Response to Referee 1

We thank Referee 1 for thorough reading of the manuscript and helpful comments. Below are the point-by-point responses (blue) to each of the comments (black). During the revision process a small timing error was found in the analysis of the spectrometer data. Thus, the temperature and brightness time series plots in Figure 1 and 2 have been re-plotted and have changed a little. This update has resulted in another event to be classified as stable, so there are now 6 cases showing a temperature decrease and 2 showing no change in temperature as an immediate response to the particle precipitation onset. The temperature super-posed epoch plot is re-done in Figure 3, leading to no significant change. Figure 3 now also includes a superposed epoch plot for the airglow brightness as well.

1. The authors set out to investigate whether electron precipitation events lead to changes in the temperature of the mesopause region. They note that there are conflicting reports on this subject, and they set out to resolve the question.

2. To do so they use electron density values from the EISCAT radar, and temperatures from the mesopause region derived from OH emissions both of which are recorded from Svalbard.

3. They start off with over 10,000 hours of radar data which sounds very impressive, but when the selection criteria are applied, it turns out that only eight events remain with which to carry out the investigation. The criteria are clearly stated and the reasons for choosing them are also clear. However, the authors must realise the weakness of undertaking a statistical study with so little data.

   We do recognise the weakness. At the same time 8 events with co-located measurements is more than a case study, and it is a more direct comparison than temperatures versus indirect all-sky particle precipitation measures. Our main point is to demonstrate that even if there is a change in the temperature it recovers fast and is not going to have a major effect on the larger scale mesospheric temperature, which is often speculated in case of EPP.

4. The next and biggest problem lies in the time resolution of the temperatures. The authors state that the effect of the EPP on temperature (if it exists) is short lived of the order of 30 minutes (page 12, line 217), and they use 30-minute averages of the OH* temperature instead of the more usual 1-hour averages in an attempt to overcome this. Unfortunately, temperature values are missing either immediately before or immediately after five of the eight EPP events selected for study. Why are there so many missing temperature values? Are the OH spectra contaminated by auroral emissions caused by the precipitating electrons?

   Missing values in temperature data mean that fitting the synthetic spectrum to the measured spectrum has not given reliable results. This can happen for several reasons: cloudiness, clouds together with light pollution (for instance the Moon), technical problems (for instance interference), or strong auroral contamination by oxygen emission at 844.6 nm, which is in the middle of the OH(6–2) spectrum. These thing are discussed in, for instance, Sigernes et al. (2003), which is cited. The main reasons for missing data have now been mentioned in the text. All these factors can vary very fast within the narrow field-of-view of the spectrometer, and thus cause SNR to change from measurement to another. We have used threshold values for the fit covariance and variances to define a good fit, according to previous work (Sigernes et al. 2003 and Holmen et al. 2013, also cited), which cover long-time series and much observer expertise. Admittedly some of the missing values may be due to the auroral precipitation, but the most dominant reason is clouds, which the Eiscat radar does not care about. Shorter integration times than 30 minutes were tested but that resulted in more missing values due to lower SNR. The observed lifetime of the temperature changes is, of course, limited by the temporal resolution of the temperature data, but the main point is that it explains why earlier observations with daily averages have not shown any changes. Observing the shorter-term temperature changes also gives some confidence to conclude that these changes will not add up to climatologically significant contributions.

5. The authors claim to have detected a decrease in OH temperature greater than 10 K (10–50 K) following the onset of an EPP in seven out of eight cases.

Our events have been re-plotted due to an unnecessary time shift found in the plotting script. With this slightly different averaging there are now 6 cases out of 8 showing a decrease in temperature, typically of the order of 10–20 K. The temperature change of 50 K during the first event is an extreme, which cannot be explained by the thinning of the airglow layer alone. This is explained in the new version.

