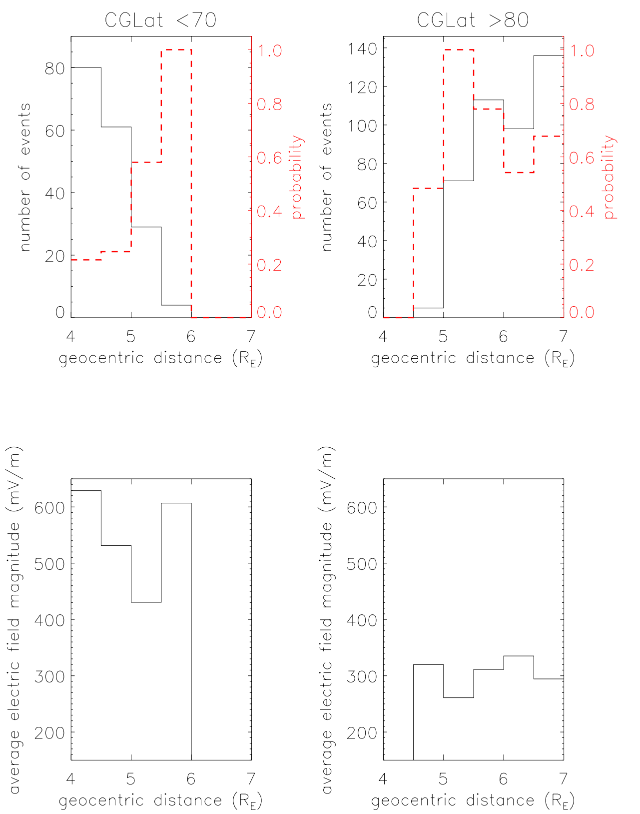

Fig. 6. Similar plot as in Fig. 3 but this time only for events at a CGLat below 70° (left column) and events at CGLat above 80° (right column). Each bin is 0.5 R_E wide.

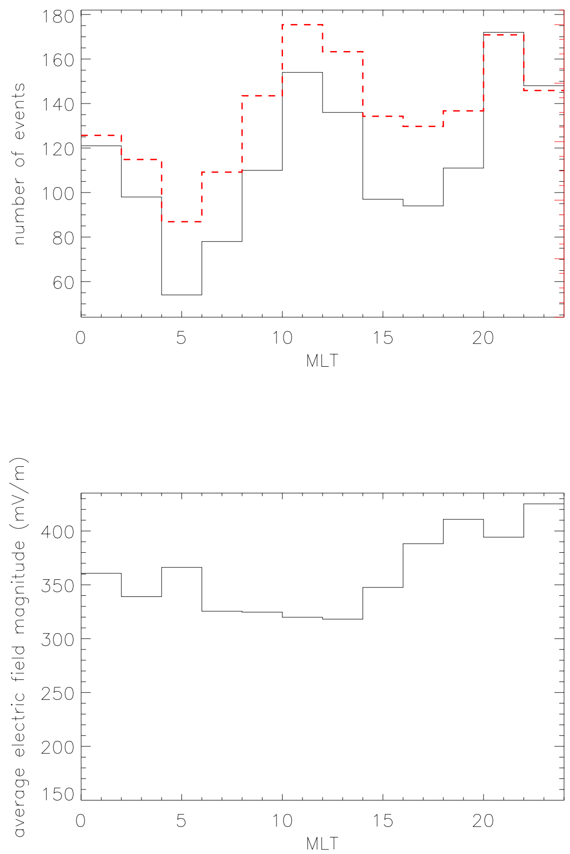

Fig. 7. Similar plot as in Fig. 3 but this time the MLT is plotted on the x-axis. Each bin is two hours wide.

distribution plot for all events show a beginning decrease at 5 R_E and the high-latitude events also display a decrease starting at 5 R_E. So, this indicates that the observed peaks in event probability seen in the altitude and latitude distributions are both due to a latitudinal effect.

