Referee #1

I have read the manuscript "Outer radiation belt and inner magnetospheric response to sheath regions of coronal mass ejections: A statistical analysis". The authors preform a very detailed study of sheath regions and how they affect the electron population of the outer radiation belt along with various geospace phenomena (e.g. EM waves, geomagnetic response, etc.). They also adopt a new approach considering not only storm events but also weak geomagnetic disturbances which I think it's quite important in order to gain a clear picture of the radiation belt response. I have several minor comments which I have commented and highlighted in the attached pdf but I also have some significant concerns mostly about the superposed epoch analysis and the way it is applied in the study.

We thank the referee for the constructive comments and suggestions that will improve the manuscript. Please find below our detailed responses.

MAJOR COMMENTS:

1) In page 5 lines 10-12 the authors report: ". Therefore, we resampled the sheath regions to match the mean sheath duration of 12.0 h (Kilpua et al., 2013; Hietala et al., 2014). The resampled data was acquired with linear interpolation." The re-sampling method needs more clarification and also justification of the use of linear interpolation. What is the mean duration of the sheaths under consideration and their standard deviation? If the larger and the shorter duration of the events is comparable to the 12h duration (e.g. 14 and 10h respectively) then the linear interpolation gives you pretty good results. If not how can we be sure about the validity of the results?

We have expanded the discussion on the superposed epoch analysis and mentioned the potential problems. We have emphasized that the sheaths were resampled to the mean sheath duration, which is 12.0 h. Additionally, we redid the superposed epoch analysis for sheaths whose duration was from 10 to 14 hours (in total 10 sheath events with the mean duration being 12.4 h). The results are similar to the results of the full set of 37 sheath events, which suggests that the resampling does not significantly affect the results.

2) In page 5 lines 21-25 the authors report: . "For the ULF waves, we calculated the wavelet spectra for each three magnetic field components measured by GOES-15 and summed them together to estimate the total wave power spectral density. We calculated the Pc5 wave power in the range from 2.5 to 10 min (2–7 mHz) and the EMIC wave power in the range from 0.2 to 10 s (0.1–5 Hz), which corresponds to the range of Pc1 and Pc2 pulsations as given by Jacobs 25 et al. (1964)." Why the authors didn't use RBSP to obtain Pc1 and Pc5 power? This way they could have a more straightforward comparison with chorus and fluxes which are obtained in the heart of the outer belt. Furthermore, Georgiou et al. 2018 (see figure 4 in the paper) performed a detailed statistical study with the use of epoch analysis and showed that there is a quite different evolution of Pc5 power beyond and below the geosynchronous orbit. Finally, why the authors apply wavelet analysis in each magnetic field component and then sum them? If they just want to see the total wave power it is more appropriate to apply the wavelet analysis in the magnitude of the magnetic field.

Calculating ULF wave power from RBSP data can be good for analysing local wave characteristics on shorter timescales, but the Van Allen Probes are not ideal for looking at long-term ULF wave statistics over the course of an event. The RBSP spacecraft move relatively fast through highly different plasma environments, observing vastly different

regions of the inner magnetosphere over the course of one half-orbit. GOES has the advantage of remaining at the same distance.

We have now discussed the effect of using ULF observations at geostationary orbit and included as references Georgiou et al. 2018 and Engebretson et al. 2018. We have also redone the wavelet analysis of ULF waves in the paper, using the magnitude of the magnetic field instead of the components. As a result, the wave power overall decreased but no significant changes were introduced in the profiles as the P-component always dominates the magnetic field magnitude.

3) In section 3.3 lines 20-24 the authors report:"It is immediately evident that for geoeffective sheaths, enhancement events are more common at all energies and L-shells, and the source and seed populations are practically always enhanced in the heart of the outer belt (L = 3.5–5). However, deviating from the superposed epoch analysis results, > MeV electrons experience depletion more frequently in geoeffective events throughout the outer belt. In non-geoeffective events depletion begins to dominate the core population response only at around L > 5." Kilpua et al 2015 showed that there are significant flux dropouts during the sheath regions they examined. Can this be due to the 4h cadence you have chosen (I strongly believe that only 4 points during the sheath are very few in order to do statistics). If by choosing a higher resolution cadence you still don’t see a dropout you need to argue about that. Another cause of that may be the averaging at L-shells. As you are showing in figure 6 there is significant depletion at L>4.5 but no depletion at L<4. In that case maybe you need to reapply the epoch analysis in different L=bins (e.g. 3-4, 4-5, 5-6). Of course this should be applied in waves as well.

Kilpua et al. 2015 only studied >2 MeV electron fluxes at geostationary orbit and showed significant dropouts during sheath regions. Our results are in agreement with this study, as flux depletions dominate at MeV energies at the highest L-shells.

It is a very interesting question how the fluxes change within the sheath more precisely, but here we are mostly interested in how sheaths affect as a whole and what is the overall trend considering the pre- and post-sheath fluxes. This is also why we considered a wide L range (L = 3.5–5) for the superposed epoch analysis, and reserved the more detailed spatial (0.1 L) and temporal (1h) resolution for the electron flux response analysis. We also tried to use higher time resolution for superposed epoch analysis and the results are practically similar. We have now discussed this in the paper.