6. The authors classify the fifth event as one of decreasing temperature. This is very strange since the temperature decrease occurs before the occurrence of the EPP, while the temperature has increased by 22 K only ∼11 minutes (∼02:31 UT) after the maximum value of the EPP (∼02:20 UT). This is one of the three events in which there are no missing temperature values either immediately before or immediately after the onset of the EPP. This event should be classified as one of increasing temperature. It is also a pity that no OH temperatures are available after 03:10 UT, since the electron density values remain consistently high until at least 05:10 UT.

This has changed due to the time averaging mistake we found in the plotting script. The minimum temperature happens shortly after the onset. It is also more explicitly explained in the revised version that the comparison for the classification is done between the data point before the EEP onset and the one at the EEP onset, where the onset data point is the time-wise closest to the EEP onset time. As for the unfortunate timings for missing data points we can only agree.

7. The mechanism suggested to explain the perceived temperature decrease, originally proposed by Suzuki et al. (2010), envisages a depletion in the number of emitting radicals at the upper part of the OH layer, the effect of which depends on the mesopause region temperature profile at that time. The time resolution of the Suzuki et al. (2010) report was 1 minute which is in stark contrast with the present study. Suzuki et al. (2010) found support for their proposal from OH VER profiles from the SABER instrument onboard the TIMED satellite. As an absolute minimum, the authors of the present manuscript should at least search for SABER temperature and OH VER profiles, or alternatively, Aura MLS temperature profiles close to the time of the eight events to try to support their argument.

The temporal resolution of the OH data used in Suzuki et al. is indeed much higher than the one employed in the study. However, that paper analysed one event, where absorption of the cosmic radio noise was used as the particle precipitation proxy. While the OH spectrometer field-of-view is narrow, that of a riometer is nearly all-sky. Thus, their comparison only works for events where the energetic precipitation fills the whole sky with a uniform precipitation spectrum, which was probably true for that one event. We have looked for SABER/TIMED profiles for temperatures for these events, and found nothing particularly close to Svalbard. Since there are large variations in the temperature profiles during the winter it is not helpful to compare to a measurement half an hour or several hundreds of kilometers away from the ground-based station.

8. A depletion of OH emitters in the upper part of the layer, leading to probing temperatures at a lower altitude could have the effect of increasing or decreasing the temperature depending on the gradient of the temperature at the time of the measurement (lines 258/259). The winter mesopause temperature is indeed quite variable as pointed out in (lines 213/214). On average (see e.g., MSISE-90) however, the gradient in the high-latitude winter temperatures profile tends to be small, and the altitude of temperature minimum tends to be above the OH layer. In this situation, a depletion in the upper part of the layer would give rise to a small increase in the OH temperature, with a corresponding decrease in the integrated emission signal.

A model temperature profile (MSIS or CIRA, as shown in Suzuki et al.) indeed gives polar night temperature profiles with very small gradients, and on average OH layer is located below the major temperature minimum, based on random SABER profiles in the vicinity of Svalbard. However, random profiles we inspected also showed quite large amplitude variations, with Earthward negative gradients of 5–10 K/km not being unusual at the heights from about 80 to 90 km.

9. However, average conditions may not be a lot of help here. At any given time, the mesopause region temperature profile is rarely at the average value, and since the time scale of the EPP effect is expected to be short, and with only eight events

available for this study, it is unlikely that assuming average conditions would lead to the correct prediction. Nevertheless, it would be surprising to find a temperature decrease in all cases. As stated already, the OH temperature data do not have sufficient time resolution to make a convincing case.

We agree with the average temperature profile not being very realistic (see the reply to point 8.). With the number of events we have, it is still possible that the randomness of the variable atmosphere gives the same sign for the temperature change for 6 out of 8 events. As mentioned earlier the temporal resolution is a limiting factor but it is more important to make the point that the temperature changes do not have much longer lifetimes than the temporal resolution of the OH data. The changes are seen in 30-min resolution but would be averaged over by 1-h resolution.