The upper panel of Fig. 7 displays the number of events versus MLT, each bin corresponding to a 2-h interval. Two peaks in the MLT-distribution are seen, one peak in the noon sector (of which a majority probably is cusp events) and one peak in the night sector. An asymmetry between the morning and afternoon sectors can be observed, with an absolute minimum at 04:00–06:00 MLT. The higher probability of finding an event around 15:00 MLT might be connected to the hot spot, a region of enhanced electron acceleration events (Newell et al., 1996). The probability of finding events follows the total number of events (there is a good coverage for all local times). As seen in the second panel, the average electric field is lower at noon and higher for the evening events. When separating low-latitude events from high-latitude events, it was found that none of the events in the 12:00–16:00 MLT bin occurred at latitudes below 70° CGLat (not shown here).

The seasonal dependence of the MLT distribution has also been investigated (not shown here). Spring and fall (defined as the three months centered at spring and vernal equinox, respectively) have the same characteristics as the overall picture. The events occurring at winter times have two pronounced peaks in the MLT distribution, one in the morning sector (02:00–08:00 MLT) and one in the evening sector (16:00–20:00 MLT), and there is a clear minimum at noon. The summer events have coarsely the same MLT distribution but the highest number of events are found at 14:00–16:00 MLT. The average electric field shows the same trend for winter and summer, somewhat higher in the afternoon/evening sector.

3.2 Scale size

The scale sizes of the electric field structures were calculated as twice the full-width half-maximum of the intense electric field peaks and mapped down to ionospheric altitude. The result is displayed in Fig. 8. The panels, show from top to bottom, the number of events, the average electric field and the estimated potential versus scale size (mapped to ionospheric altitude). The potential has been calculated by multiplying the average electric field in each bin with the scale size. Most events have scale sizes smaller than 10 km, with a peak at 4–5 km, which is consistent with earlier observations by Cluster (Marklund et al., 2001; Johansson et al., 2004) and by Freja at lower altitudes (Karlsson and Marklund, 1996). The peak

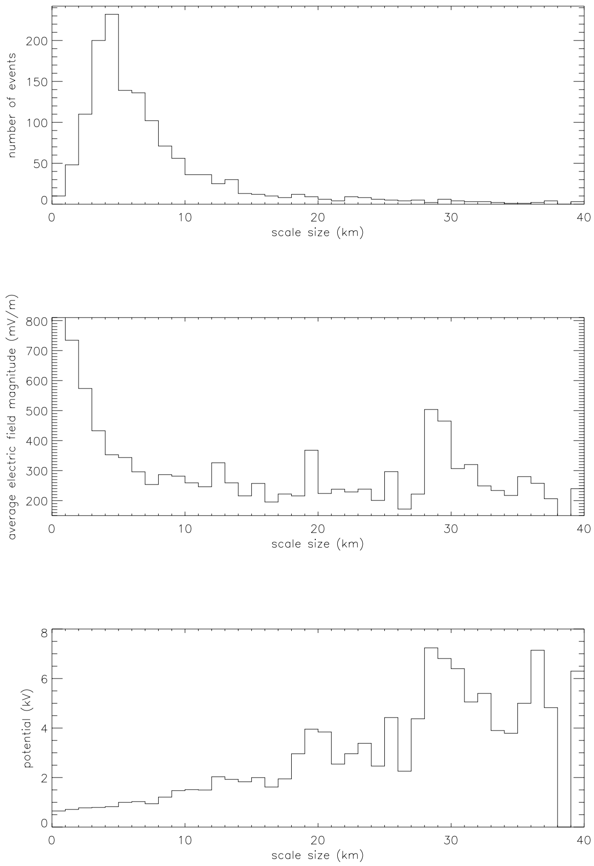

Fig. 8. The two first panels are similar to the panels in Fig. 3 but this time the scale size is plotted on the x-axis. Each bin is 1 km wide. The third panel displays an approximative potential calculated from the average electric field intensity and scale size in each bin.

