Response to Reviewer letter

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July 28, 2019

Manuscript Title: Magnetic local time asymmetries in precipitating and trapped electron and proton populations with and without substorm activity

https://www.ann-geophys-discuss.net/angeo-2019-49
https://doi.org/10.5194/angeo-2019-49-RC1

We would like to thank the reviewers for fruitful comments as they draw out attention to aspects that can be (better) answered by the used methods but somehow were off our radar.

As a couple of figures have been added (and one table has been replaced) we would like to note that the references in this reply belong to the old numbering.

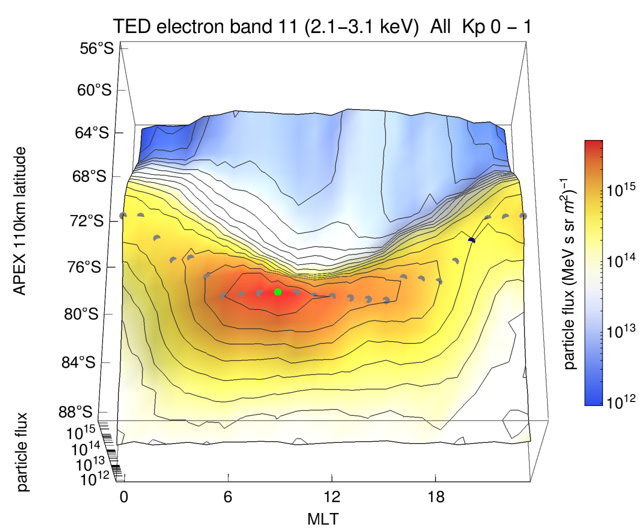
Reviewer 1 (Comments)

The paper uses POES and METOP data to evaluate how the precipitation of protons and electrons varies with magnetic local time during both isolated substorms and in the absence of substorm activity. Data collected during the declining phase of cycle 23 has been used, and measurements from multiple energy channels evaluated. Overall this is an interesting piece of work and generally well written. The introduction and motivation in particular is very well thought out.

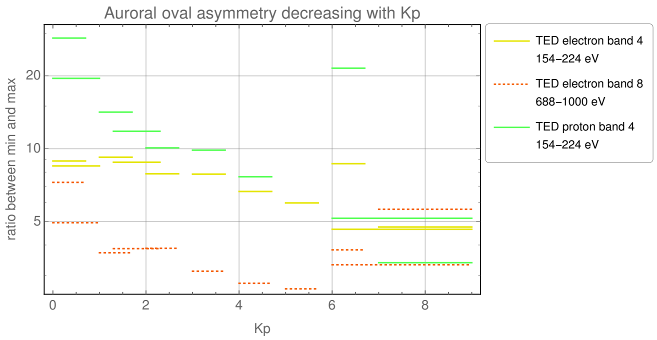
1. Comment

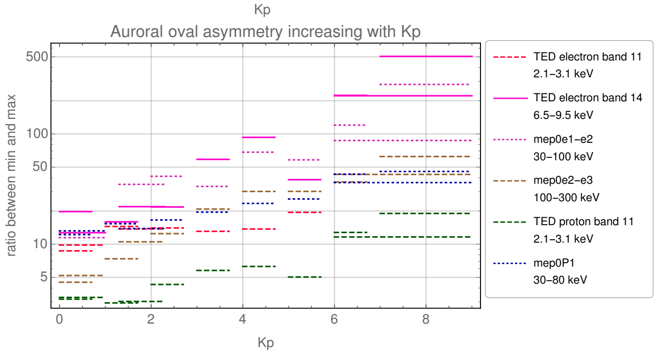
My major concern for the paper is that one of the authors main results, the Kp (or lack of) dependence of proton and electron precipitation, is discussed in the abstract as well as the summary section, but any figure actually showing this has been omitted from the paper. While an indication is given in table 2, this is difficult to assimilate and results considering different Kp bins need to be presented as a figure for this result to be claimed.

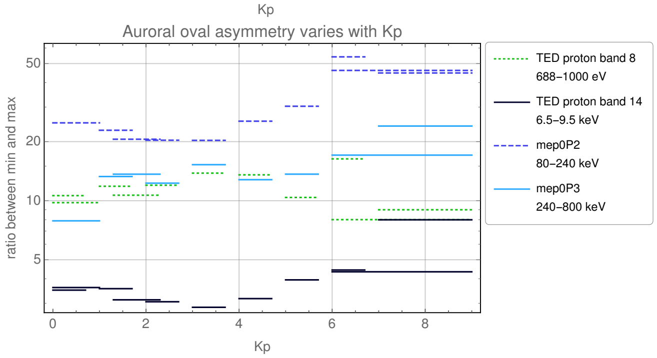
Reply: *The reviewer is right, that table 2 is just an "indication" of the Kp dependency that we noticed. However, it already pointed out what we now elaborated in more detail. As all channels and various Kp level had to be analyzed, it was now necessary to write an automated auroral oval detection algorithm for APEX 110 km latitude or MLT locations of the auroral oval or its flux maximum and minimum. The routine determines the maximum flux for each MLT-bin within the typical auroral latitude range. This results in a preliminary auroral oval. Then the latitudinal differences between MLT-predecessor and successor are determined and in case of large outliers a point is assumed to be a spike in the data and replaced by the next biggest flux-bin in that MLT zone. In case that more than 7 points have to be replaced for a auroral oval the according channel-Kp set is neglected. In sum this ends up in a well-working detection algorithm for the auroral oval and allows us to find its minimum and maximum flux, or their ratio. A sample output is given in the following figure.*



