## Anonymous Referee #1: angeo-2018-31

"Dynamics of the electrojet during intense magnetic disturbances" by Liudmila I. Gromova et al.

#### Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2018-31, 2018

We would like to thank the reviewer for the thorough evaluation of our paper. The authors appreciate the constructive comments and criticism. We have answered all comments by inserting our response behind the comment in italic and blue, and hope that our replies will clarify the critic's items. For convenience, we include the revised manuscript with corrections indicated in red.

## **General comments**

The manuscript serve to characterize how the EE, WE, and PE vary in location (latitude) and strength in the different MLT sectors during the different strom phases. Possible relationships to geomagnetic and IMF/SW indices are explored through a regression and correlation analysis.

The results appear reasonable, however, the manuscript presently fails to place the results into the present state of knowledge in the field. One example is that much attention is focused on the latitudinal variability of the EE and WE, where the electrojets are mainly found to move equatorward in the storm main phase, compared to the initial and recovery phase. However, this result in not discussed together with the expanding/contracting nature of the open magnetosphere (e.g. Cowley and Lockwood 1992, Milan 2015), largely explaining why. This needs to be mentioned, and I think the manuscript would benefit from more rather focusing on the specific latitudes that the expansion reach (that they also mention), with relation to e.g. the SYM/H index and the Newell coupling function.

Again, for the discussion section, I would very much appreciate to see how the present results add to the earlier works cited in the introduction. Presently the discussion is largely void of references, and it is not at all clear what the present manuscript has specifically done that is different from the earlier works, other than the method.

Cowley, S. W. H., Lockwood, M. (1992). Excitation and decay of solar wind-driven flows in the magnetosphere-ionophere system. Annales Geophysicae, 10(1–2), 103–115.

Milan, S. E. (2015). Sun et Lumière: Solar Wind-Magnetosphere Coupling as Deduced from Ionospheric Flows and Polar Auroras. In S. Cowley FRS, Stanley W. H. and Southwood, David and Mitton (Ed.), Magnetospheric Plasma Physics: The Impact of Jim Dungey's Research (Vol. 41, pp. 33-64). Springer International Publishing. <u>https://doi.org/10.1007/978-3-319-18359-6</u>

## Specific comments

The manuscript analyze high latitude ionospheric Hall currents derived from scalar magnetometer meaurements from LEO orbit from the CHAMP satellite during 6 different geomagnetic storm periods. On the basis of these data, the estimated Hall electrojets are characterized in different MLT sectors, and interpreted as either the Eastward (EE), Westward (WE), or Poleward electrojet (PE), the latter occurring only on the dayside in vicinity of the cusp, also in an east/west direction.

**Title:** I find the word "Characteristics" more suitable than "Dynamics" for the title. As the manuscript focus on the correlation of the location and strength of the electrojets deduced from a LEO satellite, with geomagnetic and SW/IMF variables, the study is more characterizing in nature, than describing dynamics, which is usually referred to as changes on shorter time scales than 90 min.

## Here, we completely agree with the Referee and changed the Title accordingly.

**Abstract:** The extensive listing is unusual. The abstract might be too long for the journal. I would prefer a shorter summary of the method and findings.

## The Abstract is now entirely redrafted, shortened, and we eliminated the extensive listing. We think that it now expresses essentially the main findings, next to a short description of the method.

**Introduction:** The introduction mention quite a few historic works on the characterization of ionospheric horizontal currents at high latitudes. Although this is highly relevant for the present manuscript, the authors some times fail to convey the implication of the work they describe. The introduction often reads more like a brief summary of the previous works, mainly mentioning what they have been measuring, and not putting it into broader context.

## We have added a few paragraphs to the Introduction, trying to put the topic into broader context. These additions can be found in the first four paragraphs on lines 29-60 together with several new references to historically important publications in our field of research.

In particular this is evident in the paragraph starting on line 98. I would suggest to remove this paragraph unless the authors can more directly state how this is relevant for the present study.

## This paragraph (previously starting on line 98) has been removed.

I also have a similar concern with the paragraph starting at line 160. This is mostly a listing of what the referenced literature observe, no explanation of their result is provided. For the reader it would be very satisfactory to briefly explain their findings. Example: Why does the electrojets expand to lower latitudes during increased activity (the oval expands...)? Also, how the electrojets disrupt into space could be elaborated more on, if not removed.

This paragraph has been largely modified and an essential part of it has been shifted to Section 5.2 (lines 513-516) and Section 5.1 (lines 457-475), where it belongs to. As for the latter, some sentences from other places in the former manuscript (e.g., from the former lines 255ff.) have been incorporated there, and we tried to extend the number of relevant references.

The same arguments goes for the paragraph starting at line 176. Please provide how their findings are relevant for the present manuscript. At the moment it only states that Wang et al investigated electrojet currents from space, which is not very informing.

This paragraph (formerly starting at line 176, now at lines 148-158) provides the reader with an outline of the manuscript. The subsequent sections are briefly described and put into a logical order. We think that the paragraph is justified at this place at the end of the Introduction and therefore we kept it as it was.

Possibly you meant the preceding paragraph (formerly starting at line 170), which mention the paper of Wang et al. (2008). This work is quite close to our subject and the authors made use of the same CHAMP data set. They investigated Hall currents for two intense storm periods, but didn't consider the polar electrojet at all. We think that this paper is therefore of relevance for our study and kept this paragraph, though in a slightly modified version (on lines 140-147).

Lines 96-97: "Potential differences at cusp latitudes". In the present manuscript cusp latitudes is refereed to as a point. To get a potential difference, a distance need to be involved. It is not obvious what is the distance in this case. I think you refer to the distance where dayside merging occur. To get around this, maybe an electric field, or velocity value in the east/west direction could be used?

In the present manuscript the cusp is not considered as a point, but as a distance. This distance is determined as the latitudinal interval of the existing polar electrojet (PE, lines 441-445).

Lines 134-159: Suggest to merge this into one paragraph as both paragraphs are dealing with the same Ritter et al 2004 paper.

These two paragraphs have been merged and largely shortened (line 138 ff.). It is also partly shifted to the Method section, where it belongs to (lines 216 ff.).

**Data:** Line 215: Need to define  $\Phi$  (or  $\Phi_{PC}$  as Newell calls it): Magnetic flux inside polar cap. The coupling function describe the change of this related to reconnection at the magnetopause,  $d\Phi_{MP}$ /dt. Together with the nightside reconnection rate ( $d\Phi_N$ /dt), this control the expansion/contraction of the polar cap ( $d\Phi_{PC}$ /dt). This is relevant for the present study as expansion/contractions of the polar cap lead to similar displacements of the electrojets. [Cowlet and Lockwood, 1992].

We reformulated the statements concerning formula (1), aiming at a more precise description as suggested by the Referee, and introduced the term  $\Phi$  (or  $\Phi_{PC}$  as Newell et al, 2007, call it) of open magnetic flux inside the polar cap, as well as the Index N (IndN) as a proxy of  $d\Phi/dt$  (lines 178ff.).

Also relevant for this study is the time averaging of the solar wind data used to estimate IndN. Using a long interval (20-60 min) would likely produce a better correlation to e.g. AL, than using the instant 1 min values. How is this done in the present manuscript?

For the determination of all indices throughout this study, which were available as one-minute cadences, we used time averaging intervals of the overflight intervals (about 20 minutes), as stated at the end of the Data section (lines 194-195).

**Method:** A short introduction to the ionospheric currents at high latitudes would be appreciated, along the lines that we can decompose the currents into Hall, Pedersen, and Birkeland currents, all contributing to the field measured at LEO altitude, but mainly the Hall currents are detected on the ground as explained by Fukushima (1976). As no information regarding the electric field is provided in the manuscript (needed to define the directions of Hall and Pedersen currents), it should state something like "we assume Hall currents to be divergence free, i.e close entirely within the ionosphere, while the Pedersen currents are curl free." Laundal et al. 2018 showed (see their Figure 14) that during summer conditions, which is the case in for the present manuscript, the divergence free and curl free ionospheric currents mainly represented the Hall and Pedersen currents, respectively.

We find this a very good idea and give now at the beginning of this section a short introduction into high latitude currents and the possibilities of their decomposition, as proposed by the Reviewer. These changes can be found in the first three paragraphs of the Method section (lines 197-215).

Lines 241-242: Suggest that you write that only one of the events in Table 1 is presented in the paper, and the rest are included in the Appendix. (a rewrite of the present sentence)

### Done (lines 235-236).

Line 248: which is the symmetric part of the ring current. As you write on line 252, the ring current is in general asymmetric.

### Corrected (lines 241-243).

Lines 255-260: I think these sentences belong to the introduction. Is this connection of the EE to the PRC the same as described in lines 166-168? If so, it could be moved into that location to give better background information.

## We shifted this paragraph to a suitable place in Section 5.1 and reformulated it slightly (lines 457ff.), as mentioned already above on the remark about the paragraph that formerly started at line 160.

Fukushima, N.: Generalized theorem for no ground magnetic effect of vertical currents connected with Pedersen currents in the uniform-conductivity ionosphere, Rept. Ionos. Space Res. Japan, 30, 35–40, 1976

Laundal, K. M., Finlay, C. C., Olsen, N., Reistad, J. P. (2018). Solar wind and seasonal influence on ionospheric currents from Swarm and CHAMP measurements. Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/2018JA025387

**Events:** Line 265: Is this number referring to the SYM/H index? That should be explained before presenting the values. Also a reference to the figure showing SYM/H and the orbits should appear here.

Further, from looking at the SYM/H data at the WDC Kyoto webpage, it is provided as integer numbers. How does the decimal number arise?

The decimal numbers result from averaging the 1-min integer SYM/H values over the interval of observations during the high latitude crossing, as indicated by closely related dashed vertical lines with the abbreviated orbital number in between. To characterize every pass we used peak current location and peak sheet current density only. This is then compared with one mean of any index.

Figure 1 is never introduced. This need to be improved. It would also be of interest to show the AU index in this figure as the paper discusses measurements of the EE during this interval.

Fig. 1 is now introduced in the text (lines 246-251) and, yes, the numbers are referring to the SYM/H index, as it is now explained properly. Further we have added the AU index into the plot as recommended, as well as into the corresponding figures for the other storm intervals in the Appendix / Supplementing material. By the way, we changed the notation from formerly SYM/H and ASYM/H into uniform notations at the Figures and within the text to SymH and AsyH, respectively.

Figure 2: No label or units on the y-axes. Accordingly respectively, and put to the end of the sentence.

The Figure's labeling has been changed, and the caption text corrected, indicating now the unit of the current intensity observations (A/m). This has been done likewise for all the corresponding figures in the Appendix.

Lines 282-286: It is not obvious if the method allows for the determination of the direction of the Hall currents. Is an east/west direction assumed? Sign information is provided in Figure 2, however, the text does not explain what direction positive currents represent (only the figure caption does).

The Hall current intensities, shown in Fig. 2, are now completed with an information about their direction (lines 271-275, as given already in the caption of Fig. 2). And, yes, the single-spacecraft method has to make assumptions about the East-West orientation of (infinite) current sheets, which is now expressed accordingly in the text.

Section 4.1: Although this subsection is devoted to show variations of the observed Hall currents with relation to the SYM/H index, the EE and WE is much discussed. I find it therefore appropriate to mention the expected closer relationship of the observations to the AU and AL index, which is regarded as a measure of the auroral electrojet from the ground.

A corresponding sentence about the AU and AL indices as measures of the electrojet intensities from the ground is now formulated here (lines 278-281).

Lines 378-380: Despite showing the AL index, the authors have not discussed the trend of the measurements with respect to this index.

*Correlations with the ground-based AL index are certainly similar to the AsyH behavior (line 547ff.). This is also seen in Table 3 (page 19).* 

Lines380-381: For the reader to judge this statement, a measure of the dependency should be provided, e.g. a correlation coefficient. Although mentioned in the text, this dependency is really hard to see from looking at Figures 1 and 2. This become much more evindent in the later figures where the correlation analysis is performed. This conclusion should therefore not be made at this point.

## This conclusion is kept here, but we added a reference to the Tables with the correlation coefficients later in the manuscript (line 377).

Section 4.2: From line 363 the manuscript summarizes the observed trends. This should therefore not be a part of subsection 4.2, but rater ha separate subsection (if the summary is really needed), or all the subsections could be combined into one section.

A new subsection 4.3 Summary of the observations has been created (line 358).

**Discussion:** The present discussion does a poor job in relating the observational findings (which is the majority of what is presented in this section) to the state of the art knowledge of the characteristics of the high latitude electrojets. Are the present findings mostly in agreement with the present knowledge, and where does it represent new findings/analysis that could lead to new knowledge? To my knowledge, a possible link between the asymmetric ring current and IMF By has not been established earlier.

That is one piece of information that I think the present manuscript is hinting towards.

Thank you very much for this assessment. We have emphasized this result more clearly in particular within Section 5.1 by introducing two new paragraphs (lines 457-475).

Figure 3: The caption should indicate what the red and blue points refer to.

## Added to the caption of Fig. 3.

Lines 437-439: If the PE variations during quiet intervals are not due to IMF By, what could it be then? I don't understand this sentence.

## We have reformulated this sentence (lines 532-535).

Lines 452-489: In my opinion, the term "solar wind electric field penetration" is a misleading term/concept. My take on this is that reconnection opens field-lines on the dayside. During By conditions, these newly opened field lines has a strong bend leading to tension force in the east/west direction. Field-aligned currents facilitate the energy needed to reconfigure these field lines (there will be a drag in the ionsphere due to collissions), and associated east/west plasma flows are seen in the ionosphere, together with the field aligned currents and their associated horizontal currents in the ionosphere, who's magnitude is determined by the ionospheric conductivity. On the ground one observe mainly (at least during summer) the divergence free Hall currents related to this, your PE. In this description it becomes meaningless (in my opinion) to say that the solar wind electric field (originating from the Lorentz transformation) penetrate into the high latitude ionosphere to drive currents. Hence, in order to foster understanding, to distinguish cause and effect, being one of the most

fundamental tasks for physicists, I think the "electric field penetration" is a bad term for this application. That being said, I don't see how these paragraphs really fits into the context of characterizing the PE. I therefore suggest to remove these paragraphs.

## Yes, you are right, the term "solar wind electric field penetration" and the physical concept behind it is misleading. We omitted these paragraphs completely in the revised manuscript.

Lines 495-499: This result has the strongest correlation. Could the authors try to elaborate on possible explanations for this result? The ASYM/H describe to some extent an asymmetry in the inner magnetosphere. The PE arises, as the manuscript shows, due to IMF By, which is maybe the most important paramater affecting the asymmetry in the magnetosphere. From simple linear correlation of IMF Byl and ASYM/H one get r=0.29, while with SYM/H one get r=-0.16 (using 5 min OMNI data from 1981-2016). This supports the results in the manuscript, and suggests that IMF By could be a source of asymmetry in the ring current.