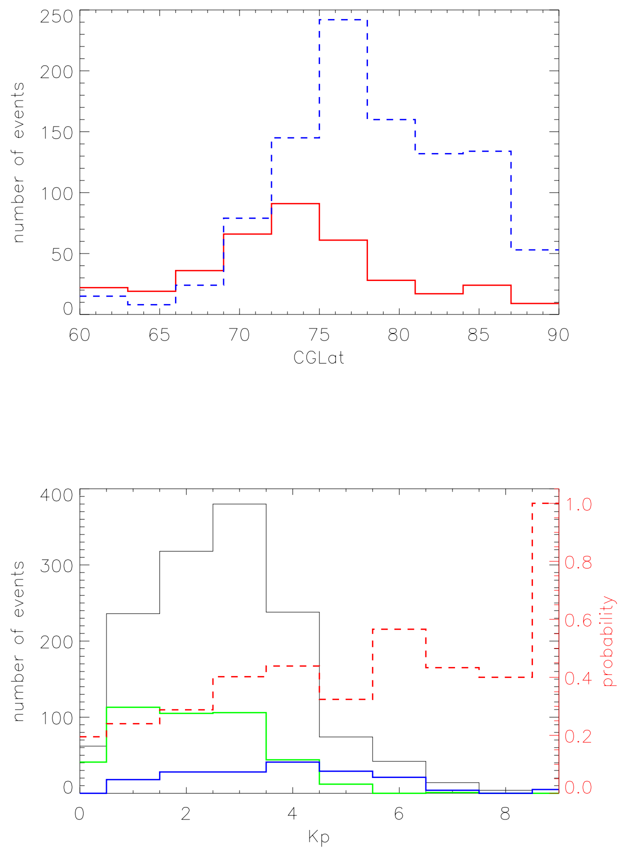

Fig. 9. The first panel displays the number of events versus CGLat for two groups of events, divided by the K_p value. The dashed blue linen is $K_p \leq 3$ and the red line is $K_p > 3$. Each bin is 3 degrees wide. The second panel displays the number of events (black line) and the probability of finding an event (dashed red line) versus K_p. The green (blue) line is the number of events for events found above 80° (below 70°) CGLat. Each bin represents one unit in K_p.

scale size value corresponds well with earlier observations of intense electric fields, as well as with the size of auroral arcs (Borovsky, 1993). The number of events fall rapidly with increasing scale size and relatively few events are found with scale sizes larger than 10 km. The middle panel shows that the average electric field is increasing with decreasing scale size below 10 km and is relatively constant above 10 km. That the electric field magnitudes are inversely proportional to the scale sizes were also observed by Karlsson and Marklund (1996). Since there are very few events at larger scale sizes, the average values for those scale sizes are not reliable. The bottom panel shows that for the smaller scale sizes there is a small increase in potential with increasing scale size up to 18 km, from 0.5 kV to 2.0 kV. Similar values of the potentials have been found in Cluster event studies (Marklund et al., 2004) and at lower altitudes in Freja studies (Karlsson and Marklund, 1996). The trend also continues in the upper, unreliable range of scale sizes, where the increase is larger. The scale sizes of high-latitude events (>80° CGLat) and low-latitude events (<70° CGLat) have also been compared but the results were unclear and no distinct difference in scale size was found.

3.3 Geomagnetic conditions

The K_p-index has been used to investigate the effect of the geomagnetic activity on the distribution and occurrence of the intense electric field events. The first panel of Fig. 9 displays the CGLat distribution for two groups of events, one with $K_p \leq 3$ (dashed blue line) and one with $K_p > 3$ (solid red line). The low activity events have a peak in number of events at 75–78° CGLat, while the high activity events have a peak at somewhat lower latitudes (72–75° CGLat). So, the CGLat distribution is shifted to lower latitudes at more active periods, reflecting the movement of the auroral oval towards lower latitudes during more active periods. The high activity events correspond to higher average electric fields at most latitudes (the difference is greater at lower latitudes) and for most local times (the difference is greater in the morning and evening sectors, not shown here), decreasing with increasing latitude from 900 mV/m to 250 mV/m.

The second panel of Fig. 9 displays the number of events and the normalized probability of finding an event (solid

Table 1. Summary of the events.