MINOR COMMENTS:
1) page 2 line 3: "...storm and substorm processes, and by changes...", delete "end"

Sentence was modified

2) page 2 line 5: suggested reference: "Daglis IA, Katsavrias C, Georgiou M. 2019 From solar sneezing to killer electrons: outer radiation belt response to solar eruptions. Phil.Trans.R.Soc.A377: 20180097. http://dx.doi.org/10.1098/rsta.2018.0097"

We have added this paper as a reference

3) page 2 line 6: suggested reference: "D.N. Baker, S.G. Kanekal, X. Li, S.P. Monk, J. Goldstein, J.L. Burch, Nature 432, 878 (2004). doi: 10.1038/nature03116"

We have added this reference

4) page 2 line 21: There is reference to the ultra-relativistic population at the results section so I think it should be mentioned here as well (even though the boundary between relativistic and ultra-relativistic population is not well defined).

Thank you for pointing this out. The ultrarelativistic population is now mentioned in the Introduction.

5) page 2 line 23: I believe that Jaynes et al. 2015 mentions that only seed electrons are accelerated by chorus.

This is correct. We have modified the sentence accordingly.

6) page 2 line 28: It's not clear what that sentence mean. Does that implies that the density modulations produced by ULF waves can reduce the minimum electron energy for cyclotron resonance with EMIC waves? If yes please give reference to "Zhang, X.-J., Mourenas, D., Artemyev, A. V., Angelopoulos, V., & Sauvaud, J.-A. (2019). Precipitation of MeV and sub-MeV electrons due to combined effects of EMIC and ULF waves. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/2019JA026566".

Brito et al. 2012 suggest that ULF Pc4–Pc5 waves modulate the electron precipitation by lowering the mirror points. We have extended the discussion slightly to make the meaning clearer and added Zhang et al. 2019 as a reference.

7) page 2 line 30: Add "Jaynes, A. N., et al. (2014), Evolution of relativistic outer belt electrons during an extended quiescent period, J. Geophys. Res. Space Physics, 119, 9558–9566, doi:10.1002/2014JA020125."

Added

8) page 2 line 31-33: I would suggest to separate references in a group which studies the response of the outer belt to storm events generally (e.g. Murphy 2018) and a group which studies the response due to different drivers (e.g. Kilpua 2015) and modify this paragraph accordingly. I would also suggest to include to references which correspond to the importance of source and seed population on the radiation belt dynamics:

Katsavrias, C., Daglis, I. A., & Li, W. (2019). On the statistics of acceleration and loss of relativistic electrons in the outer radiation belt: A superposed epoch analysis. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/2019JA026569

Bingham, S. T., Mouikis, C. G., Kistler, L. M., Paulson, K. W., Farrugia, C. J., Huang, C. L., et al. (2019). The storm time development of source electrons and chorus wave activityduringCMEâA˘R˘andCIRâA˘R˘drivenstorms.JournalofGeophysicalResearch: Space Physics, 124, 6438–6452. https://doi.org/10.1029/2019JA026689

Thank you for this good suggestion. We have divided the references into two groups and added a discussion of the importance of the source and seed populations. The two papers were added as references.

9) page 3 line 15-17: I think that this is an important novelty of this work and should be further highlighted. It is well known that even weak or "non-storm" events can produce significant variability in the outer radiation belt population and that the Dst index can often not account for the internal mechanisms that are responsible for this variability. See also:

Schiller, Q., X. Li, L. Blum, W. Tu, D. L. Turner, and J. B. Blake (2014), A nonstorm time enhancement of relativistic electrons in the outer radiation belt, Geophys. Res. Lett., 41, 7–12, doi:10.1002/2013GL058485.

Katsavrias, C., I. A. Daglis, D. L. Turner, I. Sandberg, C. Papadimitriou, M. Georgiou, and G. Balasis (2015), Nonstorm loss of relativistic electrons in the outer radiation belt, Geophys. Res. Lett., 42, 10,521–10,530, doi:10.1002/2015GL066773.

We have further highlighted the inclusion of weak and non-storm events in our study and added the suggested two papers as references.

10) page 4 line 21-23: Please modify according to the introduction. 1.5 MeV electrons are not considered as seed population but as core or relativistic. At the same extent 1.8 to 6.3 MeV electrons are relativistic and ultra-relativistic. Also, please clarify if you are using the background corrected fluxes from MagEIS.

Thank you for pointing this out. We have modified the sentence. Thank you also very much for pointing out the background correction. We were indeed using the uncorrected MagEIS electron flux measurements. We will redo the MagEIS electron flux analysis using the background corrected measurements.

11) page 5 line 17: Jaynes et al. 2014, among others, have shown that the effect of plasmaspheric hiss is significant at high energy electrons inside the plasmasphere and more important it is very slow (electron lifetimes down to 2.7 days at L=4.5). Is the study of such waves really necessary since you are studying sheaths which last for 12 hours?