## As stated before, we added two paragraphs (lines 457-475), which try to give physical explanations of this result. A part of this text was originally placed within the 'Method' section.

Line 540: What is meant by "changing SYM/H" index? Is there a criterion in the data selection that the

SYM/H should drop by e.g. a fixed amount? If so, how what is the reason for that?

This sentence is corrected to "...show cases of AE appearance with a change of the SYM/H index" (line 535). No, there is no such criterion; the former sentence was capable for being misunderstood. Hopefully it is more clear now.

Line 551: Strictly speaking, IndN does not characterize a current function, but is designed to be proportional to the amount of opened magnetic flux per unit time, which in turn affect the current systems.

## The sentence in question is now reformulated to address cause and effect more clearly (lines 544-546).

Line 563: Need to introduce Figure 5.

Introduced now (line 559).

Line 282-583: The mentioned trend of Mlat vs IndN is not obvious from Figure 6d.

This is reformulated now with more cautiousness (lines 731-733).

Lines 595-596: I disagree. As they should in principle be the same, the large observed spread (Figure 7c) give insight to the difference in technique used to probe the WE (CHAMP and AL index). I was surprised the relationship was not clearer. Could some of this variation be due to difference is in sampling/averaging window?

The Discussion section, now entitled "Correlation analyses and discussion", has largely been redesigned and reformulated, in particular with respect to Section 5.1 on the Polar Electrojet.

**Conclusion:** Similar to my comment regarding the abstract, I find the conclusion section very long. It is a very comprehensive listing of the detailed discussion provided earlier. I would have appreciated if the authors would have rather summarized what they believe is the most important and significant among their findings.

The Conclusions have been radically shorten and focused on the main findings.

Lines 606-712: This has not been mentioned before and should therefore be moved to the discussion

This long part of the former manuscript has been shifted from the Conclusions to the Discussion section, while the Conclusions section has been completely redrafted and considerably shortened. The former subsections about Hall current behavior form now a subsection within the Discussion.

## **Minor comments**

We made all the minor corrections/changes according to the Referee's recommendations. Thank you for pinpointing all these details.

Line 10: IndN needs to be defines. Suggest that you only refer to it as the Newell et al coupling function in the abstract.

Line 24: Should this be 80 degrees MLAT, to be consistent with the equatorward motion mentioned?

Line 28: Need to define acronyms in abstract. Or maybe just refer to it as ring current in the abstract.

Lines 74-77: What level of confidence does this refer to? Could a reference or a name of the formula be provided?

Line 111: compilation comparison

Line 112: demonstrates

Line 131-132: From looking at Figure 26 in Sandholt et al 2004, theese fast convection channels are located on open field lines, hence poleward of the OCB and not at the OCB as the manuscript states.

Lines 134, 139, and 153, and throughout the text: The use of "density" refering to the strength of the electrojets is sometimes unfortunate in my opinion. It can easily me mixed with how dense the current lines in the model is placed. Consider to change it to "strength".

We changed this term "density" throughout the manuscript to either "strength" or "intensity" in accordance with the respective context.

Line 151: Delete "currents"

Line 160: EISCAT is an incoherent scatter radar network, not a magnetomenter network

*"EISCAT" was till 1993 the name of a magnetometer chain (mentioned on line 514); the new name "IMAGE" was received only in 1997.* 

Line 180: electromagnetic

Line 207: 12 observatories

Line 219: BT is actually only constricted from the y and z components of IMF

Line 220: One should rather use theta = arctan2(By,Bz), which is a common algorithm that handle the different signs of By and Bz properly, compared to the mathematical function arctan().

Line 233: delete "there"

Line 236: density level

Line 245: Suggest to delete "mean"

Line 282: density intensity

Line 331: delete "there"

Line 395: Transferred is not a good word here.

Lines 405-406: Suggest to replace "occurrence and dynamics" with "strength" and "domains" with "processes"

Line 409: Delete "from geomagnetic activity researches"

Lines 411-412: This sentece is not related to any of the following text.

Line 415: add "all the" before 6

Line 414: Add something like "versus IMF and geomagnetic indices"

Lines 419-420: I dont understand this sentence.

Line 511: Suggest to rewrite: "... correlation of IndN with PE Mlat (r=0.52)."

Lines 517-518: Suggest to delete this sentence.

Line 528: Suggest to add something like "from the individual orbits". As I read these figures, each dot correspond to a specific orbit within the MLT range, among the 6 events studied.

## Anonymous Referee #2 : angeo-2018-31

"Dynamics of the electrojet during intense magnetic disturbances" by Liudmila I. Gromova et al. Interactive comment on Ann. Geophys. Discuss., <u>https://doi.org/10.5194/angeo-2018-31</u>, 2018

We would also like to thank the reviewer #2 for the thorough evaluation of our paper. Major items of this report are conform to the critics of Referee #1. We would therefore ask this Referee to consider also our answers to Referee #1. Alike there, we have answered all comments by inserting our response behind the comment in italic and blue. Further, we include the revised manuscript with corrections indicated in red for the Referee's convenience.

In the manuscript the authors analyze total magnetic field data from the CHAMP satellite during six periods of magnetic storms with respect to the relation between the phases of the storms and those of the polar and auroral electrojets. A somewhat complex procedure allows deriving sheet current densities of the Hall currents flowing underneath the spacecraft. The measurements were made during Northern summer periods and stem from noon-midnight as well as dawn-dusk crossings of the spacecraft. The main products consist of correlations between the measured Hall current locations and strengths with auroral and ring current activity as quantified by various geomagnetic indices. The results allow some interesting insights into the mutual dependences or lack of them.

The presented text contains some valuable data deserving publication. However, the presentation is too detailed and tedious to read. The main products are well presented in Figures 4 to 7 and their discussion appropriate. However, the conclusions are not concise, but rather repetitive of the earlier description of the data. One misses interpretations in terms of the build-up of the asymmetric and symmetric ring currents and the role played in that by the high-latitude magnetosphere as indicated by the behavior of the polar and auroral electrojets. I recommend to encourage the authors to shorten strongly Abstract, Introduction, and Conclusions and concentrate in the latter on the meaning of the most striking correlations.

The Abstract and the Conclusions are now entirely redrafted, shortened, and we eliminated the extensive listings. We think that they now express essentially the main findings of the study.

The Introduction has been extended by more references to important ideas and science developments in this field of research and we tried to place our study appropriately into the present state of knowledge, in particular by discussing the expanding/contracting nature of the open magnetosphere. Two additional comments.

The polar and auroral electrojets are treated as if there was no relation. One is missing a reference to the Region 1 and 2 field-aligned current systems.

## Region 1 and 2 FACs (or Birkeland currents) are now mentioned in the Introduction and the Discussion makes reference to these terms as well.

Pages 17 and 18 contain estimates of electric field penetration from the solar wind into the magnetosphere. The authors seem to take this concept literally. There is no direct electric field penetration. There is reconnection and maybe some viscous interaction by plasma waves between the solar wind and the Earth's magnetic field. Thereby forces are being transferred via magnetic shear stresses. The direction of By matters of course. Electric fields inside the magnetosphere stem from the application of these stresses to the ionospheric plasma. Therefore, the calculated percentages of electric field transfer from a partial magnetic field component are meaningless.

Yes, you are right, the term "solar wind electric field penetration" and the physical concept behind it is misleading. We omitted these paragraphs completely in the revised manuscript.

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# **Dynamics Characteristics** of the electrojet during intense magnetic disturbances

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Abstract. Hall current variations in different time sectors during six magnetic storms of the summer seasons in 2003 and 2005 are examined in detail: three storms in the day-night meridional sector and three storms in the dawn-dusk sector. We investigate tThe sequence of the phenomena, their structure, positions and the density strength of the polar (PE) and the auroral (AE) Hall electrojets were

- 5 investigated using scalar magnetic field measurements obtained from the CHAMP satellite in accordance with the study of Ritter et al. (2004a). Particular attention is devoted to the spatial-temporal behaviour of the PE at ionospheric altitudes during daytime hours both under geomagnetically quiet and under magnetic storm conditions. We analyzed the correlations of the PE and AE with various activity indices like SYM/H SymH and ASYM/H AsyH, that stand for large-scale current systems
- 10 in the magnetosphere, AL for ionospheric currents, and the IndN coupling function for the state of the solar wind. as well as the We obtained regression relations of the magnetic latitude MLat and the electrojet current density intensity I with those indices and with the interplanetary By and Bz magnetic field components.auroral and ring current activity, the interplanetary magnetic field, and the Newell et al. (2007) coupling function for the state of the solar wind. For the geomagnetic storms
- 15 during summer seasons investigated here, we obtain tThe following typical characteristics forof the electrojets dynamics were revealed:

. 1. The PE appears at magnetic latitudes (MLat) and local times (MLT) of the cusp position.

. 2. This occurs in the daytime sector at MLat~73°-80° with a westward or an eastward direction, depending on the orientation of the IMF By component. Changes of current flow direction in the PE can occur repeatedly

20 during the storm, but only due to changes of the IMF By orientation.

. 3. The current density in the PE increases with the intensity of the IMF By component from I $\sim$ 0.4 A/m for By $\sim$ 0 nT up to I $\sim$ 1.0 A/m for By $\sim$ 23 nT.

. 4. The MLat position of the PE does not depend on the orientation and the strength of the IMF By component. It depends, however, on the strength of the IMF Bz component.

25 . 5. The PE is situated at MLat~73° on the dayside during geomagnetically quiet periods and the recovery phase of a magnetic storm, and it shifts equatorward during intense substorms and the main phase of a storm.

. 6. There is no connection between MLat and the current density *I* in the PE with the magnetospheric ring current DR (index SYM/H SymH).

7. There is a correlation between the current density *I* in the PE and the partial ring current in the magnetosphere
 30 (PRC, index ASYM/H AsyH), but practically no correlation of this index with MLat of the PE.

. 8. Substorms that occur before and during the beginning of a storm main phase are acompanied in the daytime by the appearance of an eastward electrojet (EE) at MLat~64°, and then also by a westward electrojet (WE). In the nighttime sector the WE appears at MLat~64°.

9. During the development of the main storm phase, the daytime EE and the nighttime WE shift toward
 35 subauroral latitudes of MLat~56° and intensify up to I~1.5 A/m. Both electrojets persist during the main phase of the storm. The WE is then located about 6° closer to the pole than the EE during evening hours and about 2°-3° during daytime hours.

The PE appears in the daytime sector at MLat $\sim 80^{\circ}$ -73° with a westward or an eastward direction depending on the IMF By component (By<0 nT or By>0 nT). Changes of the current flow direction

40 in the PE can occur repeatedly during the storm, but only due to changes of the IMF By orientation. The PE increases with the intensity of the IMF By component from I~0.4 A/m for By~0 nT up to I~1.0 A/m for By~23 nT. The MLat position of the PE does not depend on the direction and intensity of the By component.

There is no connection between MLat and I in the PE with the symmetric part of the magne-45 tospheric ring current (index SYM/H SymH). There is a correlation between I in the PE and the ASYM/H AsyH index, but only a very weak interconnection of this index with the MLat of the PE. Substorms occurring during daytime before the storm main phase are accompanied by the appearance of an eastward electrojet (EE) at MLat~64° and then also of a westward electrojet (WE). In the nighttime sector, a WE appears at MLat~64°. During the main phase both electrojets persist.

50 The daytime EE and the nighttime WE shift toward subauroral latitudes of MLat $\sim$ 56° and grow in intensity up to I $\sim$ 1.5 A/m. The WE is then located about 6° closer to the pole than the EE during evening hours and about 2°-3° during daytime hours.

**Keywords.** high-latitude magnetic variations, magnetic storm phases, interplanetary magnetic field, Hall current modelling, equivalent ionospheric currents, current systems in the magnetosphere, polar

55 electrojet, eastward and westward auroral electrojets, SYM/H SymH, ASYM/H AsyH, AL, IndN

#### 1 Introduction

The pioneering work of Dungey (1961) about the open nature of the magnetosphere and the role of magnetic reconnection processes between the interplanetary magnetic field (IMF) and the geomagnetic main field paved the way for the understanding of the large-scale structure and dynamics of the

60 Earth's space environment. It provided the theoretical framework for subsequent successful investigations to understand the solar wind–magnetosphere–ionosphere–thermosphere coupling processes over several decades (Cowley, 2015).

The reconnection processes on the dayside give rise to open magnetic flux areas, the polar caps, and together with the nightside reconnections they are driving a large-scale internal magnetospheric

- 65 plasma convection and current systems that connect magnetospheric and ionospheric domains. Due to the large variability of the solar wind and IMF conditions, the whole system is very dynamic and the amount of open flux in the polar cap changes continuously. The theoretical understanding of the polar cap formation and its time evolution was advanced to the fully time-dependent "expanding/contracting polar cap" (ECPC) paradigm by the work of Cowley and Lockwood (1992). A
- 70 comprehensive review of all the aspects of the magnetosphere-ionosphere-thermosphere interaction processes under the solar wind driver was provided recently by Milan (2015).

The principal pattern of the large-scale field-aligned current (FAC) system, also known as Birkeland currents, which form circumpolar belts of Region-1 (on the poleward side) and Region-2 FACs (on the equatorward side) was disclosed by the work of Iijima and Potemra (1976a). On the dayside

- 75 adjacent to the cusp region, so-called Region-0 FACs are observed (Iijima and Potemra, 1976b). Using MAGSAT satellite data, Iijima et al. (1984) showed in the dayside sector of the polar cap the existence of a particular FAC system, the so-called NBZ Birkeland currents for intervals of positive IMF Bz.
- From ground-based magnetometer observations, the high-latitude electrojets have been studied already prior to the space era (cf., e.g., Chapman and Bartels, 1940). The particularities of highlatitude ionospheric current systems during magnetic disturbances were known empirically (Chapman, 1935). Levitin et al. (1982) revealed high-latitude current systems for summer conditions, which are controlled by the IMF components and solar wind parameters. Based on such equivalent current systems and considering informations about the anisotropic ionospheric conductivity,
- 85 Friis-Christensen et al. (1985) showed the possibility to determine a full current system, including FACs and horizontal currents in the ionosphere. Such a full current system can be estimated as a combination of the equivalent currents obtained both from ground-based and satellite observations of the magnetic variations (Green et al., 2007).

