Response to the Referee' comments

I thank the reviewers for valuable comments and constructive critique. All comments were carefully considered and addressed. Answers to all the questions are presented below. Corresponding changes have been made in the revised manuscript (marked in cyan). New Figure 6 has been added. Comments and replies are shown in smaller and larger letters, respectively.

1#Referee

This paper considers the evolution of the large-scale FAC morphology during the magnetic storm of September 2017, and relationship between large-scale and small-scale FACs, using observations from Swarm. The author has done a satisfactory job of addressing comments from the previous reviewers, and the manuscript is more focussed and readable as a consequence. I consider the paper to be suitable for publication, subject to the minor comments below.

Response to the 1#Referee comments

1) Clausen et al. (2013) not included in the reference list. The reference list is not in alphabetical order.

Included. The reference list has been ordered.

2) Section 1: A key aspect of the paper is the latitude of the FACs as controlled by magnetic reconnection at the magnetopause and in the magnetotail. Although the Dungey cycle is mentioned, it might be appropriate to include a reference to the time-dependent expanding/contracting polar cap model, e.g. Cowley and Lockwood (Ann. Geophys., 1992).

The recommended reference has been included.

3) p 10, l 15: oscillation misspelt

Corrected

4) Section 4.1 and Fig. 4: There are subtle differences in the FAC variations in the NH and SH which do not seem to be commented on in the paper. For instance, the NH FACs seem to be marginally less variable than the SH FACs. The period in question is close to equinox, so ionospheric conductance effects are not expected to play a role. Does the author have any suggestion why this interhemispheric asymmetry manifests itself?

In my view, based on the FACs presented in Fig. 4 it is difficult to make an unambiguous conclusion on the interhemispheric difference in the FAC variations. The greater variability in the SH FACs compared to the NH FACs is not sufficiently evident neither from the average current densities nor from the error bars. Quantitatively (see the figure below), for all local times the errors summed over the NH and SH, are of the same value (the upper plot). There is a systematic difference between the upper and lower satellites (the lower plot) in such a way that the SwB exhibits slightly larger variability.

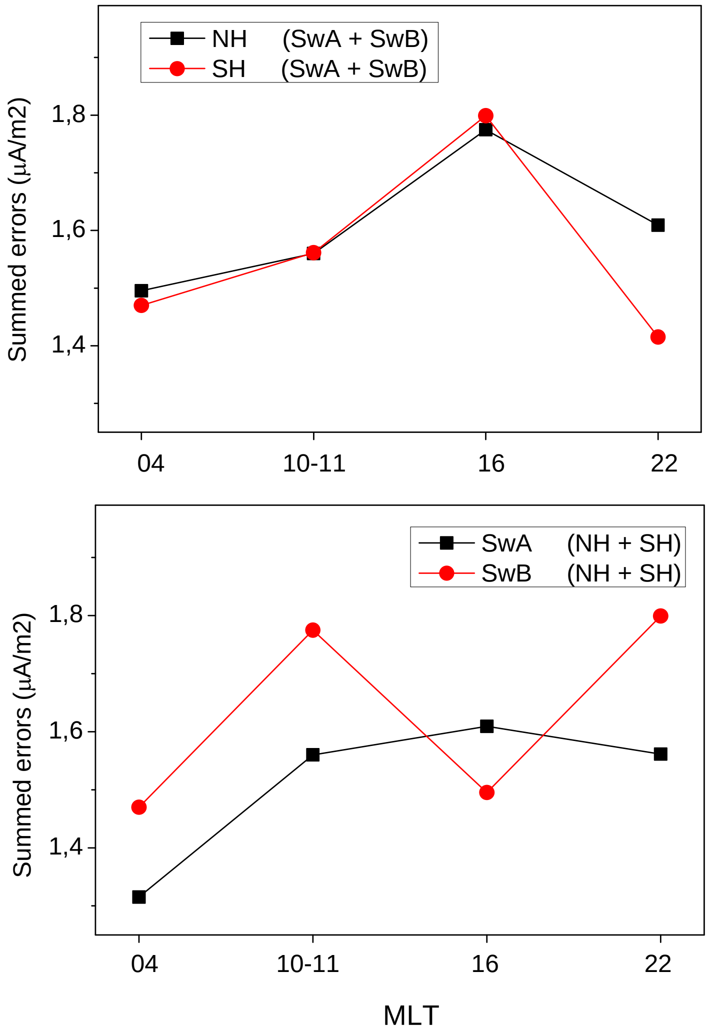


Figure. Upper plot: the errors summed over the NH and SH. Lower plot: the sums of errors for SwA and SwB.