10. The mechanism proposed for the temperature change (decrease), namely depleting the OH layer from above by the precipitating electrons, would be unlikely to give rise to the magnitude of the changes claimed (20–50 K). An approximate calculation based on a 10 K/km vertical gradient over the entire width of a typical Gaussian layer (which would be an extreme case) with a total depletion of say 30 % would only change the recovered temperature by $\sim$11 K. At most, one might expect only a few K change in temperature one way or the other with the proposed mechanism. The authors should address this question in detail, i.e., how much of a depletion would be required for a given temperature profile to achieve the temperature changes claimed with the mechanism proposed.

Since there were no measured temperature and OH profiles close to Svalbard during the events analysed in this study, we looked for any winter and nighttime temperature and OH profiles measured over Svalbard by SABER to see if the mechanism we propose is realistic. First of all, the typical OH brightness change for our events is about 20% decrease at the EEP onset as suggested by the superposed epoch of the OH band brightness in the new Figure 3. In the attached sample profile plot from January 2019 (orbit 92668, top panel of Figure 1 of this document) the temperature is the blue curve as a function of height. The red curve is an average of the two OH bands measured by SABER/TIMED at 2.0 and 1.6 μm, which correspond to OH bands at higher (9–7 and 8–6) and lower (4–2 and 5–3) vibrational level transitions than the ground-based measurement (6–2). Averaging is done to follow the procedure by Suzuki et al. (2010). The OH volume emission is scaled to bring it to the same X axis with the temperature values for illustration purposes. This OH layer peaks at 86 km. An OH depletion of 20% would remove the top 2 km of the layer. Assuming that this reduction brings the weighted average of the measured temperature down about 2 km from the peak height, it would decrease the temperature by 20 K, because the temperature under the OH peak height decreases by about 10 K/km. As the temperature epoch plot of our EEP events suggests (new versions of the epoch plots in Figure 2 of this document), the typical temperature change is -20 K. Although the profile shown here is not measured during our EEP events, it illustrates the height variation in the winter and nighttime mesosphere, which based on viewing of several tens of profiles is not uncommon. In the bottom panel of Figure 1 the Earthward negative temperature gradient at the heights of the OH peak if about 7 K/km. However, the temperature decrease of 50 K during the first event cannot realistically be explained by this mechanism alone.

11. The ideas contained in the manuscript have merit, but the data presented is insufficient to support the claim. The temperature data does not have the time resolution needed, and more data are needed to support the premise before publication is warranted.

The temporal resolution is not high enough to follow the evolution of these events in detail, but the point of the study is to show that the immediate change is so short-lived that a longer averaging would not allow to see any change at all. While a larger number of events will be available in the future, the 8 events studied here show complementary temperature evolution as compared to earlier case studies. Here we further employ co-located data with mesospheric temperatures and direct measurements of electron precipitation.

12. Minor comments

The following comments have been implemented as suggested:

P1, line 4; replace “exited” by “excited”.

P1, line 15; replace “events” by “event”.

P2, lines 30/31; suggest moving “was found” from the end of the sentence to after “40 K”.

P2, line 41; is “deepest” the most appropriate word here? Consider “largest” or “strongest.

P2, line 46; to what does “earlier” refer in this sentence. Do you mean previous reports of EPP events? Is it necessary to include “earlier”?

P3, line 71; be consistent in the use of uppercase- or lowercase-R in “EISCAT Svalbard Radar”; see e.g., P1, lines 5 and 6; P14, line 283.

P4, line 93; replace “field of view” by “field-of-view”.

P4, line 107; replace “field aligned” by “field-aligned”.

P4, lines 115/116; replace “M. S. Lehtinen (1996)” by “(Lehtinen and Huuskonen, 1996)”.

P5, line 138; insert “2019” after “January”.

P6, Figure 1, upper panel; omit the text “Produced@DESKTOP- ... 2020”.

P10, line 166; replace “(18°)” by “(18 K)”.

P12, line 213; the sentence beginning “At high latitudes the . . . ” restates information provided already on page 4 in lines 95-97.

P13, line 243; “Figure 3” should be “Figure 2”.