The gray dots represent the position of the auroral oval. The green (9 MLT) and black (20 MLT) dots indicate maximum and minimum of the auroral oval, respectively. All locations have been cross-checked manually.







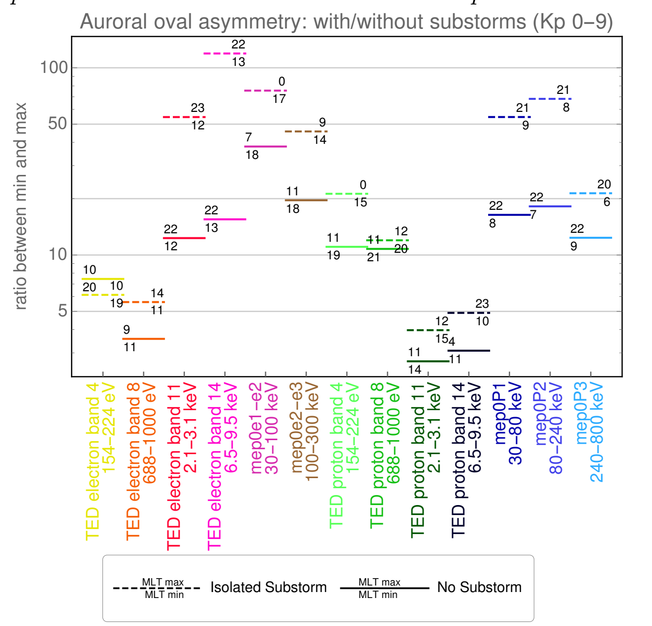
The next figure is based on these findings and presents the ratio between maximum and minimum auroral oval flux (or in other words the asymmetry of the oval) depending on Kp-level for every channel separately. Actually the channels have been grouped by their Kp dependency. The upper panel shows the 2 lowest electron channels and the lowest proton channel which all have a declining flux asymmetry with increasing Kp. The 6-6.7 Kp-bin is enhanced here, but we should keep in mind that this levels are occurring rarely and may suffer from bad statistics.

The middle panel shows all particle channels that have an increasing flux asymmetry with Kp, as they are: all remaining electron channels and the proton channels TED band 11 and mep0P1.

The lowest panel gives the flux asymmetry dependencies of the remaining proton channels that are less distinct. It seems that there is a domain change at about 3.3 Kp, since the asymmetry of TED proton band 14 and mep0P2 has a negative correlation below 3.3 and a positive one above. For the channels TED proton band 8 and mep0P3 the relationship is opposite.

All these findings are based on the whole period including all (no-) substorm conditions.

Another aspect that was mentioned in table 2 is how the asymmetry depends on substorms. The next figure presents this relation in more detail. Since an 8 year period does not contain enough values for substorms in rare Kp-levels we neglected the Kp-level here and compared isolated substorm to no-substorm periods.



Except for TED electron band 4 (where there is no significant difference between substorm and no-substorm periods) all other channels have an increased auroral oval asymmetry during isolated substorms. The numbers above and below the marked flux ratio indicate the MLT location of the minimum (below) and maximum (above). We can identify that the maximum flux during a substorm shifts to the midnight sector (if not already there in no-substorm periods) e.g. for mep0e1-e2, TED proton band 4 and 14.

For TED electron band 4 and 8 (as well as TED proton band 8 and 11) the substorm enhancement is also seen in the night sector, but it does not overshoot the dayside flux (see Figures 2 and 3), while the substorm enhancement in the night-sector of mep0e2-e3 is in the same order as the 9–12 MLT flux.

The asymmetry in both, the electron and the proton spectrum shows a local minimum in middle TED channels (TED electron band 8 and proton band 11) as well as a local maximum at higher energies (TED electron band 14 or mep0e1-e2 for electron and mep0P1 or mep0P2 for protons). At even higher energies the asymmetry de-

clines again.
This information has been added to the paper. Sections have been restructured accordingly. Given that the new figures are more detailed than the previous table, the table will be omitted.