FAC	Electric field structure	Number of events
Up	Converging	17
Down	Diverging	25
Up	Diverging	1
Down	Converging	2
Unclear	Converging or diverging	9

black and dashed red lines) versus K_p. The green (blue) line is the number of events found above 80° (below 70°) CGLat. It can be seen that most events occur in periods of medium geomagnetic activity (K_p=1–4) and that few events are found for very active (K_p>4) or very quiet conditions (K_p<1). However, the probability of finding an event increases with increasing K_p-value, although the limited number of events for the highest K_p values make the calculated probability unreliable. Since a vast majority of the events are found for $K_p \leq 4$, the probability is reliable in that range and there the probability of finding an event is increasing with increasing K_p. The maximum average electric field magnitudes are found in the range K_p=4–6 at approximately 500 mV/m. The high-latitude events (>80° CGLat) have a peak in the number of events between K_p=1 and 3 but the peak for the low-latitude events (<70° CGLat) is at K_p=4. The difference is again an effect of the auroral activity varying in latitude due to the geomagnetic activity. The average electric field magnitudes are again found to be the highest for low-latitude events, the peak is at K_p=5 while the average electric field magnitudes of the high-latitude events are fairly constant for all K_p-values.

3.4 Convergent/divergent electric fields and associated FACs for a selected number of events

Those events with electric field intensities in the range 500–1000 mV/m were inspected manually. If an event was found to have a clear bipolar signature, it was selected for further investigation. The potential structure of the event was determined by calculating the perpendicular potential, by integration of the measured electric field along the satellite orbit. A positive (negative) peak in the potential indicates a diverging (converging) electric field that accelerates electrons upwards (downwards), which should be associated with downward (upward) FACs. Magnetic field measurements were used to calculate the FAC in each of these events to check the consistency between the electric field structure and the FAC direction. The result is summarized in Table 1. For some of the events it was not possible to clearly determine the FAC direction, they are labelled “unclear” in Table 1. The electric field type is for most of the events consistent with the FAC direction. However, for three events an inconsistency is found between the FAC and the potential structure. These events are the subject of a further, on-going investigation. However, a

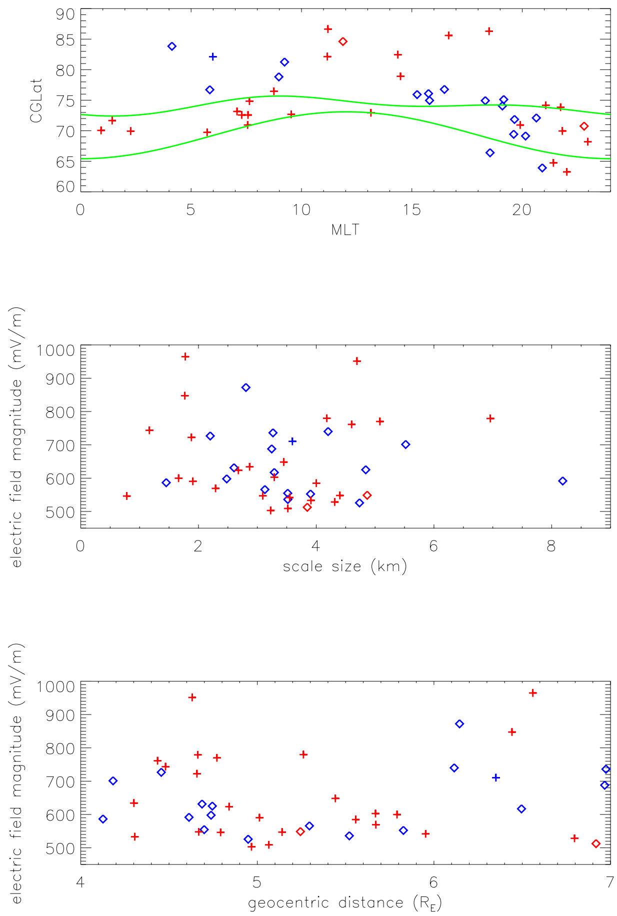

Fig. 10. The upper panel is a scatter plot of CGLat versus MLT with a statistical auroral oval indicated by the green lines. Converging (diverging) electric field structures are plotted with a diamond (+). Downward (upward) FACs are plotted in red (blue). The middle panel is a scatter plot of the electric field intensity versus scale size, while the bottom panel is a scatter plot of the electric field intensity versus geocentric distance.

fairly good number of events of both diverging and converging structures, with consistent FAC directions, are found.