An intense study of the polar electrojet (PE) at the high-latitude daytime ionosphere was initiated 90 by the works of Svalgaard (1968) and Mansurov (1969). They had demonstrated that its characteristic magnetic field variation depends on the sector structure of the interplanetary magnetic field (IMF) that is much alike the average magnetic field of the solar photosphere. The IMF lines up in a spiral structure near the ecliptic plane with IMF Bx>0 and By<0 (toward the sun) or Bx<0 and By>0 (away from the sun), where one prevalent direction is kept usually for several days. During

- 95 summer the sector structure is accompanied by intense variations of the geomagnetic Z component within the polar cap at  $\Phi \sim 86^{\circ}$  and of the H component at  $\Phi \sim 78^{\circ}$ . An increase or decrease of the magnetic field components with respect to the quiet time is determined by the activity level and the IMF sector structure.  $\Delta Z < 0$  and  $\Delta H > 0$  is found for the away sector, and the opposite variations for the toward sector. The IMF sector structure does not always correspond to the expected magnetic
- 100 field variations in the near-polar region. Friis-Christensen et al. (1972) showed that during periods of discrepancy between the expected magnetic variations and the sector structure from satellite observations, there existed always an essential deviation of the IMF from the usual spiral structure. During these cases, the azimuthal IMF By component was oppositely directed to the expected direction of the spiral. This implies, that the magnetic variation on ground is not primarily controlled by
- 105 the sector structure (toward or away the sun), but by the azimuthal component of the IMF (eastward or westward).

Various methods have been developed for the extraction of the PE magnetic field variations from groundbased observations in the near-polar region (Feldstein, 1976). The most effective approach appeared to be the correlation method (Jørgensen et al., 1972; Friis-Christensen and Wilhjelm, 1975;

- 110 Feldstein et al., 1975b). It is based on the fact, that both the direction of the PE and its intensity depend on the IMF By component. The method allows to separate the magnetic variations of the PE from variations of other sources and to show the spatial-temporal variation of the PE vector variations very clearly. Feldstein et al. (1975b) described the findings of a geomagnetically quiet interval in summer 1965 and the characteristics of the equivalent current system, controlled by the
- 115 IMF By component. In a first step, time intervals with correlations of the magnetic X(H), Y, and Z components with IMF By were identified for observatories with  $\Phi > 65^{\circ}$ . In case of existing correlations, they appeared to be practically always close to a linear dependence with a correlation coefficient r. Correlation was assumed to exist for values of r > 0.4; otherwise (for  $r \le 0.4$ ) it was assumed as non existing. Such a boundary for significant r values is justified by the correlation
- 120 correction  $S_r = (1 r^2)/\sqrt{(n 1)}$ . For values of  $|r/S_r| \ge 3$ , the relation between the X(H), Y, and Z components with the IMF By cannot be regarded as accidental. With  $n \sim 50$  the correlation is not randomly distributed for r > 0.4.

Regression lines, which relate the ground magnetic variations with the IMF By component, were estimated for all MLT, based on the observed intervals with r > 0.4. They were used to describe

- 125 the spatial-temporal distribution of the surface magnetic variations in the horizontal and vertical plane, and finally for the estimation of the equivalent current system for IMF By = 6nT. Its integral intensity amounts to 180 kA with a maximum current density of the electrojet in the dayside sector of  $\sim 0.5A/m$  at 80°  $< \Phi < 81^{\circ}$ . An analogous estimation for July-August 1966 resulted in a value of  $\sim 0.35A/m$  at the same latitudes (Sumaruk and Feldstein, 1973).
- 130 The PE in the dayside sector does not disappear during magnetic disturbances (Feldstein et al.,

2006). The PE shifts equatorward to  $72^{\circ} < \Phi < 74^{\circ}$  in the longitudinal range of 08 < MLT < 17 during intense substorms (with AL $\sim$ -800 nT), and during periods of geomagnetic storms with AL $\sim$ -1200 nT and Dst $\sim$ -150 nT it is situated at  $66^{\circ} < \Phi < 68^{\circ}$  between 09 < MLT < 15. The current intensities of the PE increases only slightly to about  $\sim$ 0.5 A/m.

- 135 The variations of the magnetic field at the Earth's surface at high latitudes, which were derived with the method of regression analysis, allowed to determine the IMF By control of the spatialtemporal distributions of the electric field potential at ionospheric altitudes as well as the ionospheric and field-aligned currents (FACs) (Friis-Christensen et al., 1985; Feldstein and Levitin, 1986). The electric field potential for an inhomogeneous ionospheric conductivity is obtained by solving a
- 140 second-order partial differential equation. Friis-Christensen et al. (1985) used magnetic observations of the summer seasons in 1972 and 1973, while Feldstein and Levitin (1986) obtained it for summer 1968. The potential differences at cusp latitudes in the daytime sector are ~20 kV for IMF By~ ±6 nT.
- Leontyev and Lyatsky (1974) postulated a penetration of the solar wind electric field into the magnetosphere at daytime cusp latitudes. This electric field is generated by the potential difference between the northern and southern boundaries of the magnetotail. Under the assumption of high conductivities along the magnetic field lines, the electric field exists only at open field lines, which have their footprints in the polar caps, and will be short-circuited along closed field lines. The model allowed to estimate the effectivity of the solar wind electric field penetration into the magnetosphere 150 to ~10%.

Olsen (1996) used MAGSAT magnetic field data in a height range of 350 < h < 550 km to determine the strength and location of the auroral electrojets at 115 km altitude. He showed for the first time the possibility to estimate the horizontal ionospheric currents from scalar magnetic measurements only. The ionospheric currents were modelled by hundreds of infinite linear currents perpendicu-

- 155 lar to the orbital plane of the spacecraft with discretisation intervals of 111 km. The problem of ionospheric current estimation is underdetermined and its solution is not unique. In order to constrain the solution, a regularization method is used. The compilationcomparison of modelled and measured variations of the magnetic field along the satellite orbit on December 04, 1979, 17:00 UT, demonstrateds the good agreement for the field-aligned component, but a significant discrepancy for
- 160 the field-perpendicular one. The discrepancy is mainly caused by magnetic fields of the FACs. The integral amplitude of the ionospheric currents during the interval November 28 till December 10, 1979, yielded a correlation of r = 0.88 with the AE-index.

The IMF By orientation influences not only the PE, but also the movements of the auroral forms at cusp latitudes (Sandholt et al., 2002). Simultaneously with permanently poleward moving discrete auroral forms at the equatorward boundary of the cusp, which are controlled by the IMF Bz

165 crete auroral forms at the equatorward boundary of the cusp, which are controlled by the IMF Bz component, there exist east-west moving auroral forms. This azimuthal movement is controlled by IMF By, such that for By>0 the discrete forms move westward and for By<0 eastward. The</p>

movement of the auroral forms is in opposite direction to the PE current flow direction. This can be expected, because the discrete auroral forms and the channels of enhanced ionospheric conductivity

- 170 are both due to precipitating electrons into the upper atmosphere. A detailed consideration of the interrelation between auroral luminosity, auroral particle precipitation, and the PE during magnetic disturbances was given by Sandholt et al. (2004). As shown there, the strong convection channel is located on the dawn side of the polar cap for IMF By>0, and on the dusk side for By<0 conditions. The electron precipitation in the regime of the convection channel in the morning sector consists of</p>
- 175 a band (~500 km) of structured precipitation. The PE is located on the high-latitude boundary of the structured luminosity region in the vicinity of the strong flow channel of magnetospheric convection close to the bright auroral arc. For By>0, this channel is located in the morning sector on the pole-ward side of the polar cap boundary with FAC out of the ionosphere, and FAC into the ionosphere equatorward of the polar cap boundary.
- 180 Ritter et al. (2004b) investigated variations in the location and density strength of the auroral electrojets, which were independently determined both from ground-based (IMAGE magnetometer network) and satellite (CHAMP) measurements. For the estimation of the Hall current from CHAMP data, a current model consisting of a series of 160 current lines were placed at an altitude of 110 km and separated by 1° in latitude. The magnetic field of the line currents were related to
- 185 the current strength *I* according to the Biot-Savart law. The density strength of each of the 160 line currents were derived from an inversion of the observed field residuals using a least-square fitting approach. They determined the geomagnetic latitude and current densities of the eastward (EE) and westward electrojets (WE) in the evening, nighttime, and morning sectors. Two- or one-dimensional ionospheric Hall current systems were independently determined from variations of the horizontal
- 190 magnetic field, measured by the IMAGE ground-based magnetometer network. Comparisons of satellite with ground-based measurements of ionospheric currents at auroral latitudes have been done for satellite passages during magnetic storms as, e.g., that of 5–6 November 2001, during substorms, and according to statistical data. The ratio of the current densities from IMAGE and CHAMP was provided for a latitudinal range of 60°-77°as well as mean values of the current densities,
- 195 variations of the correlation coefficients, and coefficients of the regression equations. The ratio of the current densities and of the correlation coefficient as determined from currents above and below the ionosphere, is close to unity. Such a correspondence between the results of two different model approaches constitute the base for the following statements: a) the estimation of the position and density strength of the auroral electrojets can be carried out with observations above the ionospheric
- 200 current layer by means of low-Earth orbiting (LEO) satellites; b) the currents can be estimated from sealar magnetic field measurements; c) the result of the calculations are the parameters of the Hall current at an altitude of ~110 km (where the maximum value of the ionospheric Hall conductivity occurs). This method of Hall current estimation from satellites was proposed for the first time by Olsen (1996). Its detailed justification has been validated quantitatively by ground-based

#### 205 observations by Ritter et al., 2004b.

Based on magnetometer data of the IMAGE and EISCAT networks, Feldstein et al. (1997) showed that the electrojets shift equatorward during the main phase of strong magnetic storms. For DST~ -300 nT, the EE in the evening and the WE in the nighttime and early morning hours shifts to ~  $54^{\circ}$ -~  $55^{\circ}$ . Feldstein and Galperin (1999) studied the correlation between EE and WE with

- 210 the structure of plasma precipitations of 30 eV-30 keV according to DMSP F08, F10, and F11 satellite observations during the magnetic storms of 10-11 May 1992, 05-07 February 1994, and 21-22 February 1994. The EE displaces in the region of diffuse aurora, equatorward of the discrete auroral forms, and projects along magnetic field lines into the inner magnetosphere between the plasmasphere and the central plasma sheet of the magnetospheric tail. The WE is located at the
- 215 auroral oval and projects along magnetic field lines toward the central plasma sheet in the tail.

Wang et al. (2008) made use of the Hall current estimations for the intense magnetic storms of 31 March to 01 April 2001 and 17–21 April 2002 to investigate the position and current densities of auroral electrojets (WE and EE) as well as the relations of the electrojets to the Dst index and the IMF Bz component. The characteristics of the PE have not been considered by these authors. The

220 currents were determined from scalar magnetic field measurements of the CHAMP satellite (orbit in the meridional plane of 15–03 MLT and 16–04 MLT) according to the method that was proposed by of Ritter et al. (2004b). The intensity of the WE on the nightside is on average two time larger than the EE on the dayside.

In this study we investigate not only the auroral electrojet, but also the polar electrojet charac-

- 225 teristics during six intense magnetic summer storms. In this introduction section we have briefly described the historic progression of method used to determine the ionospheric currents from space observations with LEO satellites and from ground magnetic field data. In section 2 we present an overview of the CHAMP data used as well as the indices, which characterize the electro-magnetic conditions in the near-Earth space during the geomagnetic storms under study. Section 3 provides
- 230 a short description of the method for the determination of the Hall currents from CHAMP scalar magnetic records. In section 4 we consider the latitudinal variation of the density strength and position of the electrojets during different phases of the magnetic storm on 29–30 May 2003. Particular attention is drawn to the polar electrojet (PE). The subsequent section 5 provides detailed correlation analyses and **T** the discussion of the control of the current direction in the electrojets, its
- 235 density strength and latitudinal position. by various indices, which characterize the disturbance level and the effectivity of the interaction of the interplanetary medium on the magnetospheric processes follows in the subsections 5.1 and 5.2 for the polar electrojet (PE) and the auroral electrojets (AE), respectively. The Conclusion's section 6 summarizes the main results of the study with respect to the Hall current variations during the various storm phases (subsection 6), the polar electrojet (6),
- 240 and the auroral electrojet within four different time sectors (6).

Table 1. Overview of CHAMP satellite orbits used for this study.

Date & Time (UT, hrs)	CHAMP	MLT range (hrs)		
	orbit numbers	ascending	decending	
29/30 May 2003, 16–10	16229–16240	~14–16	~02–04	
24 Aug 2005, 07–20	29012-29020	~11-12	~23-24	
18 Jun 2003, 03–18	16532–16541	~12–16	~00–04	
30 May 2005, 02–17	27658–27667	~19–21	~06–09	
15 May 2005, 00–19	27423–27432	~20-22	$\sim \! 08 - \! 10$	
18 Aug 2003, 00–23	17480–17494	~07–09	~19–21	

#### 2 Data

The CHAllenging Minisatellite Payload (CHAMP) spacecraft (Reigber et al., 2002) was launched on 15 July 2000 into a circular, near-polar orbit with an inclination of  $87.3^{\circ}$ . From its initial orbital height at  $\sim 460$  km, it has decayed to  $\sim 400$  km in 2003 and  $\sim 350$  km after 5 years. The orbital plane precesses to earlier local times at a rate of about one hour per 11 days so that the orbit covers all

245 precesses to earlier local times at a rate of about one hour per 11 days so that the orbit covers all local times within about 131 days. The data used in this study are scalar magnetic field measurements obtained with the Overhauser Magnetometer (OVM) at the boom tip with a resolution of 0.1 nT. In order to isolate the magnetic effect of ionospheric currents in the satellite data, the contributions from all other sources have been removed from the scalar field readings as described in the study of

The CHAMP orbital intervals during various storm periods used for this study are listed in Table 1. The quantity, locations, and intensity of the peaks along the latitudinal current density intensity distribution varies over the course of the storm development. For the description of the storm development, we utilise various solar and geomagnetic indices.

- First, we employ the auroral electrojet index (AE), which is derived from geomagnetic variations in the horizontal component observed at 12 selected (10-13) observatories along the auroral zone in the Northern Hemisphere (http://wdc.kugi.kyoto-u.ac.jp/aedir/index.html). The upper (AU) and lower envelope (AL) of the superposed plots of all the data from these stations as functions of UT is used in this study.
- Further, we employ the SYM/H SymH and ASYM/H AsyH indices, which describe the geomagnetic disturbances at mid-latitudes in terms of longitudinally asymmetric (ASY) and symmetric (SYM) disturbances for the H component (http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html or, alternatively, http://omniweb.gsfc.nasa.gov/ow\_min.html). SYM-H SymH is essentially the same as the Dst index, but with a different time resolution (1-min cadence).
- 265 Finally, Newell et al. (2007) proposed a new solar wind coupling function, representing the rate of

<sup>250</sup> Ritter et al. (2004a).

magnetic flux opened at the magnetopause,  $d\Phi_{MP}/dt$ , which is referred to here as Index N (IndN). It is used for the correlation analysis in the solar-terrestrial physics:

$$IndN = d\Phi_{MP}/dt = v^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2)$$
(1)

- Here,  $\Phi$  (or  $\Phi_{PC}$ ) is the (open) magnetic flux that constitutes the polar cap, v describes the solar wind speed or, more precisely, the transport velocity of IMF field lines that approach the magnetopause,  $B_T$  is the magnitude of the IMF,  $\sin^{8/3}(\theta_c/2)$  is the percentage of field lines, which subsequently merge, and the IMF clock angle  $\theta_c$  is defined by  $\theta_c = \arctan(B_y/B_z)$ . This function describes best the interaction between the solar wind and the magnetosphere over a wide variety of magnetospheric activity. IndN has a strong correlation with other indices that characterize both the plasma and the
- 275 IMF in the solar wind as well as the processes in the magnetosphere. By means of a statistical study of the electrojet characteristics, the new function IndN was used together with the classical indices SYM/H SymH, ASYM/H AsyH, and AL. For the determination of all indices throughout this study we used time averages of the overflight intervals.