5) Section 4.3: There has been some previous work on the latitude of the auroras (and hence FACs) in relation to ring current intensity, e.g. Milan et al. (Ann. Geophys., 2009) and Milan (GRL, 2009), showing that the oval expands to low latitudes during storms, and even for moderate Sym-H levels is expanded lower than quiet times. It would be appropriate to cite these papers, and to discuss in relation to the current observations.

The following additions have been made (p. 25, ll. 8-16):
"High FAC intensity is associated with the auroral oval. Previous studies based on particle precipitation and optical observations have shown that the oval radius increases when the ring current is intensified during magnetic storms (e.g., Meng, 1982; Yokoyama et al., 1998). Significant variations in the location of the aurora take place during the substorm cycle. Substorms occurring on expanded auroral ovals during magnetic storms are most intense, since they close the most magnetospheric open magnetic flux and the presence of the enhanced ring current increases the open flux threshold

at which substorm onset is favoured (Milan, 2009). It was also shown that changes in oval radius associated with dayside and substorm driving occur on timescales of minutes and hours, while changes associated with the ring current are more protracted as the ring current dissipates slowly (Milan et al., 2009)."

Yokoyama, N., Kamide, Y., and Miyaoka, H.: The size of the auroral belt during magnetic storms, Ann. Geophys., 16, 566–573, 1998, www.ann-geophys.net/16/566/1998/.

Meng, C.-I.: Dynamic variation of the auroral oval during intense magnetic storms, J. Geophys. Res., 89, 227–235, 1984.

Milan, S. E.: Both solar wind-magnetosphere coupling and ring current intensity control of the size of the auroral oval, Geophys. Res. Lett., 36, L18101, doi:10.1029/2009GL039997, 2009.

Milan, S.E., Hutchinson, J., Boakes, P.D., and Hubert, B.:Influences on the radius of the auroral oval Ann. Geophys., 27, 2913–2924, www.ann-geophys.net/27/2913/2009/, 2009.

2#Referee

General comment: In this paper, the author conducted comprehensive investigations on the evolution of the fieldaligned currents (FACs) at different scales during a recent intense geomagnetic storm by using the Swarm level-2 FAC products. However, some conclusions obtained in this study are not well supported by figures presented in the paper and some conclusions are degraded by the data quality, data coverage and methodology used in this study. In addition, some conclusions do not convey any new ideas. Therefore, this paper may have not reach substantial conclusions that suitable for publication. Meanwhile, conceptual and grammatical mistakes are frequently shown in the manuscript. A major revision is needed before the next submission.

Response to the 2#Referee comments

Major Comments:

Comments for the Conclusion #1:

1) "The FACs become enhanced starting from the SW shock arrival despite of the prolonged period of the northward IMF. The night-time FAC densities primarily follow the substorm development while the dayside FACs are intensified in response to the SW shock and then stay enhanced. At the peak of substorm, the FAC densities averaged over a track within a given MLT sector, reach 3 μA/m2, while the undisturbed level is about 0.2 μA/m2."

a) It seems that this sentence is concluded from Figure 4, in which the evolutions of the average upward/downward FACs at four different MLT sectors and at both hemispheres are shown. Indeed, the average values increase after the significant drop of the SYM-H. However, the standard deviations are extremely large in comparison with the averages. If the standard deviations are taken into account, one can say that the FACs do not necessarily increase during the storm.