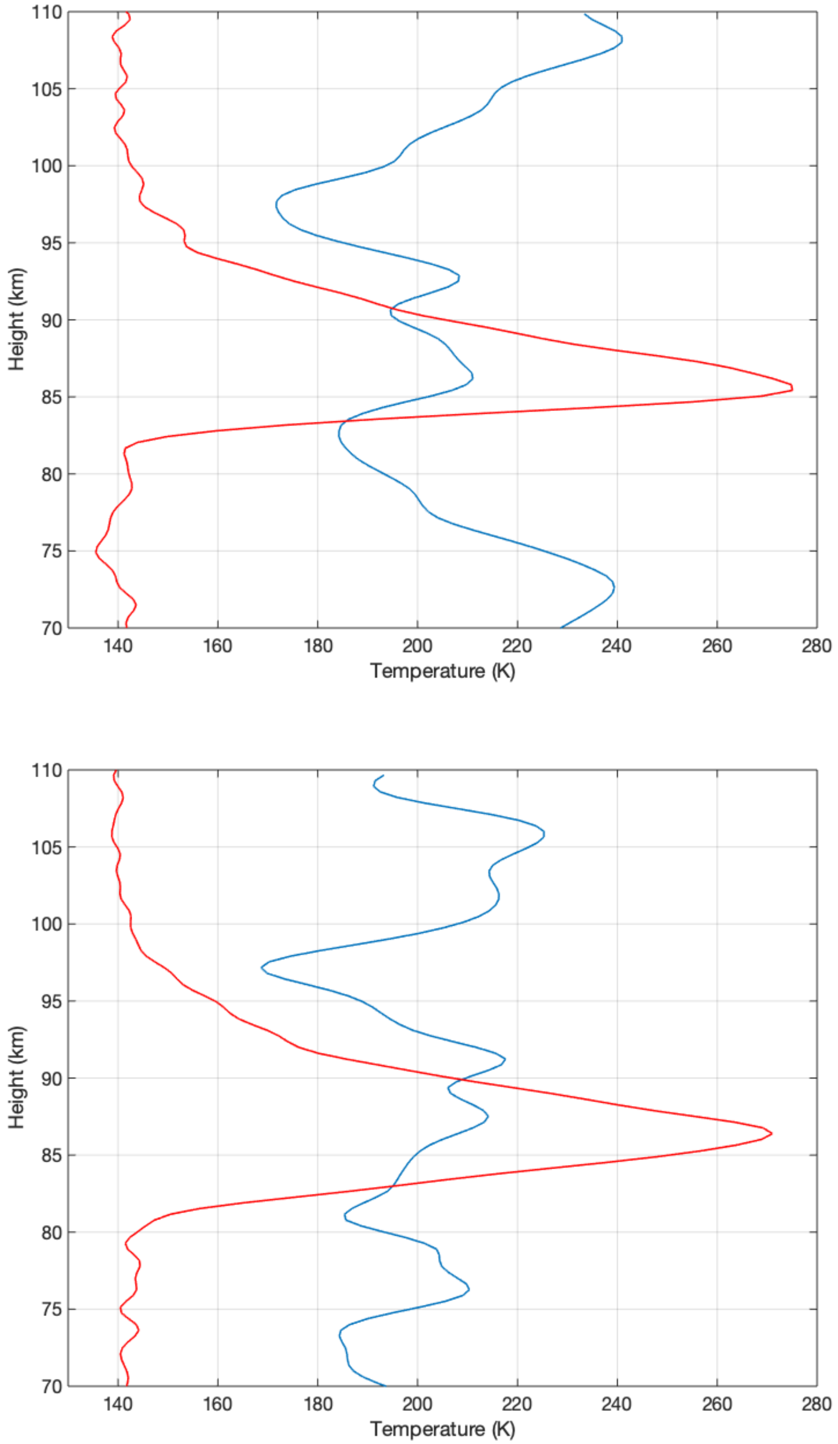

Figure 1. Two examples SABER/TIMED measurements of OH emission rate (red, scaled to temperature axis) and temperature (blue) over Svalbard in January 2019. Top panel: Orbit 92668, bottom panel: orbit 92624.