#### 3 Method

- 280 Ionospheric currents at high latitudes, which are recorded by low-Earth orbiting (LEO) satellites as magnetic field deviations, represent the sum of FACs between the magnetosphere and ionosphere (Birkeland currents) and predominantly horizontal ionospheric currents, which flow mainly in the highly conducting ionospheric E layer below the satellite orbit.
- The horizontal sheet currents are commonly decomposed in two different ways. The classical fundamental theorem of vector calculus, known as Helmholtz's theorem, states that any vector field can be decomposed into the sum of a curl-free and a divergence-free part. On the other hand, considering the relation to an electric field, the sheet current is composed of Pedersen currents, which flow in the direction transverse to the magnetic field and parallel to the electric field in the neutral wind frame of reference (e.g., Baumjohann and Treumann, 1996; Richmond, 1995), and
- 290 Hall currents, which are perpendicular to both fields. The latter decomposition requires, however, the knowledge of the electric field in the neutral wind frame of reference, which is not given in our case.

Using the Helmholtz theorem, we assume the Hall currents to be divergence-free, i.e., they are supposed to close entirely within the ionosphere, while the Pedersen currents are curl-free, connect-

295 ing essentially various branches of FACs. Laundal et al. (2018) showed (see their Figure 14), that during summer conditions, which is the case for the six storm intervals analysed in this study, the divergence-free and curl-free ionospheric currents are mainly represented by the Hall and Pedersen currents, respectively.

The Hall current flows at high latitudes are derived from CHAMP scalar magnetometer records along the satellite orbits according to the method that was proposed presented by Ritter et al. (2004b). This method of Hall current estimation from scalar magnetometer records of satellites was proposed for the first time by Olsen (1996). These calculations make use of a current model consisting of a series of 160 infinite current stripes lines, which were placed at an altitude of 110 km and separated by 1° in latitude. , the magnetic field of which corresponds to the measured values.

- 305 line currents were related to the current strength *I* according to the Biot-Savart law. The strength of each of the 160 line currents were derived from an inversion of the observed field residuals using a least-square fitting approach. The model does not take into account the contributions from field-aligned and Pedersen currents, measured at CHAMP altitudes. The comparison with ground-based geomagnetic variations of the horizontal component that considers only the contributions from the
- 310 ionospheric Hall current field, because the contributions from the field-aligned and the Pedersen currents largely cancel there each other (Fukushima, 1976), showed the applicability with high reliability of the modelling assumptions by Ritter et al. (2004b) even particularly for the estimation of the Hall currents.
- The density level of ionisation in the near noon hours at latitudes of  $75^{\circ} < \Phi < 80^{\circ}$  decreases 315 from summer to winter season by about an order of magnitude (Feldstein et al., 1975a). The PE current density strength amounts during winter to ~0.1 A/m, which makes it difficult to be measured adequately by magnetometers onboard of satellites. Because of that we investigate in this study summer storms only: three storms with CHAMP orbits in the midday-midnight plane and three in the dawn-dusk plane (listed in Table 1). Here, we describe only one of these storms, namely that of
- 320 May 29–30, 2003. Five of the The five other storms are described in the appendix / supplementary material to this paper.

The storm phases are identified in this study according to the SYM/H SymH index, which describes together with the ASYM/H AsyH index the large-scale variations of the geomagnetic field with a 1-min cadence. In essence, they SymH represents the mean values of the magnetic field devi-

- 325 ation from the quiet time level for a longitudinally distributed chain of six mid-latitude observatories stations. The current at the magnetopause (DCF) and the currents within the magnetosphere as the ring current (DR), which is asymmetric with respect to the geomagnetic axis, and the tail current (DT), which closes via the dayside magnetopause, determine the intensity and the development of the magnetic disturbances. These currents carry the main contributions to the SYM/H values
- 330 of the magnetic disturbances during magnetic storm intervals (Maltsev, 2004; Alexeev et al., 1996). The density intensity of the ring current varies with longitude. This variability is identified as the partial ring current (PRC), denoted by the ASYM/H AsyH index, and is determined as the difference range between the maximum and minimum magnetic field values of the disturbance field minus the SymH from a the longitudinal chain of mid-latitude observatories stations. The PRC current system
- 335 is a 3-D one that is confined to a limited azimuthal range of the ring current in the magnetosphere, FACs between the magnetosphere and ionosphere at the border of the PRC, and an EE in the evening sector at ionospheric heights. The latitude position is controlled by MLT and toward the near noon

sector it shifts toward the ionospheric footpoint of the cusp region Feldstein et al., 2006. The FAC of the PRC maps from ionospheric heights to the near-cusp magnetopause region, where the Hall eurrents flow, which are controlled by the IMF By component.

340 currents

#### 4 The storm of 29–30 May 2003

The orbit of the CHAMP satellite in its ascending branch was on the dayside ( $\sim$ 14–16 MLT), while its descending branch was in the nighttime sector ( $\sim$ 02–04 MLT). Figure 1 shows various geomagnetic indices and the variation of the By and Bz components of the IMF during the storm progression

- 345 together with the times of CHAMP satellite observations during crossings of the northern polar cap regions, indicated by dashed vertical lines. The respective CHAMP orbit numbers are given above the uppermost panel with the first three digits on the left side and the last two digits in between the two vertical dashed lines that indicate the corresponding observation intervals.
- The beginning of the main magnetic storm phase was identified during orbit 16233 at 22:24 UT 350 (with an average SymH value of -61.6 nT) for the overflight interval, while the minimum value of SYM/H SymH was recorded during orbit 16234 at 23:59 UT (-123.5 nT) and orbit 16235 at 01:33 UT (-139.5 nT). The four orbits prior to the main phase (16229–16232) at 16:18 UT–20:53 UT are characterized by SYM/H SymH values of -1.6 nT, -35.6 nT, -59.6 nT, and -27.0 nT as well as the occurrence of three substorms with intensities according to AL values in the range of ~-1600 nT
- to ~-2400 nT. ASYM/H AsyH increases sharply prior to the beginning of the main phase (208.3 nT during orbit 16231) and during the beginning of the main phase (290.7 nT during orbit 16233). In the maximum of the main phase, the values of this index decrease to 75.5 nT during orbit 16234 and 145.0 nT during orbit 16235. Following the main phase, the recovery phase develops (orbits 16236–16240) at 03:03 UT–09:21 UT, in the course of which the SYM/H SymH values return to the initial values at ~-60 nT and ASYM/H AsyH decreases to 51 nT during orbit 16239.

Let us now consider the structure and the latitudinal variation of the position and <del>density</del> strength of the electrojet during the various phases of the analysed storm. The eastward (EE) and westward electrojet (WE) can exist in the daytime sector at latitudes of the auroral zone( $\sim 60^{\circ} < MLat < 70^{\circ}$ ), while poleward of it, at latitudes of the auroral oval ( $\sim 73^{\circ} < MLat < 79^{\circ}$ ), the currents of the polar

- 365 electrojet (PE) can appear. The direction of the PE, however, can be eastward or westward. This is determined by the sign of the IMF By component: eastward current in the PE for By>0, and westward for By<0. In the nighttime sector, the current is westward directed (WE) in the majority of cases at auroral latitudes. Fig. 2 shows the direction, MLat, and density strength of the Hall currents along the orbit for dayside (left column) and nightside (right column) sectors as obtained from scalar</p>
- 370 measurements of the geomagnetic variations corresponding to the modelled current variations of Ritter et al. (2004b). The current direction is related to the orientation of the satellite orbit: positive currents point eastward for the descending orbital parts and westward for the ascending. The auroral



**Fig. 1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the  $B_y$  and  $B_z$  components of the IMF for the storm of 29–30 May 2003 (analysed interval from 16:00 UT on 29 May to 10:00 UT on 30 May 2003, orbits 16229–16240). The paired vertical dashed lines indicate the UT time moments intervals of each satellite orbit crossing over the northern polar cap. The orbit numbers are splitted into two parts: the two digits above the UT-axis of each uppermost frame denote the last two digits of the orbit numbers of the CHAMP passes, while the first three digits are indicated at the lower upper left side.



**Fig. 2.** Direction and density intensity values of the Hall current in units of [A/m] along the satellite orbit at the dayside (left column, 14–16 MLT, corresponding to the ascending section of the orbit) and nightside sectors (right column, 02–04 MLT, descending orbit section). Positive currents denotes eastward current for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.

electrojet current flow is assumed to be in strict east-west direction due to method constraints. It is obvious that the quantity, locations, and intensity of the peaks along the latitudinal current density

375 intensity distribution vary in the course of the storm development. A close correlation of the EE and WE can be expected for the AU and AL indices, respectively, which are regarded as a measure of the auroral electrojets from the ground. We are considering, however, magnetic records along the satellite orbit well above the ionospheric current layer.

#### 4.1 Observations related to SYM/H SymH variations

- 380 The latitudinal variation of the position and density strength of the EE is shown in Fig. 2, left panels. During the orbits 16229 and 16230, one singular peak of eastward current was observed, which occurred at MLat =  $63.4^{\circ}$  and MLat =  $64.0^{\circ}$  with intensities of 1.0 A/m and 0.6 A/m, respectively. This means that the EE peak current diminishes in density intensity with increasing disturbances according to the SYM/H SymH index and shifts to higher latitudes. During the orbits 16231-16233
- 385 (in the substorms interval and at the beginning of the main storm phase), one can clearly note two intense peaks: one of the eastward current (EE), and another of the westward current (WE - the westward electrojet). The EE peak during orbit 16231 amounts to ~1.83 A/m at MLat = 56.3°, decreasing in the course of the next orbit to 0.94 A/m at MLat = 63.9°.

With the beginning of the main phase, the current again intensifies to 1.61 *A/m* at MLat = 57.6°.
390 The EE variations in density strength and latitudinal position during the orbits 16231–16233 proceed analogeous to the SYM/H SymH changes: the more intense SYM/H SymH, the closer to the equator shifts the EE peak and the stronger becomes its current density intensity.

But such an accordance is broken again in the maximum of the main phase similar to orbits 162<del>2934</del> and 162<del>305</del>: SYM/H SymH</del> increases in intensity, while the EE in its peak diminishes to

- 395 0.44 A/m and even 0.29 A/m at MLat =  $61.0^{\circ}$ . The EE peak amounts to 0.23 A/m at MLat =  $65.2^{\circ}$  during orbit 16236 in the recovery phase and diminishes further to values <0.2 A/m during the subsequent orbits, which complicates the identification of the EE position. This way the EE follows with its varying current densities at auroral latitudes the growth (or creation) and main phases of the magnetic storm. It should be noted, that SYM/H SymH remains still significant during the recovery
- 400 phase, with values of  $\sim$ -60 nT. This exceeds the intensity of SYM/H SymH during the substorm interval and at the beginning of the storm main phase, while the EE during the recovery phase is much smaller than during the substorm interval.

In contrast to the EE, a westward current exists on the dayside sector during the whole interval considered, except the two first orbits, and achieves during the substorm interval values of 1.1–

405 1.3 A/m within the peaks at 64° <MLat<70°. It is obvious that the WE does not attain the CHAMP meridian (~14–16 MLT) during the first two orbits, while it strengthens in the nighttime sector and propagates toward the evening hours. During the orbits 16231–16233, the latitude and density strength of the WE peak changes in phase with the SYM/H SymH intensity, analogous to the current

variations in the EE peak. During the maximum of the main phase the WE peak diminishes to 410 0.8-0.25 A/m at 71°<MLat<74° in antiphase to SYM/H SymH.

The peaks of westward current remain at a level of  $\sim 0.6 \ A/m$  within  $73^{\circ} < MLat < 76^{\circ}$  during the recovery phase. An additional peak of eastward current with a density strength of 0.49 A/m appears during orbit 16236 at MLat =  $80.5^{\circ}$  during early afternoon hours (MLT $\sim 14.5$  hrs). This latitude and the MLT range around midday imply that the current observed is the PE. In this case its

- 415 orientation is controlled by the IMF  $B_y$  component and for an eastward PE the  $B_y$  component should be positive (Friis-Christensen et al., 1972; Sumaruk and Feldstein, 1973; Feldstein, 1976). Indeed, according to Fig. 1,  $B_y = 9 nT$  during the period of this orbit. During the two subsequent orbits, the Hall current changes its direction to westward at MLat~80°. If this westward current prove to be the PE, then its appearance should be connected with a change of the IMF By component. Indeed,
- 420 the currents are accompanied with a change of sign of the IMF  $B_y$  component, corresponding to -17.5 nT (MLat = 80.7°) during orbit 16237 and -5.2 nT (MLat =80.6°) during orbit 16238. During the orbits 16239 and 16240 the IMF  $B_y$  component turns to positive values again and weak eastward directed currents appear accordingly at MLat~80°.

In the majority of latitudinal profiles of the nighttime sector (Figs. 2, right panels), there one peak of the WE exists at latitudes of the auroral oval and some weakly spreaded eastward currents. Two orbits constitute an exception - one prior to (16231) and another during the beginning of the main storm phase (16233). These orbits pertain to the period of intense substorms. Within the polar cap up to the geomagnetic pole, there exist quite intense (up to 0.9 A/m) eastward currents.