Yes, this conclusion is based on Fig. 4, which does show the storm time increase of FACs. The increase of standard deviations indicates as the larger variability and as the larger magnitude of the 1 s values. In Fig. 4 each red (blue) point is determined by averaging the 1-s downward (upward) current densities, when the satellite crosses the region filled with FACs (about 500 1-second measurements per crossing). Thus the increase of the error bar indicates that a satellite flying over the particular FAC region measures (at least during one second) the large-amplitude FAC. The smaller error bar indicates that the 1-Hz FACs are approximately of the same amplitude.

b) Meanwhile, Figure 4 does not evidently indicate that "the night-time FAC densities primarily follow the substorm development", since the FAC intensity increases when both SYM-H and AL indices decrease and the FAC intensity decreases when both SYMH and AL indices increase on the night side. Therefore, the night-side FAC evolutions may be modulated by both the geomagnetic storm and substorm. The data shown in Figure 4 cannot rule out the important role that the geomagnetic storm plays in the modulation of the evolution of the night-time FAC.

Yes, the night-side FAC evolutions are modulated by both the storm and substorm. The conclusion on "the night-time FAC densities primarily follow the substorm development" is based on the comparison between the dayside and nightside FACs. Even visual examination of Figure 4 shows that the dayside FACs are much less compared with the evolution of AL index and less affected by substorms. The conclusion #1 stays unchanged.

2) “The dawn–dusk asymmetry is manifested on the enhanced dusk side downward (R2) FAC on both hemispheres.”

a) Although Table 2 shows the responses of FACs in certain MLT sectors on the dawn side are different those in certain MLT sectors on the dusk side, it cannot be concluded as “dawn-dusk asymmetry” since the results based on Table 2 are MLT biased. Perhaps it might be different in other MLT sectors. To better study the dawn-dusk asymmetry, data with better MLT coverage, such as AMPERE data, are useful. Without using data with reasonable MLT coverage, the statement associated with the dawn-dusk asymmetry may be problematic and needed to be removed.

As mentioned in the last para of section 5.1, the AMPERE data provide more global and reliable estimate. However, it is curious that an indication of the dawn-dusk asymmetry can be inferred even from the instantaneous observations made by Swarm. However, because the estimate based on the Swarm data is approximate and indeed may suffer of the MLT bias, the statement on the dawn-dusk asymmetry has been removed from the Conclusion 2.

b) It seems that the results in Table 2 are calculated by using 1 Hz FAC data. If so, the upward/downward FACs do not necessary mean R2/R1 (R1/R2) FACs on dawn (dusk) side. Typically, R1/R2 FACs represent large-scale FACs.

Yes, the results in Table 2 are calculated by using 1 Hz FAC data and their averages are not necessary a representation of the large-scale R2/R1 FACs. The corresponding comment has been added to the last para of Section 5.1 (“Although the *Swarm* observations unable to provide the instantaneous global FAC distribution, the responses of FACs in certain MLT sectors on the dawn side are different from those on the dusk side. Note that the results in Table 2 are calculated by using the 1 Hz FAC values and their averages do not necessary represent the large-scale R1/R2 FACs. Nevertheless, for the storm of September 2017, the dawn–dusk asymmetry is manifested in the enhanced average density of the downward FACs on the dusk side. This feature is consistent with the global observations by AMPERE, from which the asymmetry of large-scale FACs can be identified.”).

Comments for the Conclusion #2:

“The equatorward displacement of FAC sheets (in the north and south and at all MLTs) correlates with the storm intensity as monitored by the SYM-H index. The minimum latitude of the equatorial FAC boundaries is limited to 50° MLat. Displacement of FAC sheets is more gradual and occurs with a considerable time delay compared to the changes in current intensity.”

a) The first sentence is not a new idea since it has been well studied in previous studies. For example, Wang et al. (2006) stated that “The response of the equatorward FACs is found to roughly correlate with the IMF Bz, Dst Em and ε”. Since the SYM-H index is the high-resolution version of Dst index, the first sentence does not bring anything new to the community. In addition, since only four MLT sectors have been studied in each hemispheres and they do not cover all MLTs, the content in the parenthesis is not precise enough and may need to be removed.

The Conclusion #2 has been modified in order to emphasize the role of substorms in the SYMH-EqB relationship. A new figure illustrating this relationship has been added. The correlation coefficients for the main and recovery phases are very similar (cc=0.88 and 0.87), while the corresponding regression equations are considerably different. During the storm main phase, the equatorward expansion of EqB is described by the equation MLat=63.1+0.1·SYMH, while during the recovery phase the poleward shift of EqB is described by the expression MLat=79.5+0.3·SYMH. The fast recovery of EqB is mainly due to the fast decrease in substorm activity on September 9. This result is not similar to what was found by Wang et al. (2006), because these authors did not consider the role of substorm activity.