2. Comment

Line 19, section 1, discusses how the SML index was used to define the substorm onsets. While the reviewer agrees that SML is a good choice to define substorm onsets, perhaps the authors could elaborate on why SML was used instead of the AE index as in the Reeves et al., 2003 study.

Reply: *The link between AE and SML now is explained in more detail. The paragraph now reads: The occurrence of substorms depends on the orientation of the interplanetary magnetic field (Reeves et al., 2003). As shown in Reeves et al. (2003) these external solar wind parameters subsequently impact the magnetic field on the ground and are represented in the Auroral Electrojet (AE) index. Auroral Electrojet indices AE=AU-AL are a good proxy of the global auroral power, where AU and AL are the upper and lower components of AE, which means the largest and smallest values of the H component among 12 magnetic stations (Davis und Sugiura, 1966). AU represents the strength of the eastward electrojet, while AL represents the westward electrojet. Consequently AL seems to be the index which best corresponds to westward intensification of the auroral current aka substorm activity. Prior to substorm onset, AL index is typically small in magnitude, with the contributing station near dawn, whereas during substorm onset, the station contributing to the lower envelope is usually in the dusk sector under the auroral expansion. However, due to the limited spatial coverage of the 12 magnetometer stations the auroral expansion can be missed, which means that this index does not always reflect the onset (Gjerloev et al., 2004). The use of SuperMAG SML, an index derived likewise to the AE but based on all available magnetometer stations (typically more than 100) at these latitudes, considerably improves the detection of substorm onsets (Newell und Gjerloev, 2011). Thus we use the SML index in this study to define substorm onsets.*

3. Comment

In section 3, line 11-12 reads "the SAA allows energetic particles in the radiation belt to reach altitudes low enough to be reached by the satellites orbit". Considering that the authors are solely using the T0 flux measured by POES and METOP, Figure 1 in Rodger et al. (2010) would suggest that, even over the SAA, the T0 measured flux is still precipitating.

Reply: *Comparing Figure 1 in Rodger et al. (2010) to the upper panel of our Fig. 1 (in geographic coordinates) we can see that the SAA region (between 280 and 360 degrees East and -45 to 0 degrees North) covers a mix of all populations. The central part of the SAA is even located in the yellow area labled with "trapped+drift loss cone+bounce loss cone". In so far we disagree with the reviewer and conclude that the T0 flux measured in the SAA is not precipitating in total since it also contains a fraction of the trapped particles. As the following sentence reads "Thus the high flux values are not necessarily connected to high particle precipitation." we already tried to mention that. However, to point that out, we now added the following sentence: "According to Rodger et al. (2010: Fig. 1) the particle population in the SAA consists of particles precipitating in bounce and drift loss cone as well as trapped particles."*

4. Comment

In Figures 2, 3, and 4, as well as in the text, could the different energy channels be referred to by the energy range covered rather than the channel name? This would make the results easier to interpret without constantly flicking back to table 1.

Reply: *We agree with the reviewer that it might be helpful to give the energy ranges in every figure. However there are some caveats about the energy ranges that need to be mentioned: a) Some channels suffer from degradation. This mostly holds for the MEPED proton channels and is a result of structural defects caused by the impinging particles. On the long run it causes an energy shift (to higher particles energies) since less electron-hole pairs are produced per deposited particle energy. Consequently the mentioned energy ranges are nominal ranges. Further details on degradation of the MEPED channels can be found in e.g. Asikainen et al. (2012). b) For at least one channel the energy range seems to be doubtful as NOAA describes the same detectors in two technical documents with divergent ranges for mep0P2: 80–240 keV in (Evans und Greer, 2006) and the same channel in Green (2013): 80–250 keV. The electron channels also have different ranges as Green (2013) lacks an upper threshold energy. But since we subtract the electron channels in order to get differential channels this does not matter in our case anyway.*
We added the nominal energy range to all figures and added a note about the possible degradation.

5. Comment

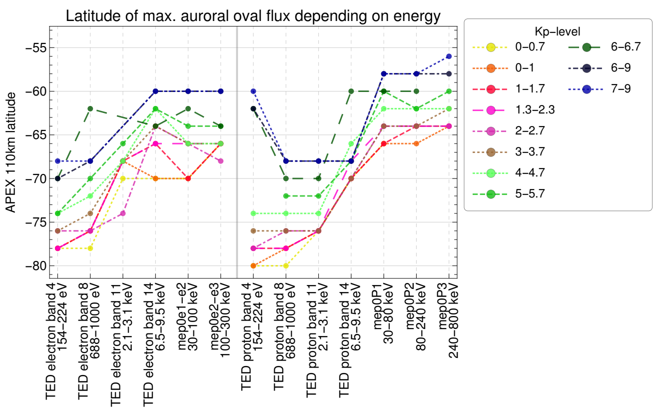
When discussing figure 2 in section 4, point c and d mention that the noon sector flux decreases during a substorm. Could the authors speculate on why this is?