- These currents might contain irregularities, which are caused by the appearance of a peak of eastward currents in the latitudinal profile. The monotonicity of the eastward current variations within the polar cap during most orbits provides some reason to assume, that these currents result from the closure of an intense WE current, which occurs at latitudes of the auroral oval in the nighttime sector.
- At the beginning of the substorm interval (orbits 16229 and 16230) with the intensification of **SYM/H** SymH, the WE peak shifts to lower latitudes and the current density intensity diminishes. The most intense peaks of the nighttime WE are obtained during the substorm interval prior to the main phase start with and retain values of 2.7 A/m at MLat = 64.4° (orbit 16231), 1.7 A/mat MLat = 60.9° (orbit 16232), and during the beginning of the main phase with 1.79 A/m at MLat = 58.0° (orbit 16233). Later in the maximum of the main storm phase, the WE peak current
- 440 density strength diminishes to 1.07 A/m at MLat = 59.5° (orbit 16234) and 0.9 A/m at MLat = 55.8° (orbit 16235). Hence, the latitudinal peaks of the WE vary during nighttime in phase with the intensification of SYM/H SymH (storm development) before the main phase commences at higher latitudes, while shifting to the equator during the maximum of the main phase. The peak intensities changes both in phase and in antiphase with the SYM/H SymH intensity. During the recovery phase,
- the peak density intensity of the WE current is smaller than 0.2 A/m, while the eastward currents

within the polar cap are too small to be recorded.

#### 4.2 Observations related to ASYM/H AsyH variations and to high-latitude currents

In the dayside sector during the existence of the EE (orbits 16229–16236), the peak current intensities and the peak latitude positions vary synchronous with the ASYM/H AsyH changes, except

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of one orbit (16235) during the main phase. During this orbit, the ASYM/H AsyH index abruptly intensifies to 145 nT with a pertaining small density intensity of the EE with ~0.29 A/m and a shift of MLat by 1.8°. For the WE, the change in latitude and density strength of the peak currents is in phase with the ASYM/H AsyH variations during the storm, with the exception of orbit 16235.

In the nighttime sector, the intensity of the peaks and their latitude (except orbit 16235) change in 455 phase with the <del>ASYM/H</del> AsyH variations.

#### 4.3 Summary of the observations

Summarizing the results of Hall current observations by the CHAMP satellite during the magnetic disturbance period of 29–30 May 2003 in the daytime and nighttime sectors (12–16 MLT and 00– 04 MLT, respectively) we conclude:

460 – Intense >1 A/m eastward and westward electrojets can occur at latitudes of the auroral zone during substorm periods, which precede the magnetic storm, and during the beginning of its main phase. During the maximum of the main phase, the density strength of the Hall currents as well as the substorms diminish in antiphase to an increase of the SYM/H SymH index.

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 A fast decay of the EE and WE occurs during the recovery phase at auroral latitudes both during daytime and nighttime hours. The westward or the eastward currents can be influenced during this storm phase by the existence of a PE at 73°<MLat<80° in the region of the dayside cusp.

- The direction of the current in the PE is determined by the IMF  $B_y$  component: for  $B_y > 0$ the current is eastward, for  $B_y < 0$  westward. The change of the current direction within the PE can occur several times during the storm development, but always in accordance with the change of the IMF  $B_y$  orientation.

- The Hall currents in the auroral ionosphere, both the EE and the WE, vary usually in phase with the SYM/H SymH and ASYM/H AsyH variations (but sometimes also in antiphase). There are time intervals, where any correlation between the geomagnetic activity indices and the Hall current parameters is missing (see Tables 2 and 3 below in section refsec:anal). There is a closer connection of the current density intensity and the MLat variations with ASYM/H AsyH than with SYM/H SymH.

- In the daytime sector (14-16 MLT) during a period of intense substorms, the EE is located in

a latitude range 56°<MLat<64°, while the WE is at 64°<MLat<70°. During the main phase</li>
of the storm, the EE shifts to 58°<MLat<62°, while the WE is situated at 64°<MLat<73°, and during the recovery phase, finally, the WE is observed at latitudes of 73°<MLat<76°. Therefore, the EE stays at about the same latitudes during the both the intense substorms and the main phase of the storm, attaining extreme equatorward values of MLat~ 56°. An analogue situation exists with regard to the change of position for the WE in various storm phases, but during daytime hours the WE is located about 6° closer to the pole.</li>

- In the nighttime sector (02–04 MLT), there exists practically only the WE, which is located during substorms at 61°<MLat<64°, and during the main storm phase at 56°<MLat<60°. Therefore, extremal positions of the WE and EE can reach latitudes below 60°. This occurs in the daytime sector for the EE, while in the nighttime for the WE.</li>
- 490 The detailed description of the Hall current dynamics characteristics during five further magnetic summer storm intervals is transferred to the Appendix/Supplementary material.

#### 5 Discussion Correlation analyses and discussion

In the section 4 and in the appendices A1–A5 we have investigated several geomagnetic storm periods, based on magnetometer measurements onboard the CHAMP satellite. The Hall currents in the 495 high-latitude upper ionosphere of the Northern Hemisphere were analysed for various MLT sectors with regard to their position in geomagnetic latitude, their <del>density</del> strength and direction. The empirical description concerned the appearance of the EE, the WE, and the PE during various storm

phases and was carried out primarily qualitatively.

Below we are going to analyse the current directions, their densities, and MLat positions for various MLT sectors with regard to solar wind parameters and some indices of the planetary magnetic activity (SYM/H SymH, ASYM/H AsyH, AL, IndN). We use activity indices, which characterize the occurrence and dynamics of large-scale plasma domains in Earth's magnetosphere that are responsible for the existence of concrete variations of the geomagnetic field at Earth's surface.

5.1 Polar electrojets

- 505 It is well-known from geomagnetic activity researches that the intense magnetic disturbances at the high-latitude projection of the magnetospheric cusp are not related to the occurrence and dynamics of magnetospheric substorms. Wang et al., 2008, investigated the behaviour of electrojets by means of CHAMP satellite observations during two magnetic storm events with the focus on the auroral electrojets. Fig. 3a–f shows the correlations of the various IMF parameters and geomagnetic indices
- 510 with the magnetic latitude (left side panels) and the Hall current density intensity I (right side panels) obtained by CHAMP satellite crossings over the polar electrojets during 6 geomagnetic storms. The

direction of the Hall currents can be distinguished in the upper panels (Fig. 3a): westward and eastward currents are indicated with blue and red data points, respectively. For the further study, we selected the electrojet parameters at their extremal values of current density strength for each

515 orbit. The data pool was augmented yet be including also neighbouring values before and after the extremal points.

**Table 2.** The dependent (X) and independent variable (Y), their correlation coefficients (r), the coefficients A and B of the regression equations X = A + B \* Y, and their dispersions  $\sigma$ .

X	Y	$r$	A	В	σ
I (density intensity, A/m)	By (>0)	0.59	0.535	0.018	0.160
I (density intensity, A/m)	By (<0)	-0.72	0.291	-0.024	0.134
I (density intensity, A/m)	By	0.56	0.433	0.018	0.170
I (density intensity, A/m)	<del>ASYM/H</del> AsyH	0.74	0.396	0.004	0.138
MLat (deg)	AL	0.46	78.540	0.006	2.542
MLat (deg)	IndN	-0.52	77.750	-0.006	2.415

Fig. 3a differentiates the current measurements with regard to the azimuthal IMF component (By), i.e., between those, obtained during By>0 and those during By<0 conditions. It is clearly seen that the direction of the current within the PE is determined by the IMF By sign. For intervals with

- 520 positive IMF By>0, we observe for all cases an eastward directed Hall current; for negative IMF By<0 intervals the Hall current is always westward. The current density strength within the PE is correlated with the magnitude of the azimuthal IMF component By: it increases from 0.3–0.4 A/m for near-zero values to  $I \sim 0.9$  A/m for  $|B_y| \sim 23$  nT (i.e., the maximum By value during the periods investigated shown). Correlation coefficients r between current density intensity I and the IMF By
- 525 component for By>0 and By<0 are shown in the upper right and upper left corner, respectively (Fig. 3a, right panel). The coefficients for the offset (A) and the slope (B) of the linear regression line (for  $r \ge 0.46$ ) as well as the dispersion values  $\sigma$  are listed in Table 2.

The current density intensity values I for  $B_y \sim 0$  nT are somehow different in the regression equations for  $B_y > 0$  and  $B_y < 0$ . Fig. 3b (right panel) shows the current density intensity I as

- 530 a function of the IMF component's magnitude  $|B_y|$ , i.e., independent of the IMF By sign. This increases the number of data points for linear regression estimation. According to this estimation, the current density intensity amounts to  $I \sim 0.4$  A/m for  $|B_y| \approx 0$  nT, while it attains  $\sim 0.9$  A/m for  $|B_y| = 23$  nT, i.e., about twice as large. The increase of the Hall current density strength within the PE might take place during can also occur in magnetically quiet intervals during the absence of
- 535 magnetic activity at latitudes of the auroral zone, which is because such disturbances are not directly related to the IMF By component.

We could not find any essential correlation between the MLat position and the IMF By component

for both  $B_y > 0$  (r = 0.04) and  $B_y < 0$  (r = 0.32) nor for  $|B_y|$  (r = 0.15, see Fig. 3a and b). The current density strength and its direction (eastward or westward) within the PE is controlled

- 540 by the IMF By component, but the latitudinal position of the current density intensity maximum does not depend on IMF By. The observed morphological peculiarity of the PE is caused by its generation mechanism. This is assumed to be due to the interaction between the magnetosphere and the supersonic plasma flow (solar wind) with a "frozen-in" magnetic field (IMF). The PE currents are generated at magnetic latitudes of the cusp due to reconnection processes between the IMF and the
- 545 geomagnetic field (Jørgensen et al., 1972; Wilhjelm and Friis-Christensen, 1971). The reconnection of magnetic fields brings about a north-south electric field and an east-west Hall current at cusp latitudes in the ionosphere. A possible generation mechanism for the PE current system has been suggested by Leontyev and Lyatsky (1974), including the structure of the PE current system.

Leontyev and Lyatsky (1974) postulate the penetration of the electric field  $E_z = V_x \times B_y$ , where 550  $V_x$  is the solar wind velocity past the magnetosphere. This electric field will cause a potential difference U between the northern and southern boundaries of the magnetotail:  $U = E_z \times D_m$ , where  $D_m$  is the size of the magnetosphere along the z-axis. On the assumption of high conductivity along the magnetic field lines, the electric field  $E_z$  can exist only in the region of open field lines, rooted at the polar caps, and will be short-circuited along closed field lines. Thus, the boundary

555 between closed and open field lines (OCB) will be the line of zero potential for the field  $E_z$ , and U = 0 at this boundary in the ionosphere.

Feldstein et al. (1975b) estimated the effectiveness of the electric field penetration from the solar wind to the cusp. During summer season (July–August 1969) the integral Hall current within the PE was estimated to  $\sim$ 220 kA.

560 The integral conductivity in the ionosphere during summer around noon is  $\sim$ 7 mhos, i.e., the potential drop in the cusp is about  $U \sim$ 30 kV. The potential difference between the northern and southern boundaries of the magnetotail amount to  $U_m \sim$ 600 kV.

The following assumptions were made for the estimation: solar wind speed  $V_x \sim 400$  km/s, IMF  $B_y = 6$  nT, and the magnetospheric size along the z-axis  $\sim 40 R_E$ .

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5 If the voltage drop is the same in the northern and southern hemispheres, then the efficiency of the electric field penetration from the solar wind to the high-latitude ionosphere during summer season is  $\sim 10\%$ .

Here, we present estimations of the efficiency of the electric field penetration into the cusp region for two concrete orbits of the CHAMP satellite over the daytime sector.

570 During orbit 16238 of 30 May 2003 we observe a maximum Hall current density at 06:15 UT.

The solar wind velocity at this time was  $V_x = 640.7$  km/s, the plasma density in the solar wind  $n_p = 21.4 \text{ cm}^{-3}$ , and IMF  $B_y = -6 \text{ nT}$ . The electric field in the solar wind amounts to  $E_z = V_x \times B_y = 3.8 \text{ mV/m}$ . The dynamic plasma pressure at the subsolar point  $P_{sw} = 0.88P_{sw}^{dyn} = 12.9$  nPa, while the distance of the subsolar point at the magnetopause is  $\sim 7 \text{ R}_E$ .

575 The potential difference along the z-axis between the northern and southern tail boundaries amounts to  $U_m = 338$  kV, and in the cusp of one hemisphere hence  $U_m = 169$  kV.

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According to the CHAMP data, the mean density intensity of the current is  $\sim 0.3$  A/m over  $\sim 8.5^{\circ}$ , the integral current in the cusp therefore  $\sim 295$  kA, and the potential difference in the cusp  $\sim 42$  kV. The efficiency of the electric field penetration from the solar wind into the ionosphere is thus about  $\sim 25\%$ .

During orbit 29018 of 24 Aug 2005, 16:42 UT, with  $V_x = 630.5$  km/s,  $n_p = 18.6$  cm<sup>-3</sup>, and IMF  $B_y = -20.9$  nT results in  $E_z = 12.6$  mV/m,  $P_{sw} = 10.8$  nPa, and distance of the subsolar point at the magnetopause is  $\sim 7.3$  R<sub>E</sub>. The potential difference in the cusp of one hemisphere can thus be estimated to  $U_m = 585$  kV. According to the CHAMP data, the mean density intensity of the current

- 585 is ~0.4 A/m over ~7.5°, the integral current in the cusp therefore ~348 kA, and the potential difference in the cusp ~49 kV. The efficiency of the electric field penetration from the solar wind into the ionosphere is thus about ~9%. Therefore, for a quite variable electric field voltage applied to the magnetosphere from the magnetized solar wind flow (from 585 kV to 169 kV), the efficiency of its penetration to the ionosphere varies between 9% and 25%.
- 590 The SYM/H SymH index varied during the intervals of CHAMP overflights above the polar electrojets considered in this study from -10 nT to -170 nT. As shown in Fig. 3c, there is no correlation between SYM/H SymH and the MLat positions (r = -0.13) nor the PE current density strength (r = -0.01). The absence of any correlation is as expected, because the current systems of the DCF, DR(sym), and DT are is located completely within the magnetosphere. In case of absent FACs, they it cannot serve as a sources for Hall currents in the ionosphere that is responsible for the existence
- of PE.

According to Fig. 3d, there is a high correlation between the ASYM/H AsyH index and the PE current I ( $r \sim 0.74$ ) and an absence of correlation with the MLat position of the PE ( $r \sim -0.29$ ). The PE current density strength has therefore a direct relation to the intensity of the ASYM/H AsyH

600 current system: with increasing longitudinal asymmetry increases the PE current density intensity, but the latitudinal position of the PE does not depend on ASYM/H AsyH.