The words "at all MLTs" have been removed to avoid ambiguity. Note, however, that in the previous version "all MLTs" implied the MLTs covered by the orbits.

b) The second sentence also brings nothing new and is not precise enough. For example, after 12 UT on September 8, the equatorward boundary reached <50° MLAT, therefore the statement that "the equatorial FAC boundaries is limited to 50° MLAT" is not precise. In addition, Fujii et al. (1992) stated that "The equatorward boundary of the FAC system reached as low as 48° MLAT" although a different storm was studied in their paper. But no new message has been conveyed by the second sentence.

Here, a notable feature is that for the September 2017 storm the Dst was about -100 nT, while for the events studied previously the Dst was much lower (-400/-600 nT). Despite the large difference in Dst, for all storms the minimum of the equatorward boundary is found at approximately the same latitude, not lower than 48 - 50° MLat. For clarification, the second sentence of conclusion #2 has been replaced by the following: "The correlation coefficients for the main and recovery phases are about 0.9, while in the course of the main phase the rate of equatorward expansion of FACs is slower than their poleward displacement during the recovery phase. This is likely due to the relatively fast decrease in substorm activity. The minimum latitude of the equatorward FAC boundaries is limited to 49-50° MLat. Although the storm of September 2017 is relatively weak (Dst is about -100 nT), the FAC region expands approximately to the same latitudes as those observed for the much severe storms."

c) For the third sentence: a. What do you mean by time delay? Delay with what? Did you show it in any figure and provide any quantitative description in the context?

Because, indeed, no quantitative estimate of time delay is presented, the sentence has been eliminated.

d) To study the displacement of the equatorward boundary of FAC you have utilized the 21-s averaged FAC, but to generate Figure 4, I suspect that you have utilized 1-s original data given the very large error bars, so you may not compare the same thing. If you want to substantiate your statement, you may need to use FACs on the same scale (e.g., 150 km or larger scales)

The 1-s data, without any averaging, were used to generate Figure 4 and Figure 5. To determine the lowest MLat at which FACs were terminated, the 20-point sliding window (but not the 20-point averaging) were applied to the 1 s FAC values in order.

Comments for the Conclusion #3:

"The filamentary structures of high-density FACs are always presented in the Swarm observations. A bipolar structure (i.e. the adjacent upward and downward small-scale FACs), ~80 μA/m2, 7.5 km width, is observed in the vicinity of the newly developed westward electrojet just prior the substorm onset. Simultaneous plasma perturbations indicate that the FAC pattern is likely associated with mesoscale auroral arc."

a) Although high-frequency FAC data can be used, cautions are needed when using the high-frequency FAC data. Because the assumptions used to derive the single-satellite FAC data may break down at small scales. Did you apply any data quality control technique for your small-scale FAC data? How? Since you have focused on those very isolated structures, the reliability of data is extremely crucial. Otherwise, your results may be degraded by using unreliable data.

No special data quality control technique for the small-scale FAC data has been applied. The original FAC data from the Swarm data base, as it is, were used. However, the magnetic East and North components were checked. The B-E (and the B-N, to the less degree) shows considerable perturbations which can be interpreted as a signature of FACs. In addition, all storm times during the Swarm operational period were checked. During each storm, the high-amplitude 1-second FACs, similar to those shown in Fig. 10, are presented. During the non-storm periods, no such peaks are observed.

b) The connection between the "bipolar structure" and "enhancement of the electron density" is not obvious. After a careful inspection, it seems that the strong upward portion of the bipolar structure actually corresponds to the depletion of the electron density (Figure 9), and does not correspond to the enhancement of the electron density.