Reply: *We added the following information: "The noon sector flux decreases most probably because dayside particle precipitation occurs often during northward orientated IMF which is not usual for substorms."*

6. Comment

When discussing Figure 3, the first point claims that protons also show an equatorial movement of the main precipitation zone with increasing particle energy. More direction to this in the figure is required here for the reader as I do not see this.

Reply: *The following figure presents the dependency of the latitude of the main precipitation zone to the particle energy.*



The figure has been derived by the auroral oval determination method discussed before and displays the latitude of maximum auroral oval flux. Except for some outliers, most of them belonging to TED proton band 4 during high Kp levels (> 6), the graphs show a clear equatorial dislocation with increasing energy. The 110 km APEX latitudinal range at a specific Kp-level is about 10° for electrons and 12-16° for protons. This dislocation however appears to be stepwise: TED electron band 4 and 8 are on the same latitude as well as TED electron band 14, mep0e1-e2 and mep0e2-e3 share the same latitude. For protons TED proton band 4, 8 and 11 are on one latitude and the higher particle energies mep0P1 and mep0P2 are colocated. This implies that these particles origin from the same souce region.
Every color graph represents the spectral location of the main precipitation zone for a certain Kp-range. Thus we can infer that increased geomagnetic disturbance (high Kp-values) causes a dislocation of up to about 8° towards the equator.
Concerning the outliers in TED proton band 4, for low Kp-values there is a clear flux maximum at noon, which is located at rather high latitudes (compare Fig. 2). At high Kp, the MLT asymmetry declines and then flips. Consequently the maximum flux for high Kp-levels is not in the day-sector and thus at significantly lower latitudes. This information has been added to the paper.

7. Comment

The second point made when discussing Figure 3 was that there is a second auroral oval. This is then stated to be an artefact of the MLT binning. Could the authors add further explanation to justify this here?

Reply: *We added a figure tha shows the APEX latitude and longitude. This figure nicely shows that the double auroral structure is on the same latitude as the drift loss cone. Also further explanation has been added. The following information now is included: "Figure 1 shows the TED proton band 11 in geographic coordinates (top row) and modified APEX 110 km coordinates (bottom row). The left column shows latitude against longitude while the right column shows latitude against MLT. No selection according to Kp-level or substorm intensity has been made, while all available data from METOP 2 and POES 15, 16, 17 and 18 for the years 2001–2008 has been included. This allows a spatial resolution of 3.75 degrees longitude (or 15 min MLT). Please note that latter figures show a reduced longitudinal resolution of 15 degrees (or 1 h MLT) only to avoid statistical noise in e.g isolated substorms periods."*
and
"Figure 1 (top, right) shows the same data on a geographic latitude vs. MLT grid. As the auroral oval is not visible as an oval any more but mixes up local time differences and the latitudinal variations that can already be seen in Fig. 1 (top, left)."
and
"Switching to magnetic modified APEX 110 km coordinates (see Fig 1, bottom, left) straightens the auroral oval and mostly removes the longitudinal dependence except for the SAA and the drift loss cone in the South of the SAA. Consequently we can replace the APEX longitude by MLT (see Fig. 1, bottom, right). Features that depend on magnetic local time now become visible and the auroral oval itself does not show a hemispheric dependence. The SAA and the drift loss cone, however, are now smeared out and still produce a hemispheric asymmetry. The drift loss cone that is located at a distinct modified APEX 110 km longitudinal range even appears as an double auroral structure at the same latitude but covering all longitudes. Which of course is an artifact of this kind of MLT binning."
In addition several references to the figure have been updated.

8. Comment

In the text, table 3 is not discussed or explained. Perhaps it is not needed? Otherwise the relevance needs to be discussed.

Reply: *The table is now referenced in the text.*

Typo

Additionally, there are a number of typographical errors in the manuscript:

Page 4, line 3: “furtunately”,
Reply: *Corrected.*

Typo

Page 4, line 15: “trapped particles in low altitudes” should be “at low altitudes”.

Reply: *Assuming that latitudes are meant we corrected the wrong preposition throughout the manuscript.*

Typo

Page 4, Line 25: “mainly located in about 110 km altitude” should be “at about 110 km...”.

Reply: *Corrected.*

Typo

Page 4, Line 34: you have not defined the QD acronym - please write out quasi-dipole.

Reply: *The acronym has been added were the quasi-dipole system is introduced.*

Typo

Spelling of “avoid” throughout the manuscript is wrong.

Reply: *Corrected.*

Typo

Page 5, line 20: “independend”.

Reply: *Corrected to “independent”.*

Typo

Page 6, line 29: “Substorm depended precipitation...”

Reply: *Corrected.*

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