A partial ring current (PRC) emerges during geomagnetic disturbances. The PRC is a westward directed current in the equatorial plane of the evening to nighttime sector at geocentric distances of  $R\sim3-4$   $R_E$ . The basic PRC current system includes Region-2 FACs into the ionosphere within this sector (Iijima and Potemra, 1976a), and an EE in the ionosphere (Feldstein et al., 2006; Kalegaev

- et al., 2008). Observations of fluxes of energetic neutral atoms (ENA) show increased ion fluxes in the evening-nighttime sector within the inner magnetosphere during geomagnetic disturbances, which appears to be the experimental evidence for the existence of the PRC (Kozyreva and Liemohn, 2003). A successful modeling of the PRC and the EE has been performed by Kalegaev et al. (2008)
  610 for the magnetic storm event of November 06-14, 2004.
  - The high correlation between AsyH and the intensity of the PE gives reason to assume an IMF

By control about the characteristics of the magnetic field asymmetry inside the magnetosphere. This component of the IMF does not directly influence the intensity of the PRC, but via the current system, that forms by the PE with FACs between the PE and the PRC. The PRC position in the equatorial

615 plane is controlled by MLT and toward the near noon sector it shifts to the ionospheric footpoint of the cusp region (Feldstein et al., 2006). The geocentric distance of the PRC increases therefore from the nighttime via the evening toward earlier hours. FACs of the PRC map from inner-magnetospheric heights to the near-cusp region, where the Hall currents flow, which are controlled by the IMF By component. In this way forms a PRC current system, which in addition to the basic one is controlled

620 by the IMF By component.

Fig. 3e shows the correlation between the MLAT position and the density strength of the PE with the AL index of geomagnetic activity. This index describes the reduction of the horizontal component of the geomagnetic field at auroral latitudes on Earth's surface during disturbances with respect to quiet-time conditions, using a longitudinal chain of magnetic observatories. The AL index

- appears to be a sensitive tracer for processes in the central plasma sheet of the magnetospheric tail. These processes are created by injection of energetic particles, their accumulation, and the dissipation of their energy during storm times and is accompanied by changes of the boundary positions of large-scale plasma structures. They appear to have relatively small influence on the density strength and MLat position of the PE (with r = -0.38 and r = 0.46, respectively). However, there is a
- 630 distinctive tendency for the shift of the PE from  $\sim$ 78° to  $\sim$ 74° with an increase of the AL index up to -900 nT.

As shown in Fig. 3f, there is a correlation of IndN with MLat in the daytime sector (r=-0.52). This is obvious, because both components By and Bz are included in the definition of IndN. With increasing IndN, the latitude of the current decreases. The correlation coefficient of IndN with the Hall current density intensity (I) is r=0.3.

635 Hall current density intensity (I) is r=0.3.

To summarize, the values of the correlation coefficients r and the coefficients A and B of the regression equations are listed in Table 2. They relate the PE current intensity and their MLat position to the indices that characterize the situation in the solar wind and within the magnetosphere at the time of the observations. The PE are characterized by the following peculiarities:

- 640 The PE appears at magnetic latitudes and local times of the cusp.
  - The direction of the current in the PE is controlled by the IMF By (azimuthal) component: for By>0 the current is eastward, for By<0 the current is westward directed.</li>
  - The current strength in the PE increases with the intensity of the IMF By component from  $I \sim 0.4$  A/m for By $\sim 0$  nT up to  $I \sim 1.0$  A/m for By $\sim 23$  nT.
- The MLat position of the PE does not depend on the orientation and the strength of the IMF By component.

- There is no connection between MLat and the current intensity *I* in the PE with the magneto-spheric ring current DR (index SymH).
- There is a correlation between the current intensity *I* in the PE and the strength of the partial ring current in the magnetosphere (PRC, index AsyH), but practically no correlation of this index with MLat of the PE.
- The currents in the central plasma sheet appear to have a weak influence on the current intensity and the MLat position of the cusp.
- We realized a correlation between MLat and the IndN solar wind coupling function.
- 655 5.2 Auroral electrojets

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The most intense Hall currents at ionospheric heights, which are responsible for the electrojets, are located at auroral latitudes in the nighttime hours. It is even there, where intense auroras occur most often in the zenith (Chapman and Bartels, 1940; Harang, 1951). These electrojets were named auroral electrojets (AE). A huge number of studies has been published on their morphology, their

- 660 connections with the solar wind parameters and the plasma domains in Earth's magnetosphere, as well as on their internal processes. The AE are present during all hours of the day. Based on magnetometer data of the IMAGE and EISCAT networks, Feldstein et al. (1997) showed that the electrojets shift equatorward during the main phase of strong magnetic storms. For DST~ −300 nT, the EE in the evening and the WE in the nighttime and early morning hours shifts to ~ 54°-~ 55°.
- 665 The number of electrojets, their internal current structure, and the interconnection with the individual magnetospheric plasma domains depends both on the activity level and on the MLT position of the observation (Feldstein et al., 2006). Therefore, we consider below the results of the Hall current observations of the CHAMP satellite separately for each of the following four MLT sectors: daytime, nighttime, evening, and morning hours.
- 670 Figures 4–7 consider the MLat positions (left columns) and current densitites *I* (right columns) during the moments of extreme values of current density strength in dependence on the SYM/H SymH, ASYM/H AsyH, AL, and IndN indices. As in Fig. 3a, data points of electrojets with an eastward direction are indicated by red colour and those with westward direction by blue colour.

Table 3 provides the correlation coefficients r, the coefficients A and B of the linear regression 675 equations of the type X = A + B \* Y, which were obtained by the least-squares method with correlation coefficients r > 0.46, and the mean-square deviation  $\sigma$  from the regression line.

5.2.1 Daytime sector 09:00–14:00 MLT

The AE in the daytime sector can coexist with the PE. These two types of current can be distinguished according to the following indications (that are valid for AE in contrast to PE):

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**Table 3.** The dependent (X) and the independent variable (Y), their correlation coefficients (r), the coefficients A and B of the regression equations X = A + B \* Y, and their dispersions  $\sigma$ , listed for four different MLT intervals.

X	Y	r	А	В	σ			
MLT 09:00-1 <del>3:594:00</del>								
MLat (WE, deg)	ASYM/H AsyH	-0.54	74.136	-0.052	3.89			
MLat (EE, deg)	<del>ASYM/H</del> AsyH	-0.49	70.327	-0.047	3.91			
MLat (EE, deg)	AL	0.68	70.192	0.005	3.28			
MLat (WE, deg)	IndN	-0.74	72.215	-0.011	3.13			
MLat (EE, deg)	IndN	-0.67	70.271	-0.025	3.43			
MLT 14:00-2 <del>0:59</del> 1:00								
MLat (WE, deg)	<del>SYM/H</del> SymH	0.49	72.783	0.041	4.23			
MLat (EE, deg)	<del>ASYM/H</del> AsyH	-0.54	65.971	-0.036	3.67			
Intensity (WE, A/m)	<del>ASYM/H</del> AsyH	0.68	0.168	0.003	0.24			
Intensity (EE, A/m)	<del>ASYM/H</del> AsyH	0.64	0.217	0.004	0.29			
MLat (EE, deg)	AL	0.46	64.707	0.004	3.88			
Intensity (EE, A/m)	AL	-0.59	0.320	-0.001	0.31			
MLT 21:00-0 <del>1:59</del> 2:00								
MLat (WE, deg)	<del>SYM/H</del> SymH	0.53	63.806	0.032	2.25			
Intensity (WE, A/m)	<del>ASYM/H</del> AsyH	0.50	0.205	0.005	0.33			
Intensity (WE, A/m)	AL	-0.67	0.233	-0.001	0.28			
Intensity (WE, A/m)	IndN	0.76	0.207	0.003	0.25			
MLT 02:00-0 <del>8:599</del> :00								
MLat (WE, deg)	<del>SYM/H</del> SymH	0.47	67.343	0.040	3.24			
Intensity (WE, A/m)	<del>ASYM/H</del> AsyH	0.69	-0.089	0.010	0.38			
Intensity (WE, A/m)	AL	-0.52	0.328	-0.001	0.44			

680 1. The AE are as a rule located at MLat<73° during low geomagnetic activity conditions;

2. the Hall current direction in the AE does not depend uniquely from the orientation of the IMF By component.

Fig. 4a shows only those cases of AE appearance in the daytime sector with ehanging a change of the SYM/H SymH index. Usually, SYM/H SymH has negative values (SYM/H SymH<0 nT)</li>
during geomagnetic storms. Fig. 4a shows, however, beside of the mostly negative values also some values with SYM/H SymH>0. They occur as a rule during the first few hours of magnetic storms.

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The large scatter of the data points and their low correlation coefficients (maximum for MLat(EE, r = 0.39) and I(EE, r = 0.29) in Fig. 4a) indicate the weak control of the AE parameters by the symmetric ring current, the index of which is SYM/H SymH.

- 690 The MLat position of the AE in the daytime sector correlates with three other indices: ASYM/H AsyH, AL, and IndN. The AE shifts with increasing disturbances toward lower latitudes: the WE from 72° to 66°, and the EE from 70° to 57° (Fig. 4b–d). The largest correlations of MLat are found with the IndN coupling function (WE, r = -0.74), the smallest values for ASYM/H AsyH (EE, r = -0.49). IndN is proportional to the amount of opened magnetic flux per unit time in the polar
- 695 cap, which in turn affects the current systems.

These three AL and AsyH indices characterize the large-scale current systems, the magnetic fields of which influence the magnetic field configuration of the dayside sector. It should be noted that there are tendencies for the WE to be located during daytime hours a few degrees more poleward than the EE. These tendencies are clearly visible with regard to the MLat(EE and WE) positions and their

700 relation to ASYM/H AsyH and IndN (Fig. 4b and d). The constant term A is in the case of ASYM/H AsyH 3.8° larger for the WE than for the EE, and 1.9° in the case of the solar wind coupling function IndN.

The correlation coefficients for the Hall current with the IMF By vector component and its magnitude is low (not shown). A significant correlation coefficient |r| > 0.49 is achieved in the daytime

705 sector only for the MLat positions of the electrojets, while the correlation with the current densities is minimal for all indices. The electrojets can be both westward and eastward. The EE can be observed for very intense disturbances during the storm period down to MLat~57°.

5.2.2 Evening sector 14:00–21:00 MLT

Figure 5 provides data presentations in the same format as Fig. 4, but now for the evening sector. 710 Significant correlation values r exist in the evening sector for both the current densities and the MLat positions of the electrojets. The largest values of  $r \sim 0.6 - 0.7$  were obtained for current densities I, independent of the current directions (westward or eastward) in the electrojets.

There appears a dependence of MLat(WE) from the SYM/H SymH index: the electrojets shifts equatorward with an increase of the ring current. The EE is located more equatorward than the WE

715 by about  $\sim 6^{\circ}$ . The constant term A of the regression equations amounts accordingly to MLat(EE) $\sim 66^{\circ}$  with respect to ASYM/H AsyH and MLat(WE) $\sim 72^{\circ}$  with respect to SYM/H SymH.

The EE current density strength exceeds those of the WE. That means, the interpretation of the EE in the evening sector as a branch-off from the WE at higher latitudes will become more unlikely (Feldstein et al., 2006).

The electrojets move more equatorward with increasing disturbance level according to any geomagnetic activity index. Their current densities rise from <0.2 A/m to 1.6 A/m for the EE, and up to 1.3 A/m for the WE. The current strength of the EE increases hence stronger than that of the WE (by about 30%). The EE is observed equatorward of MLat $\sim$ 60° during magnetic storm periods with the threshold latitude for the EE shift of  $\sim$ 53°.

725 5.2.3 Midnight sector 21:00-02:00 MLT

In this sector, the WE exists almost exclusively (Fig. 6). Moreover, the current density intensity correlates here well with the ASYM/H AsyH, AL, and IndN indices with a maximum value of r = 0.76 for the IndN coupling function.

Otherwise, t The MLat(WE) position, however, correlates only with the SYM/H SymH index. It
730 decreases from 62° to 58° for a change of SYM/H SymH from ~-40 nT to ~-170 nT. The lowest possible MLat appears to be ~58°.

The WE current density strength increases from values <0.2 A/m to  $\sim 1.5$  A/m for an intensification of the disturbance according to the IndN coupling function from 0 to 325, while the WE position moves equatorward until a may have an equatorward threshold value of  $\sim 58^{\circ}$ .

735 5.2.4 Morning sector 02:00–09:00 MLT

Similar to the midnight sector, the WE exists also almost exclusively within the morning sector (Fig. 7). The current density intensity correlates here well with the ASYM/H AsyH and AL, with a maximum value of r = 0.69 for the ASYM/H AsyH index. The WE current density strength increases from values 0.32 A/m to 1.92 A/m with an increase of the ASYM/H AsyH value from

- 740 40 nT to 200 nT, while the electrojet position moves equatorward until a threshold value of ~56°. The MLat(WE) position correlates only with the SYM/H SymH index. In this regard the midnight and morning sectors show the same behaviour. The MLat positions are controlled predominantly by the SYM/H SymH index, i.e., by the density intensity of the ring current DR rather than by any other current system.
- 745 The central plasma sheet of the magnetospheric tail is the source region of the WE in the nighttime sector. An increase of the DR is accompanied by a change of the geometry of the magnetic field lines that are interconnected with the central plasma sheet. This results in a shift of the ionospheric projection of the WE toward the equator. The relation between the current density intensity in the WE and the AL value is not needed for the interpretation.

#### 750 6 Conclusions

In this paper we investigated the density strength and spatial-temporal distribution (versus magnetic latitude MLat and MLT) of Hall currents at high latitudes. The currents were determined from measurements of total scalar magnetic field data, sampled by magnetometers on board the CHAMP satellite at ionospheric altitudes of  $\sim$ 430 km (Ritter et al., 2004a) . In this study we used these

755 current estimations to explore the dynamics characteristics of the polar and auroral electrojets during

a selection of six magnetic storms (see Table 1). We identified their distinctive features and the correlations with activity indices that are usually used to characterize large-scale current systems in the magnetosphere. The main findings obtained are listed below as follows.

The current intensity of the PE increases with the magnitude of the IMF By component, while no correlation at all could be found between the MLat position of the PE and the IMF By component. The PE is eastward directed for IMF By>0 and westward for IMF By<0. Changes of current flow direction in the PE can occur manifold during the storm, but only due to changes of the IMF By orientation. There is a strong correlation between the PE current strength and the extent of the ring current asymmetry as indicated by the AsyH index, while there is no connection with the SymH

765 index, the symmetric part of the ring current. There is an IMF By control of the magnetic field asymmetry inside the magnetosphere that manifests in the high correlation between AsyH and the PE current intensity.

Auroral electrojets are located at auroral latitudes (MLat $<72^{\circ}$  during daytime hours, and MLat $<68^{\circ}$  during nighttime) and exist during all MLT. The number of electrojets in a certain latitude range, the

- 570 structure of the currents in them, and the interconnection with concrete magnetospheric plasma domains, depend on the disturbance level, which is controlled by UT as well as local time (MLT) at the observational points. Around midnight, the WE is predominant, and it exists almost exclusively in the morning sector. During daytime hours, the MLat positions of the auroral electrojets, both WE and EE, correlate with the activity indices AsyH, AL, and IndN. The correlation with the current
- intensities, however, is relatively small there for all indices. The largest correlations ( $r \sim 0.6-0.7$ ) exist between the AsyH index and the current intensity of the electrojets in the evening sector.