A higher frequency (> 1 Hz) is desirable to determine unambiguously the small-scale FACs. The figure below explains how the 1-second time shift between FACs and the depletion of Ne may originate. The magnetic eastward component shows a positive spike at 00:10:18 (upper plot), from which the automatic procedure calculates the consecutive upward and downward FAC with the time stamp of 00:10:18 and 00:10:19, respectively (middle plot). In this case the current density is calculated as

FAC(i)=(B(i+1)-B(i))/dx. (1)

The depletion of Ne has the time stamp of 00:10:19 and thus, indeed, it turns out that the upward portion of the bipolar structure coincides with a drop in Ne (lower plot). However, the FAC can be also calculated as

FAC(i+1)=(B(i+1)-B(i))/dx. (2)

Formulas (1) and (2) are equally correct. In case (2) the time stamps for the upward and downward currents are 00:10:19 and 00:10:20, and the downward FAC that corresponds to the Ne depletion.

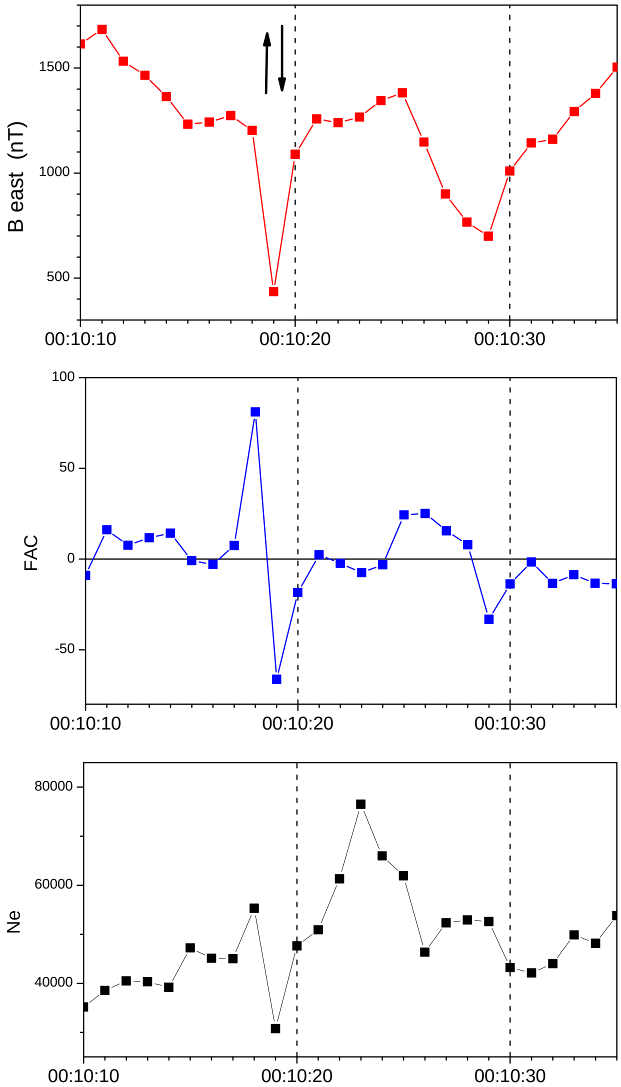


Figure. The original 1 s values of the eastward magnetic component, FAC density and electron concentration at 00:10:10-00:10:35.

Minor Comments:

1) Abstract:
Evolutions→a. Page 1, Line 8: Evolution

Corrected

b. Page 1, Line 15: “a substantial fraction of R1/R2 FACs is composed of many small-scale currents”: May need to be altered, since theR1/R2 FACs are referred to the large-scale currents, which are not necessarily related to the small-scale currents.

“R1/R2 FACs” has been eliminated.

2) Introduction:

high-latitude→Page 1, Line 29: high latitude

Corrected.

Page 1, Lines 32: Please add some references to support the statement. Also add "the" at the beginning.

Added (p. 1. L. 33).

Page 2, Line 5: Since the connections between the auroral oval and FACs are still unclear, perhaps you can simplify the sentence to "The large-scale FAC consists of Region 1(R1) and Region 2 (R2) currents …"

Slightly rephrased (p. 2. L. 8).

Page 2, Line 8: Add "currents/FACs" after "R1/R2" and "R1" and keep it consistent below.

Added (p. 2. L. 10).

Page 2, Line 19: Please define the spatial scale sizes of "large scale" and "small scale".

The large scale is defined as those >150 km (p. 2. L. 21).

"counterparts"→f. Page 2, Line 30: Add some references to support your statement.

The appropriate reference is (Clausen et al. 2013).