Figure 10 displays in the form of scatter plots the distribution of the events in CGLat, MLT, geocentric distance and scale size. The electric field intensities versus mapped FAC magnitudes are shown in the upper panel of Fig. 11 while the two other panels display the mapped magnitudes of the FACs versus CGLat and MLT. Upward (downward) FACs are color-coded blue (red), converging (diverging) electric field structures are designated by diamonds (+). A statistical auroral oval (Kauristie, 1995) is indicated by the green lines in the upper panel of Fig. 10, where the observed distribution in CGLat and MLT is combined. Most of the converging and diverging electric field events occur, within or close to, the auroral oval but there are also high-latitude events. It is also found that upward FACs occur at high latitudes (poleward of the auroral oval) in the morning sector but at lower latitudes (within the auroral oval) in the evening sector. The

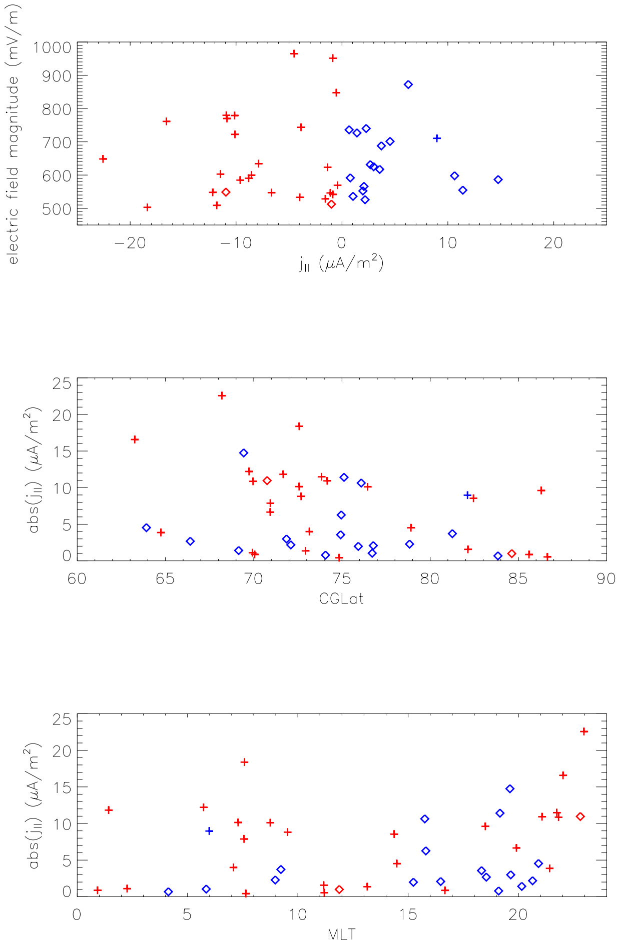

Fig. 11. The upper panel displays the electric field intensity versus the FAC magnitudes while the other two panels display the FAC magnitudes versus the electric field intensity and MLT, respectively, all in the form of scatter plots. The plotting symbols and colors are as in Fig. 10.

downward FAC, on the other hand, occur within the statistical auroral oval in the morning sector but at higher latitudes in the noon/afternoon sectors. There are also events of downward FAC at lower latitudes in the evening sector. The general trend is that the small-scale FACs have directions which are consistent with the large scale Region 1 currents and, at higher latitudes, with the NBZ-current system (Iijima and Shibaji, 1987) prevailing during northward IMF conditions. In the middle panel of Fig. 10 the magnitudes of the electric field events are plotted versus their scale sizes. All events are small scale but the events below 2 km are dominated by downward FAC diverging electric field structures. Most events are observed to have scale sizes in the range 3–4 km, somewhat smaller than the 4–5 km range seen in Fig. 8, obtained from all events. The bottom panel in Fig. 10 displays the magnitude of the electric field events versus altitude. No clear difference between diverging and converging electric fields can be seen in the altitude distribution, but both types are found throughout the altitude range covered in this study (4–7 R_E geocentric distance).