Certain characteristic features of the electrojets appear during the different phases of a geomagnetic storm. With the development of the main phase both the daytime EE and the nighttime WE shift to subauroral latitudes MLat~56°, while increasing in strength up to  $I \sim 1.5$  A/m. During evening

780 hours, the WE is located by  $\sim 6^{\circ}$  closer to the pole than the EE. A splitting of the WE is possible in the morning hours during the recovery phase, analogous to the splitting of auroral luminescence in the auroral oval.

During evening and nighttime hours the EE displaces in the region of diffuse aurora, equatorward of the discrete auroral forms, and projects along magnetic field lines into the inner magnetosphere

- 785 between the plasmasphere and the central plasma sheet of the magnetospheric tail (Galperin and Feldstein, 1996). Additional to this basic term, an appreciable contribution to the EE comes during daytime hours from the PRC, which is situated in the nearnoon sector of the equatorial magnetosphere close to the magnetopause. The WE comprises nighttime MLT from the morning to evening hours and is located in the central plasma sheet, projecting along the magnetic field lines into the
- 790 auroral oval. The generation of the WE takes place deep inside the plasma sheet, far from magnetic field lines that form the polar cap boundary at the nightside. The PE is controlled by the IMF By component and closely related to dayside reconnection processes, which cause the increase of open

magnetic flux in the polar cap.

6.1 Variations of the Hall currents during storms

- The characteristics and density intensity of Hall currents change in the course of geomagnetic storms. Their structure correspond basically to the well-known characteristics and dynamics of electrojets in MLat and MLT during magnetic storms. A splitting of the WE is possible in the morning hours during the recovery phase, analogous to the splitting of auroral luminescence in the auroral oval. These are additional, though indirect affirmations for the applicability to use magnetic field measurements at altitudes above the main ionospheric current layer for the determination of currents in the upper ionosphere.
  - Substorms occuring prior to or during the beginning of the main phase of a storm are accompanied by an EE at auroral latitudes (MLat ~64°) during daytime MLT hours. Later they appear as WE both in the afternoon (64° < MLat <70°) and during nighttime (MLat~64°).</li>
- With the development of the main phase both the daytime EE and the nighttime WE shift to subauroral latitudes MLat~56°, while increasing in density strength up to I ~1.5 A/m. Both electrojets exist during daytime and evening hours in the main storm phase. During evening hours, the WE is located by ~6° closer to the pole than the EE, and about 2°-3° during daytime hours.
- The current densities of EE and WE decrease quickly during the recovery phase, i.e., the electrojets vanish, but in the daytime sector at MLat~73°-80° appears a PE (polar electrojet) with a westward or an eastward direction, depending on the orientation of the IMF By component. The PE is eastward directed for By>0 and westward directed for By<0. Changes of current flow direction in the PE can occur manifold during the storm, but only due to changes of the IMF By orientation.</li>

#### 6.2 Hall current in the polar electrojet

While auroral electrojets are present at all local time hours, the PE is confined to daytime hours. Fig. 3a–f shows the results of the correlation analysis of the PE characteristics and the IMF By component as well as various activity indices. The values of the correlation coefficients r and the coefficients A and B of the regression equations are listed in Table 2. They relate the current density intensity and their MLat position to the indices that characterize the situation in the solar

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-The PE currents and their MLat positions are characterized by the following peculiarities:

- The PE appears at magnetic latitudes and local times of the cusp.-

wind and within the magnetosphere at the time of the observations.

- The direction of the current in the PE is controlled by the IMF By (azimuthal) component: for
   By>0 the current is eastward, for By<0 the current is westward directed.</li>
  - The current density strength in the PE increases with the intensity of the IMF By component from I~0.4 A/m for By~0 nT up to I~1.0 A/m for By~23 nT.
  - The MLat position of the PE does not depend on the orientation and the strength of the IMF By component.
    - Assuming that the penetration of the solar wind electric field into the cusp causes the generation of the PE, we estimate the efficiency of such a penetration. Based on two CHAMP orbits across the dayside sector of the high-latitude ionosphere, we estimate the potential difference over the cusp with 169 kV and 585 kV. The efficiency of the electric field penetration into the cusp would then amount to 25% and 9%, respectively.
    - There is no connection between MLat and the current density intensity *I* in the PE with the magnetospheric ring current DR (index SYM/H SymH).
    - There is a correlation between the current density intensity *I* in the PE and the density strength of the partial ring current in the magnetosphere (PRC, index ASYM/H AsyH), but practically no correlation of this index with MLat of the PE.
    - The currents in the central plasma sheet appear to have a weak influence on the current density intensity and the MLat position of the cusp.-
    - We realized a correlation between MLat and the IndN solar wind coupling function.
    - 6.3 Hall current in auroral electrojets
- Auroral electrojets are located at auroral latitudes (MLat<72° during daytime hours, and MLat<68° during nighttime) exist during all MLT. The amount of electrojet current in a certain latitude range, the structure of the currents in them, the interconnection with concrete magnetospheric domains, depends on the level of disturbance, which is controlled by UT as well as local time (MLT) at the observational points. Therefore we present the conclusions from the observations for each of the</li>
   850 four time sectors: daytime, evening, nighttime, and morning hours.
  - Daytime sector (09–14 MLT):
  - The MLat positions of the auroral electrojets, both WE and EE, correlate with the activity indices ASYM/H AsyH, AL, and IndN. The auroral electrojets shift toward lower latitudes with increasing activity. For ASYM/H AsyH ~220 nT the EE shifts to MLAT ~57°.
- MLat(EE) collocates 3.8° equatorward of MLat(WE) according to the ASYM/H AsyH index and 1.9° according to the IndN coupling function.

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- Significant correlation coefficients with r > 0.49 are obtained only for MLat, correlations with the current density intensity *I* are, however, very small for all indices.

Evening sector (14-21 MLT):

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- Significant values of the correlation coefficients r with activity indices exist both for MLat and for the Hall current density intensity I.
  - The largest correlation coefficients (r ~0.6–0.7) exist between the ASYM/H AsyH index and the current density intensity I(WE, EE).
  - The EE shifts  $\sim 6^{\circ}$  more equatorward compared to the WE.
- The EE and WE shift equatorward with increasing activity. This shift occurs with respect to all activity indices inspected here. The EE is located equatorward of MLat ~60° during magnetic storm periods; the farthest shift attains MLat ~53°.
  - The equatorward shift for increasing activity is accompanied by increasing current densities from I < 0.2 A/m for ASYM/H AsyH~40 nT to ~1.7 A/m in the EE and ~1.3 A/m in the WE
- 870 for ASYM/H AsyH~380 nT. The current density strength of the EE increases hence stronger than that of the WE (by about 30%).
  - The current density strength in the EE is larger than in the WE. The WE is missing for a certain confined MLT interval of the evening sector, in case of an existing EE (Feldstein et al., 2006).
     That means that the EE in the evening sector cannot be a low-latitude branch-off from the WE current.

Near-midnight sector (21-02 MLT):

- Around midnight, the WE is predominant.
- The current density strength in the WE correlates with the activity indices ASYM/H AsyH, AL, and IndN, with a maximum correlation coefficient of  $r \sim 0.76$  for the IndN.
- The MLat(WE) position correlates only with the SYM/H SymH index, shifting equatorward from 62° to 58° for a SYM/H SymH increase from -40 nT to -170 nT. The lowest possible MLat is ~58°.
  - The equatorward shift of the WE is acceptanied by an increase of the current density intensity from I < 0.2A/m to  $\sim 1.5$  A/m.

885 Morning sector (02–09 MLT):

The characteristics of the auroral electrojets is almost identical for midnight and morning hours.

- The MLat position at that MLT is controlled for the most part by the SYM/H SymH activity index, i.e., by the density strength of the ring current.

- In the morning sector, there exists almost exclusively the WE only.-
- 890 The current density intensity in the WE correlates with the ASYM/H AsyH and the AL indices with maximum values of r = 0.69 with respect to ASYM/H AsyH.
  - The current density strength increases from 0.5 A/m to 2.1 A/m for intensifications of ASYM/H AsyH from 40 nT to 200 nT.
  - With increasing activity, the WE shifts equatorward. The lowest observed MLat for the WE is  $\sim 58^{\circ}$ .

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The existing morphological differences between the EE and the WE probably testify differences of the physical sources, which are responsible for the existence of the EE and WE. One possible option is the interpretation of the EE in the evening and daytime sectors as continuation of the magnetospheric partial ring current (PRC) through the ionosphere via a system of FACs. The

900 WE, which is situated ~6° poleward of the EE in the evening sector, might be the ionospheric continuation of the WE in the evening hours, which is connected via FACs with the central plasma sheet in the magnetospheric tail in the nighttime and morning sectors.

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#### Appendix A Detailed description of the dynamics of further storm intervals

A1 The magnetic storm of 24 August 2005

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1010 This storm began with a sudden storm commencement (SSC) at 06:15 UT, which appeared as a jump-like increase of the SYM/H SymH index up to  $\sim$ 30 *nT*. The storm phases were identified according to the 1-min values of the SYM/H SymH index. Fig. A1.1 shows the magnetic activity indices SYM/H SymH, ASYM/H AsyH, AU, AL, and the IMF components By and Bz.

The orbits 29012 and 29013 take place during the ereation growth phase of the storm, the orbits

- 1015 29014 and 29015 during the main phase, and the orbits 29016–29020 during the recovery phase. The direction and density strength of the Hall currents along the orbits are shown in Fig.A1.2 during daytime hours on the left hand side corresponding to the ascending orbital sections, and on the right hand side during nighttime hours for descending orbital sections. The crossings of the auroral oval occurs between 12–13 MLT during daytime and 23–24 MLT for the nighttime column. Positive
- 1020 values denote an eastward current (EE) for the descending orbits, and a westward current (WE) for the ascending orbital sections.

The index values during the ereation growth phase of the storm are in the range of 25.5–32.7 nT for SYM/H SymH, 121.1–72.0 nT for ASYM/H AsyH, while the substorms achieve  $\sim$ -1000 nT according to the AL index. SYM/H SymH intensifies during the main phase up to -155.6 nT and ASYM/H AsyH to 206.6 nT, where intense substorms with AL  $\sim$ -3000 nT occur. ASYM/H AsyH

values decrease to 43.5 nT during the recovery phase, and we observe weakly variable SYM/H SymH index values around -120 nT (see Fig. A1.1).

An EE exists during daytime hours of orbit 29012 with a current density intensity of up to 1.37 A/m at MLat  $72.6^{\circ}$ . During the subsequent orbit, the eastward current density dimin-

- 1030 ishes to 0.44 A/m at MLat 70.3°. The intensification of SYM/H SymH during the main storm phase (orbit 29015) is accompanied by a continuing decrease of the eastward Hall current to 0.38 A/m at MLat=65.4°. An EE with a density strength of ~0.7 A/m around midday is recorded at Mlat=57.3°, i.e., below 60°, only in connection with very intense substorms (Fig. A1.1, orbit 29014). Eastward currents at such low latitudes are missing during the other orbits of this storm period. The variations
- 1035 of the ASYM/H AsyH index reflect quite clearly the variations of the Hall current density intensity: it attenuates from the orbits 29012 to 29013, and increases during orbit 29014, while it decreases again during orbit 29015.

A westward current on the daytime occurs at MLat 72°-80°, beginning with orbit 29015 and continuing until orbit 29020, i.e., throughout the recovery phase and in the absence of intense substorms.

1040 The currents achieve a maximum density strength of I=1.53 A/m during orbit 29018 at MLat 76.3°. This current is controlled by IMF By>0 and changes its direction with the IMF By orientation. It is therefore definitively a PE.

The currents in the midnight sector (Fig. A1.2, right column) are generally westward directed with

weak density intensity. The only exception occurs during orbit 29014, where the current density

- 1045 intensity achieves I $\sim$ 1.2 A/m. This orbit coincides with the development of a very intense substorm, where the Hall current distribution is very broad with two maxima of the current density intensity at MLat 61.2° and 73.0°. Such a broad latitudinal distribution of the auroral luminescence, with various maxima at different latitudes, is characteristic for the recovery phase of an auroral substorm (Elphinstone et al., 1996). But for the present storm of 24 August 2005, the broad splitting up in
- 1050 latitude appeared in the Hall currents during the main phase of the storm.

Summarizing the results of Hall current observations by the CHAMP satellite during the magnetic disturbance period of 24 August 2005 in the daytime and nighttime sectors (11–13 MLT and 23–24 MLT, respectively) we conclude:

For the midday sector:

- An EE with a current density strength of 1.37 A/m exist during the creation growth phase at MLat~73.0° for substorms in the auroral zone with intensities of AL~-1000 nT.
  - The EE is observed at MLat<60° during the main storm phase for intense substorms with intensities of AL $\sim$ -3000 nT.
  - The variations of the EE intensities during the ereation growth and main phases of the storm occur synchronous with the ASYM/H AsyH index. Comparable variations with the SYM/H SymH index are not observed.
    - Westward or eastward directed currents are observed during the recovery phase at 72°<MLAT<80° with a maximum density intensity of ~0.9 A/m. Their direction is controlled by the IMF By component, i.e., they are in accordance with the PE.</li>
- 1065 For the midnight sector:

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- As a rule, the Hall currents are westward directed during nighttime. In the concrete observations, the WE can be splitted into several parts with several maxima versus latitude.
- A2 The magnetic storm of 18 June 2003
- Fig. A2.1 shows the variations of the SYM/H SymH and ASYM/H AsyH indices for the magnetic
  1070 storm of June 18th, 2003. The storm phases are represented by the orbit numbers 16532 and 16533
  for the ereation growth phase, 16534–16536 for the main phase, and 16537–16541 for the recovery phase. Extreme values of SYM/H SymH and ASYM/H AsyH are observed during the main phase with -163 nT and 91 nT, respectively, while the substorm index AL achieves -1298 nT. The CHAMP trajectories are situated during this storm period along the meridional plane of 13–14 MLT
- 1075 (afternoon) and 00–02 MLT (near midnight). In the daytime sector, a EE exist during the ereation growth phase at MLat  $\sim$ 67° with I $\sim$ 0.43 A/m, and a WE at MLat  $\sim$ 72° with I $\sim$ 0.42 A/m. Both electrojets are retained during the main storm phase with an EE of I $\sim$ 0.8 A/m at MLat  $\sim$ 62° and a

WE of I $\sim$ 0.5 A/m at MLat  $\sim$ 67°. The WE only persists during the recovery phase with I $\sim$ 0.3 A/m at MLat  $\sim$ 78°(orbits 16537 and 16538) This high-latitude westward current near MLat  $\sim$ 77° with

1080 I~0.4 A/m does not vanish till the end of the recovery phase. Such a high-latitude position of a westward current near noontime MLT gives reason to suggest that this is a polar electrojet (PE). This assumption would apply, if the IMF By component is negative. Indeed, the By component appeared to be at a steady neagative value during the orbits 16537–16541.