Page 3, Line 4: "counterpart"
Page 3, Line 11: Rephrase the sentence starting at Line 11.
"as compared to the"; What do you mean by "stationary"?

"stationary" has been replaced with "non-storm".

Page 3, Line 14: "extreme values are often reached" is not precise.

Removed

Page 3, Line 13: "compared to" "have focused"
Page 3, Line 15: "focus"
Page 3, Line 16: Please add "For example," before "Utilizing"
Page 3, Lines 25~28: Please rephrase the corresponding statements.
"orbits"

Corresponding corrections have been made.

3) Section 2:

Page 4, Line 11: "orbit"

Corrected.

Page 4, Line 15: What is the speed of the Swarm satellites?

Added.

Page 4, Third paragraph: Please simplify this paragraph and only provide the most important information related to the FAC data used in this study.

The description of the one- and two-satellite techniques has been included after the comment of one the previous referee.

Page 6: Where is the Figure 1b? Also please add one plot showing the orbital coverage at southern hemisphere.

The plot showing the orbital coverage at southern hemisphere has been added to Figure 1.

4) Section 3:
Please check the verb tense (Also in other sections).

Corrected.

Page 7, Line 16: Add the UT to indicate when the IMF Bz turned northward.

Added (p.7, L 16).

5) Section 4.1:

a. Page 9, Lines 23-25: R1/R2 currents typically represent large-scale (e.g., >500 km) FACs. And a 21-point moving window (~150 km) not only captures the large-scale currents but also captures some mesoscale FACs. Thus, the smoothed FAC in Figure 3b has more structures than typical R1/R2 current scheme. If you try to associated the downward/upward currents with R1/R2 currents, a larger moving window (e.g., ~500-km width) is needed. Otherwise, the corresponding discussion does not make too much sense and can be removed.

The 21-point smoothing is used because it is recommended by Ritter et al. (2013). At the same time, the larger (e.g. 51-point) smoothing can also be applied to show the large scale currents. Figure 3 has been modified accordingly.

b. As mentioned in the major comment, the results shown in Figure 4 are significantly degraded by the large error bars. I think that you may have utilized the original 1-Hz data to calculate the results shown in Figure 4. If that is the case, the large error bars may be related to the very intense small-scale FACs as shown in Figure 3a. From you Section 5.1, it seems that you want to investigate the evolution of the large-scale FAC. If so, you need to use the smoothed FAC data rather the original data to conduct the study, which may give you smaller error bars and improve the results. Did you do in this way? If so, you need to mention it in the context. Otherwise, you may need to use the smoothed FAC. If you want to focus on the average FACs, you can also calculate the standard errors, which are the standard deviation divided by the square root of samples, and use them as the errors bars.

As mentioned above, Figure 4 is generated using the 1 s data and, indeed, the large error bars are related to the very intense small-scale FACs. No smoothing procedures apply to the original 1 s data, except for those shown in Figure 3b and 10a. In most cases the sums of 1 s values are used. To avoid ambiguity the title of Section 5.1 has been modified as follows: “Large-scale characteristics of FACs”.

c. Page 11, second paragraph: The relative importance of substorm and geomagnetic storm in controlling the nightside FAC evolutions cannot be directly distinguished according to Figure 4. It might be straightforward to show the correlation between FAC and SYM-H/AL to indicate which one plays a more important role.

Even visual examination of Figure 4 shows that the dayside FACs are much less compared with the evolution of AL index and less affected by substorms. The nightside FACs strengthen sharply with the AL index increases. Correlations between the AL and FAC intensities may be questionable, because the AL varies on the minute time scale, while the time of the satellite crossing of FAC region is several minutes. As far as the quantitative estimate of the correlation between SYM-H and the FAC characteristics is concern, a new figure (Figure 6) illustrating the SYMH-EqB relationship has been added.

d. Page 11, last paragraph: The last two sentence can be removed since they are not directly related to figures shown in the paper.

Removed.

6) Section 4.2: a. Please see the second item of the comment for Conclusion #1.

Please see the reply to the comment Conclusion #1.