Figure 11 displays the electric field intensity versus the FAC magnitudes in the upper panel, while the other two panels display the FAC magnitudes versus the electric field intensity and MLT, respectively. It is seen in the middle and lower panels of Fig. 10, and also in the upper panel of Fig. 11, that a majority of the most intense events (>750 mV/m) are diverging electric field structures associated with downward FACs. The FACs with the largest magnitudes (>7 μA/m^2, mapped to the ionosphere) are mostly downward FACs. However, no correlation between electric field intensity and FAC magnitude can be observed for these events. The highest magnitudes of the FAC are found at latitudes corresponding to the auroral oval and in the morning and evening sectors, together with a few events of high FAC magnitude close to 15:00 MLT, as seen in the two last panels of Fig. 11.

In the subset of events it is clear that diverging electric fields at low latitudes are likely to occur in the evening and morning sectors (first panel of Fig. 10 and bottom panel of Fig. 11). The diverging electric fields at high latitudes are found in the afternoon sector. This is, for the low-latitude events, consistent with earlier Freja studies (Karlsson and Marklund, 1996; Marklund et al., 1997).

4 Discussion and conclusions

We have presented results of a statistical investigation of intense electric fields (>150 mV/m) observed by Cluster at geocentric distances of 4–7 R_E and a latitudinal coverage corresponding to very high latitudes from the poleward part of the auroral oval and the entire polar cap.

Due to the orbit of the Cluster satellites, there is a co-dependance between latitude and altitude. This makes the interpretation of the electric field latitude and altitude distributions more complicated. To resolve this ambiguity, high and low latitude events were separated into two groups. For each of the two groups the number of events, the probability of finding an event and the average electric field were plotted versus the geocentric distance. The observed peak in the altitude distribution could then be explained as due to latitudinal variations.

In a subset of events, with electric field intensities in the range 500–1000 mV/m, identified by having clear bipolar signatures, both diverging and converging electric field structures were found. This implies that U-shaped potential structures extend up to and beyond 4–7 R_E geocentric distance. The type of structures are also found to be consistent with the direction of the associated FACs. A lack of intense electric fields associated with U-potentials (above 4 R_E geocentric distance) were reported by Janhunen et al. (1999). In a later study on auroral potential structures (Janhunen et al., 2004), the lack of an intense electric field was found to be restricted to the range of 3–4 R_E geocentric distance. Unfortunately, that range is not investigated in this statistical study, where the range is 4–7 R_E geocentric distance. Above 4 R_E geocentric distance Janhunen et al. (2004) found auroral potential structures. Event studies of Cluster observations (Marklund et al., 2001; Vaivads et al., 2003; Marklund et al., 2004) show that both diverging and converging electric field structures do extend to Cluster altitudes. Figueiredo et al. (2005) found a Cluster converging electric field event at a geocentric distance of approximately 4.6 R_E, conjugated with an auroral arc structure observed by the ground-based South Pole All-Sky Imager. Janhunen et al. (1999) discarded some events since they were either considered to have too small potentials (1–2 kV) or that were too small they were not consistent with U-shaped potential structures. In the Cluster observations, perpendicular potentials inferred from electric field measurements in the range 2–3 kV have been shown to be consistent with the characteristic energies of electron beams (e.g. Marklund et al. (2004)). Further, monopolar electric fields, indicating S-shaped potential structures, have been observed by Cluster (Johansson et al., 2004). For the larger set of events in this study where the types of electric field structures have not been determined, it is reasonable to believe that there are both diverging and converging electric fields corresponding to U-shaped potentials structures, as well as S-shaped potential structures.

The direction of the FACs associated with the subset of intense electric field events are found to occur consistently with those of the large-scale Region 1 and NBZ current systems. It is not obvious why the small-scale current systems should match the large-scale current systems but the fact that they do, supports the picture of the large current system being roughly the sum of the small-scale current systems.