We have included the study of hiss waves among with other wave modes for completeness. We have now mentioned this in the paper with a reference to Jaynes et al. 2014.

12) page 5 line 28-29: The 4 hours binning provides you with ONLY 4 POINTS during the sheath region. Is that statistically enough?

See our response above for major comment 3

13) page 5 line 30-31: There is a significant variability of the MagEIS lower energy channels up to September 2013 as discussed in Boyd et al. 2019. Does such a variability affect your data? If not, please argue.

Boyd,A.J.,Reeves,G.D.,Spence, H. E., Funsten, H. O., Larsen,B. A., Skoug, R. M., et al. (2019).RBSP-ECT combined spin-averaged electron flux data product.Journal of Geophysical Research: SpacePhysics,124. https://doi.org/10.1029/2019JA026733

We have in our study 13 events before September 2013. We have now mentioned this possibility in the paper and included Boyd et al. 2019 as a reference.

14) page 6 line 15-16: The post-event flux is the average of the 12 h or the max or something else?

The post-event flux is a 6-hour average after the sheath, similarly to the pre-event flux which is a 6-hour average before the sheath. We modified the sentence to make the definitions of the pre- and post-event fluxes clearer.

15) page 6 line 18: Again, do you mean the maximum flux during the sheath or some kind of averaging such as in the pre-event flux?

See above

16) page 7 line 15: delete "SYM-H"

Deleted

17) page 7 line 18-19: I don’t understand the meaning of this sentence. You are referring to typical undisturbed condition but then you are talking about enhancement.

Changed “electrons being enhanced” to “electron fluxes being higher”

18) page 7 line 27-28: The format of the last panel does not allow the reader to discriminate the wave power enhancements. I believe it would be best if you showed Pc1 and Pc5 wave power separately.

We have added a panel to Figure 3 showing the wave power of ULF Pc5 and EMIC waves during the event.

19) page 8 line 19-20: I don’t think this is accurate. As shown by the median, the substorm activity is pretty much comparable. The difference lies on the lower quantile.

We have added that the substorm activity shown by AL index is weak during both the sheath and ejecta.

20) page 8 line 30-31: Once again, if you consider the median, I believe that AL shows similar behavior during the sheath and during the ejecta which consequently explains the behavior of chorus activity.

We agree with the referee and have changed the discussion accordingly.

21) page 9 line 5-6: " That is, the median response of 346 keV electrons is an enhancement, as well, by a factor of about 8." Please rephrase.

Rephrased to "The 346 keV electron median flux increases by a factor of about 8."

22) In page 12 the authors report: "Interestingly, a feature in the outer belt response is that the depletion progresses to lower energies when L increases. At L â´Lij 4.5 depletion dominates only at > 2 MeV energies, while at L â´Lij 6 it has reached down to seed energies at around 500 keV. Depletion is most likely at high energies and high L-shells". This strongly indicates magnetopause shadowing effect.

We have suggested in the discussion that magnetopause shadowing is an explanation for the losses at high L-shells.

23) page 12 line 6: Mention again your definition of geo-effectiveness

Added

24) page 16 line 7-9: Add "Claudepierre, S. G., S. R. Elkington, and M. Wiltberger (2008), Solar wind driving of magnetospheric ULF waves:Pulsations driven by velocity shear at the magnetopause,J. Geophys. Res.,113, A05218, doi:10.1029/2007JA012890" as well as discussion about the generation process of ULF.

We will add this reference and discuss shortly in the Introduction how ULF waves are typically generated.

25) page 18 line 3-5: This is not correct. High energy electrons can penetrate deep inside the inner edge of the belt even during relatively weak events. For example, the relatively weak storm of April-May 2017 produce enhancements up to 10 MeV at L=3-3.5

see for reference: "Katsavrias, C., Sandberg, I., Li, W., Podladchikova, O., Daglis, I. A., Papadimitriou, C., et al. (2019). Highly relativistic electron flux enhancement during the weak geomagnetic storm of April–May 2017. Journal of Geophysical Research: Space Physics, 124. https://doi.org/10.1029/2019JA026743

and

Zhao, H., Baker, D. N., Li, X., Jaynes, A. N., & Kanekal, S. G. (2018). The acceleration of ultrarelativistic electrons during a small to moderate storm of 21 April 2017. Geophysical Research Letters, 45, 5818–5825. https://doi.org/10.1029/2018GL078582

We have now mentioned that high-energy electrons can penetrate to lower L-shells also during weak storms and added the two papers as references.

26) page 18 line 10-13: I don't understand the meaning of this sentence. If depletions are more pronounced with increasing energy and L-shell you have a clear indication for outward diffusion combined with magnetopause shadowing. Of course other wave particle interactions can contribute but at different energies and pitch angles each.

We agree with the referee that outward diffusion could play a role in concert with magnetopause shadowing at higher L-shells. We will discuss this in more detail in the revised manuscript.

27) page 19: I would recommend to briefly summarize your most important results in bullets.

We have now written the summary in bullet points.