7) Section 4.3:

a. Page 14, Line 12: Please Add some references after “equatorward”

The equatorward shift of FACs is discussed in (Milan et al., 2004). This reference has been moved to the end of the next sentence.

b. Page 14, Line 15: “20-point”? You mentioned “21-point” in Line 19 on Page 10. Please keep it consistent.

The 20-point sliding window is used to determine the latitudinal boundary of the FAC region, where FACs are terminated. The 21-point smoothing is used to reveal large (meso) scale currents.

c. Page 15, Line 6: After 22 UT on September 7, the SYM-H was not stable.

Corrected.

d. Page 15, Line 9: 04 MLT is probably too prenoon. 04 MLT à 10 MLT?

Corrected: 10 MLT.

e. Page 15, Lines 22-24: Please see the third item of the comment for Conclusion #2

Figure 6 illustrating the SYMH-EqB relationship and corresponding comments have been added.

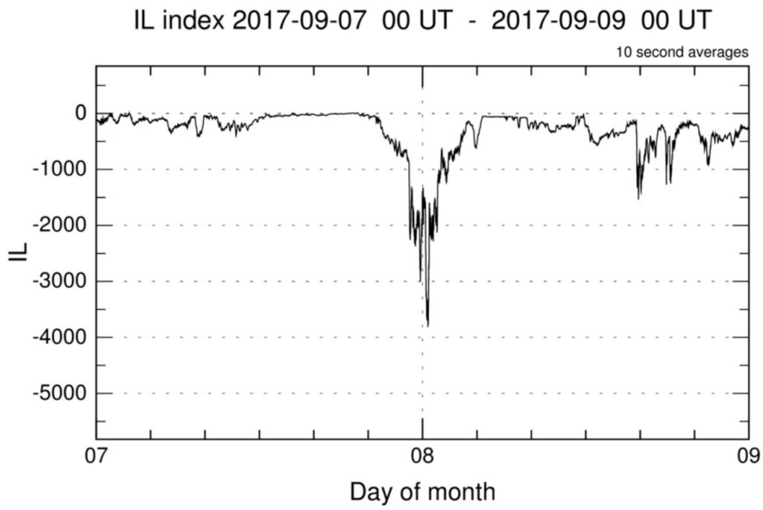
8) Section 4.4:

a. Figure 6: Perhaps you could use the shade to highlight the period when SYM-H < -20 nT;

Period when SYM-H < -20 nT started at 00 UT, Sept 8, and lasted till the end of Sept 9. This note has been added to the Figure 7 (former Figure 6) caption.

b. Page 20, Line 1: From the IL index, it is difficult to tell that the substorm was in the growth phase when the bipolar FAC was identified since it seems that the IL index was relatively stable at the time when the bipolar FAC was identified.

The the IL index was relatively stable on the short time scale only. At ~00 UT Sept 8 the AL was already -1500 nT, indicating a strong substorm activity prior the AL drop to -3700 nT. "The growth phase" has been replaced by "the storm-time substorm intensifications" (p. 20, ll. 3-4).



c. Page 20: Line 12: The difference of 15 µA is not trivial in comparison with your peak FACs (20%~25%), so that the downward and upward currents are not comparable. So this whole sentence may need to be removed.

Yes, the difference between positive and negative values may be considered as significant. But compared with the majority of the extreme FACs (>~10 µA/m2 in Fig. 7), they both are large. The word "relatively" <comparable values> has been added.

d. Page 20, Line 13~14: First, FACs at 150-km scale size may not well represent large-scale R1/R2 FACs. Second, From Figure 9a, the bipolar structure is located in the downward FAC rather than between the "large-scale" downward and upward FAC.

The sentence has been modified as follows: "…the bipolar structure is located at the edge of the mesoscale downward FACs."

9) Section 5.1:

a. First paragraph: I think the content is related to Figure 4, where your results may not really represent the evolution of large-scale FAC, especially you haven't pointed out whether the original data or the smoothed data have been used. Given the large error bars you have presented, it seems that the original data have been used, which are mixtures of FACs on different scales.

The title of Section 5.1 has been modified to avoid the ambiguous usage of the term "large-scale FACs".

b. Last paragraph: See comments for Section 4.2.

Corrected and clarified as described above.

10) Section 5.2: a. See the last general comments

In Section 5.2, several sentences have been modified in accordance with the corrections made after the comments listed above.