The average electric field magnitudes are found to be smaller at higher latitudes, implying that the high-latitude auroral events are typically less intense than those at lower latitudes in the auroral oval. The probability of finding an intense electric field event also decreases above 75° CGLat. The events found at noon are all observed above 70° CGLat, i.e. these events are likely to occur in the cusp region (Marklund et al., 1990; Palmroth et al., 2001). The conclusion is that the observed intense electric fields are most likely to be found within the auroral oval, although there are also observations of events at higher latitude in the polar cap.

Borovsky (1993) give the scale sizes of the most fine-structured auroral arc elements as approximately 100 m, while the scale sizes of auroral arcs are one order of magnitude larger and the region of diffuse glow around auroral arcs are some hundreds of km. In a statistical study of intense electric fields observed by Freja (Karlsson and Marklund, 1996) the typical scale size were found to be less than 5 km. In this study the scale sizes of the electric field structures are mostly less than 10 km (mapped values), with the number of events peaking in the range 4–5 km, consistent with what has been observed in Cluster event studies of intense converging/diverging electric field structures associated with the auroral current system (for example, Marklund et al. (2004)). Theoretical predictions give scale sizes in approximately the same range (Borovsky, 1993). The events having the smallest scale sizes were associated with the highest average electric fields, as found by Karlsson and Marklund (1996). It is also found in this study that diverging electric field structures (in the subset of events) are associated with smaller scale sizes than converging electric field structures.

The MLT distribution is found to have peaks in the late evening to early morning sectors (consistent with Karlsson and Marklund, 1996) and in the noon sector, where the second peak corresponds to high-latitude cusp events. The dayside events observed by Karlsson and Marklund (1996) were found at more geomagnetic active periods but no dependency on geomagnetic activity was found for the midnight and early morning events. In this study the occurrence of events was found to increase with increasing K_p value, i.e. for greater geomagnetic activity. This discrepancy in the midnight and morning sectors might be explained by the geomagnetic activity having a greater effect at higher altitudes and latitudes. The activity dependence is also seen as variations in the latitude distribution, consistent with the equatorward movement of the auroral oval during more active periods. Low activity events have a peak in number of events at higher latitudes compared with the high activity events.

Keiling et al. (2001) have used Polar data to study the distributions of the electric fields in the auroral oval. A majority of their events were found in the nightside auroral oval but a concentration of events was also found around 15:00 MLT, which they contribute to the hot spot (a region of increased low-latitude acceleration activity (Newell et al., 1996)). The MLT distribution found in this study is consistent with the nightside peak found by Keiling et al. (2001). A peak in MLT distribution is not seen around 15:00 MLT. However, since this study also cover high latitudes, including a peak of cusp events at noon, an afternoon peak in the MLT distribution might not be revealed. More events are tough found in the afternoon sector as compared to the late morning sector. Further, Keiling et al. (2001) found that all their most intense events occurred at periods of geomagnetic disturbances. The events found in this study occur mostly in periods of medium geomagnetic activity, with an increasing probability up to at least K_p=4. Keiling et al. (2001) also reported that they found most of their intense events in the plasma sheet boundary layer (PSBL), and with a smaller part occurring in the central plasma sheet (CPS). The location of the events of this study relative to the PSBL or CPS has not been determined from particle data. This is the subject of an on-going investigation which also looks at the relation of the kind of electric field structure (monopolar or bipolar) to different density gradients.

The altitude distribution is unclear due to the orbit of the Cluster satellites and the co-dependance between high-latitude and high altitude. The number of events and the probability of finding an event peak at 5.0–5.5 R_E geocentric distance but most of these events are found around 75° CGLat, where the latitude distribution also peaks. However, intense electric fields (presumably diverging or converging bipolar or monopolar electric field structures) are found throughout the investigated altitude range (4.0–7.0 R_E geocentric distance), although the events observed at the highest geocentric distances ($>$6.5 R_E) are at the highest latitudes ($>$75° CGLat).

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