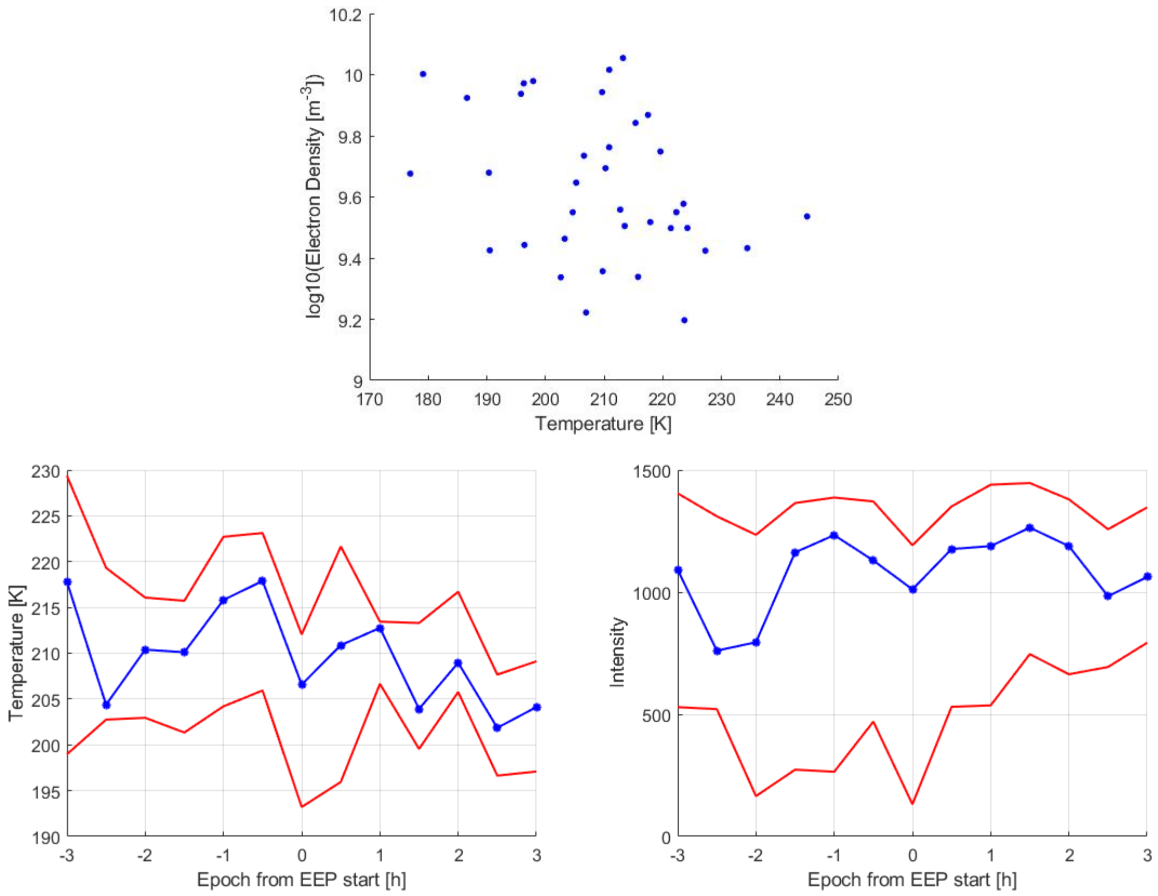

Figure 2. This figure illustrates the average temperature and intensity response to the EPP onset. The upper left panel shows a scatter plot of the electron density and the airglow temperature values (before, at and after the EPP onset). The superposed epoch of the airglow temperature in the lower left panel (airglow intensity, lower right panel) includes the 25% (lower red line), 50% (blue) and 75% (upper red line) percentiles of the temperature (intensity) for all eight events. The zero epoch time corresponds to the EPP onset. Each 30 min epoch time bin contains 3–7 temperature (intensity) values, maximizing around the zero epoch time.