As a rule, the ionospheric currents in the nighttime sector are westward directed in the MLat range 1085 of 57.8°-63.0° with I~0.5 A/m. Only during two orbits in the <del>creation</del> growth and main phases, the current <del>density</del> strength achieved I~(1.1–1.4) A/m.

It should be noted that this storm had relatively intense SYM/H SymH values, while the ASYM/H AsyH values remained however at a relatively low level. The EE and WE intensities were small as well.

- 1090 Summarizing the results of Hall current observations by the CHAMP satellite during the magnetic disturbance period of 18 June 2003 in the daytime and nighttime sectors (13–14 MLT and 00– 02 MLT, respectively) we conclude:
  - The quite strong geomagnetic storm (according to the SYM/H SymH<-150 nT index value during the main phase) is accompanied by substorms with AL up to -1500 nT and with the lower uppermost index value for the asymmetry of the field ASYM/H AsyH<-100 nT. The</li>
  - peculiarities of this storm period caused obviously the appearance of an EE in the daytime sector and a WE in the nighttime sector at MLat $< 60^{\circ}$ .
    - A stable PE with a current density intensity up to 0.4 A/m in westward direction persists during the recovery phase with an IMF By<0 nT component.</li>

1100 A3 The magnetic storm of 30 May 2005

1095

Fig. A3.1 shows the variations of the SYM/H SymH, ASYM/H AsyH, AU, and AL indices for the magnetic storm of May 30, 2005, between 02 UT and 20 UT. The vertical dotted lines indicate the time intervals of the satellite crossings over high latitudes of the Northern Hemisphere (MLat> $60^{\circ}$ ), and the numbers denote the satellite's orbit counter. Prior to the storm onset (orbits 27659 and

1105 27660), the geomagnetic field is according to all indices, including the AL index, relatively quiet. It is recovered from -28.6 nT to -17.3 nT in terms of SYM/H SymH, from -38 nT to -18 nT 37.8 nT to 17.8 nT for ASYM/H AsyH, and from -40 nT to 0 nT with respect to the AL index. These changes correspond to a recovery process toward a quiet time level after the previous disturbance.

The main phase of the magnetic storm starts with a steady increase of SYM/H SymH from -29
1110 -28.6 nT during orbit 27661, a jump-like increase from 44.5 nT to 104.2 nT in ASYM/H AsyH during the same overflight and continues with an in decrease of SYM/H SymH to -118.4 nT during orbit 27665. The peak values of ASYM/H AsyH and AL during the main storm phase are 162.1 nT

and -1200 nT, respectively. The recovery phase takes place during the orbits 27666 and 27667, after which during the orbit 27668 the appearance of a new disturbance is recorded (according to the AL

- 1115 and SYM/H SymH indices). The ascending CHAMP trajectory during the storm goes along the 19– 21 MLT meridian (evening), while the descending orbit section is along the 06–09 MLT meridian in the morning sector. Fig. A3.2 shows the direction and the density strength of the Hall currents for the evening (left side) and morning (right side) sectors.
- During the orbits prior to the beginning of the main phase, the Hall current is either missing in the 1120 evening sector or exists only in terms of a distributed eastward current with maximum densities of J~0.3 A/m at MLat~66°. In the morning sector, a WE is recorded with J~0.9 A/m at MLat~80° and MLT~09 hours. The existence of such intense currents during daytime hours at such high latitudes during relatively quiet geomagnetic conditions is unusual. A reasonable explanation might be the assumption that this current concerns the PE. In this case, the orbits investigated should occur during
- 1125 conditions of IMF By<0 nT. Indeed, according to Fig. A3.1 a quite stable negative IMF By~-18 nT is observerd prior to the main storm phase The beginning of the main phase (orbit 27661) is characterized by the appearance of two currents in the evening sector: the EE with J~0.6 A/m at MLat~63° and the WE with J~0.3 A/m at MLat~68°. In the course of the storm, the EE attains a density strength of J~0.7 A/m, shifting equatorward until MLat~80°. The displacement in MLat</p>
- 1130 toward the equator reflects the more general tendency, according to which the the electrojets move more equatorward with increasing current J. The current density intensity in the WE retains at J~0.4 A/m. In the morning sector, the current stays at MLat~70°, and its current density strength during orbit 27661 is kept at J~0.4 A/m. This is obviously the first appearance of an auroral WE in the morning sector. The WE at auroral latitudes increases during the subsequent orbits and attains
- 1135 1.5 A/m during orbit 27665 at MLat~ $64^{\circ}$ . The recovery phase during orbit 27667 is characterized by a westward current with J~-1.0 A/m in the morning sector at MLat~ $68^{\circ}$  and a weaker current with J~0.3 A/m at MLat~ $63^{\circ}$ ,. In the course of the storm, the current density intensity J in the morning sector exceeds significantly the Hall current density intensity values of the same orbit in the evening sector.
- 1140 Summarizing the results of Hall current observations by the CHAMP satellite during the magnetic disturbance period of 30 May 2005 in the dusk and dawn sectors (19–21 MLT and 06–09 MLT, respectively) we conclude:
  - Two auroral Hall currents (EE and WE) exist in the evening, and one current only (WE) in the morning sector;
- The currents are positioned, as a rule, at latitudes MLat of the auroral zone (63°-68°). During the main phase, the current can be shifted to MLat~58.5°;
  - In the evening sector, the position of the EE is more equatorward than the WE;
  - During early evening hours, the Hall current density strength of the EE exceeds the WE current

density intensity, and in the morning hours the WE current density intensity is larger than during the evening;

 The recovery process toward the quiet-time level can be accompanied at by late evening or polar electrojet (PE) at MLat~80° in the late morning hours of the PE with J~0.8 A/m.

A4 The magnetic storm of 15 May 2005

1150

Fig. A4.1 shows the variations of the SYM/H SymH, ASYM/H AsyH, and IndN indices, as well as
the IMF By and Bz components and the solar wind velocity in the interval 00–23 UT for the magnetic storm of May 15, 2005. The main phase of the magnetic storm takes place during the orbits 27426 and 27427 with a SYM/H SymH index value of ~-274 -274.5 nT, an ASYM/H AsyH of ~186.1 nT, and AL sim-1700 nT. The orbits 27423 and 27424 prior to the main phase occur during weakly disturbed magnetic field conditions with SYM/H SymH ~50 nT and ASYM/H AsyH ~75–16 nT.

- 1160 During orbit 27425 with SYM/H SymH ~48.8 nT, the ASYM/H AsyH index increases strongly to ~121.3 nT, which appears to be the onset of an intense magnetic storm. The recovery phase takes place during the orbits 27428 and 27432, during which occurs a steady decrease of the SYM/H SymH index to ~125.2 nT and of the ASYM/H AsyH index value to ~70.1 nT. The ascending CHAMP trajectory during the storm spread along the 20–22 MLT meridian, and the descending
- 1165 trajectory is along the 08–10 MLT meridian in the morning sector. Fig. A4.2 shows the direction and the density strength of the Hall currents for the evening (left side) and morning (right side) sectors.

The current density strength for the EE during orbit 27425 is with ~0.4 A/m quite small in the evening sector prior to the main phase. Both an EE and a WE exist during the main phase with
1170 J~0.6 A/m. The EE shifts on average to a MLat of ~52.5° with SYM/H SymH ~-250 nT. The Hall currents are practically absent during the recovery phase.

In the evening sector, the currents turn out to have difficult characteristics, changing with the storm phases. A WE at MLat $\sim$ 72° with J $\sim$ 1.0 A/m is recorded during the magnetically quiet period prior to the main phase. With the development of the main phase, the WE shifts to MLat $\sim$ 61°. During

- 1175 the recovery phase, the WE decays at auroral latitudes, but in the latitudinal range  $77^{\circ} < Mlat < 80^{\circ}$ an EE appears with J~1.0 A/m (orbits 27428–27431). The orbits with an EE coincide temporally with an interval of IMF By>0 nT in the solar wind (Fig. A4.1). All characteristic features of the PE are therefore present here. During orbit 27433, the direction of the current changes to WE. This is accompanied by a corresponding change of the IMF By orientation as can be seen in Fig. A4.1.
- 1180 The characteristic features of this storm are the following:
  - The quiet-time level of the magnetic field variations prior to the storm main phase can be describes as missing or unimportant intensities of the EE and WE Hall currents in the evening sector, while in the morning sector exists only the WE at auroral latitudes.

- During the main phase of this intense storm with a SYM/H SymH index of  $\sim$ -250 nT in the
- 1185
- evening sector, the WE shifts to MLat $\sim$ 52.5°, and the WE to MLat $\sim$ 54.0°.
  - A PE appears during the recovery phase in the late morning hours at 77°<Mlat<80°, where the Hall currents are controlled by the direction of the IMF By component.
- A5 The magnetic storm of 18 August 2003
- Fig. A5.1 shows the variations of the SYM/H SymH, ASYM/H AsyH, AU, and AL indices, as well
  as the IMF By and Bz components in the interval 00–23 UT for the magnetic storm of August 18, 2003. The main phase of the magnetic storm takes place during the orbits 17482–17489 with peak values of SYM/H SymH and ASYM/H AsyH of ~-1353.8 nT and ~101.4 nT, respectively, and an AL value of sim-1400 nT. During the orbits 17480 and 17481 prior to the main phase the values of SYM/H SymH and ASYM/H AsyH are ~-18.4 nT to -43.3 nT and ~72.0–498.8 nT,
- 1195 and during the recovery phase in the course of orbits 17490–17493 they amount to  $\sim$ -115.4 nT and  $\sim$ 56.7 nT, respectively. The CHAMP trajectories during the storm spread along the 07–09 MLT meridian (morning) and along the 19–21 MLT meridian(evening). Fig. A5.2 shows the direction and the density strength of the Hall currents for the morning (left side) and evening (right side) sectors.

The characteristic peculiarities of the spatial-temporal distribution of the FACs during this storm 1200 concur with those described for the other storms. During the main phase in the evening sector, there

exists, as a rule, an EE. The EE appears at MLat~ $66.5^{\circ}$  with J~0.6 A/m, and shifts then equatorward to MLat~ $58.8^{\circ}$  with J~1.0 A/m during orbit 17486. A WE exists in the morning sector at auroral latitudes of  $61^{\circ}$ <Mlat< $65^{\circ}$  with J~1.2 A/m. A weak distributed eastward current in the polar cap persists due to the closure of parts of the electrojets across the near-polar region.



Fig. 3. Dependence of the magnetic latitude MLat (degrees) position of the peak (left column) and its density intensity (I in A/m, right column) of the Hall current in the polar electrojet (PE) on the IMF By component (a) and its magnitude (b), on the geomagnetic activity indices SYM/H SymH (c), ASYM/H AsyH (d), AL (e), and the solar wind coupling function IndN (f). The blue and red data points indicate westward and eastward currents, respectively. For the cases of correlations with r > 0.46, the correlation coefficients (r) and the dispersion ( $\sigma$ ) according to a linear regression are shown as labels.



**Fig. 4.** Daytime sector (09–14 MLT): Dependence of the magnetic latitude MLat (degrees) position of the peak (left column) and of the density intensity (*I* in A/m, right column) of Hall current in the WE (blue) and EE (red) on the geomagnetic activity indices SYM/H SymH (a), ASYM/H AsyH (b), AL (c), and the solar wind coupling function IndN (d). For the cases of correlations with r > 0.46, the correlation coefficients (*r*) and the dispersion ( $\sigma$ ) according to a linear regression are shown as labels.



Fig. 5. The same as in Fig. 4, but for the evening sector (14–21 MLT).



Fig. 6. The same as in Fig. 4, but for the midnight sector (21–02 MLT).



Fig. 7. The same as in Fig. 4, but for the morning sector (02–09 MLT).



**Fig. A1.1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the By and Bz components of the IMF for the storm of 24 Aug 2005 (analysis interval from 07:00–20:00 UT, orbits 29012–29020). The time of each orbit and its orbit number are indicated as in Fig. 1 of the paper.



**Fig. A1.2.** Direction and density intensity values of the Hall current along the satellite orbit at the dayside (left column, 11–13 MLT, corresponding to the ascending section of the orbit) and nightside sectors (right column, 23–24 MLT, descending orbit section). Positive currents denotes eastward current for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.



**Fig. A2.1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the By and Bz components of the IMF for the storm of 18 June 2003 (analysed interval from 03:00–18:00 UT, orbits 16532–16541). The time of each orbit and its orbit number are indicated as in Fig. 1 of the paper.



**Fig. A2.2.** Direction and density intensity values of the Hall current along the satellite orbit at the dayside (left column, 12–16 MLT, corresponding to the ascending section of the orbit) and nightside sectors (right column, 00–04 MLT, descending orbit section). Positive currents denotes eastward current for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.



**Fig. A3.1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the By and Bz components of the IMF for the storm of 30 May 2005 (analysis interval 02:00–17:00 UT, orbits 27658–27667). The time of each orbit and its orbit number are indicated as in Fig. 1 of the paper.



**Fig. A3.2.** Direction and density intensity values of the Hall current along the satellite orbit at the duskside (left column, 19–21 MLT, corresponding to the ascending section of the orbit) and dawnside sectors (right column, 06–09 MLT, descending orbit section). Positive currents denote an eastward current flow for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.



**Fig. A4.1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the By and Bz components of the IMF for the storm of 15 May 2005 (analysis interval 002:00–19:00 UT, orbits 27423–274323). The time of each orbit and its orbit number are indicated as in Fig. 1 of the paper.



**Fig. A4.2.** Direction and density intensity values of the Hall current along the satellite orbit at the duskside (left column, 20–22 MLT, corresponding to the ascending section of the orbit) and dawnside sectors (right column, 08–10 MLT, descending orbit section). Positive currents denote an eastward current flow for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.



**Fig. A5.1.** One-minute values of the ASYM/H AsyH, SYM/H SymH, AU, and AL indices and of the By and Bz components of the IMF for the storm of 18 Aug 2003 (analysis interval 00:00–23:00 UT, orbits 17480–17494). The time of each orbit and its orbit number are indicated as in Fig. 1 of the paper.



**Fig. A5.2.** Direction and density intensity values of the Hall current along the satellite orbit at the dawnside (left column, 07–09 MLT, corresponding to the ascending section of the orbit) and duskside sectors (right column, 19–21 MLT, descending orbit section). Positive currents denote an eastward current flow for the descending orbit section, and, accordingly, westward current for the ascending section, respectively.