Journal: ANGEO

Title: On the relationship of energetic particle precipitation and mesopause temperature

Author(s): Florine Enengl et al.

MS No.: angeo-2020-44

MS type: Regular paper

Iteration: Major Revision

Special Issue: Special Issue on the joint 19th International EISCAT Symposium and 46th Annual European Meeting on Atmospheric Studies by Optical Methods

Review

The paper presents a study of temperature changes at the polar winter mesopause during energetic electron precipitation (EEP) associated with geomagnetic storms. From over 10 years' data between 2007 and 2019, ten events are identified where electron density measured by the EISCAT Svalbard Radar shows distinct enhancements at 80–95 km and overlapping collocated OH airglow observations are available. Rotational OH temperatures, and intensities, have been derived from analysis of the night-time airglow measurements as 30-minute moving averages. Six of the 10 EEP events coincide with temperature decreases in the range 10–20 K, with temperatures recovering in less than an hour. The other four events show no significant temperature change. The observed temperature changes are interpreted as changes in the vertical profile of the OH airglow layer leading to a larger contribution from altitudes with lower rotational temperatures.

There is considerable scientific interest in understanding the impact of energetic particle precipitation (EPP) on the chemical and physical structure of the Earth's middle and upper atmosphere. EPP associated with auroral activity, geomagnetic storms, and solar proton events deposit energy into the polar mesosphere and lower thermosphere (MLT), together with Joule heating and the effects of atmospheric waves and tides. Temperature changes at the mesopause due to natural processes, and long-term trends associated with environmental change, are poorly understood. This study contributes to ongoing debate about the impacts of space weather and EPP on the MLT region, where heating modifies the thermal structure, chemistry, and circulation with subsequent coupling upwards affecting atmospheric density and satellite drag and downwards drivers linking to climate. Such observational studies can make an important contribution to understanding the various processes and improving model parametrisations.

The introduction and methodology sections of the paper are reasonably well written with sufficient relevant detail and citing of prior work. The choice of observational datasets, combined with the analysis techniques, is appropriate for the study. The main topic area – mesopause temperatures, EPP, and composition – is suitable for the journal. The results and discussion follow a logical order. My main concern about the paper is in the discussion of the ten selected events and conclusions about the atmospheric temperature response to EPP. These concerns are expressed in my two major comments. I have identified other areas in the text and figures where clarifications are needed and where the presentation and readability could be improved. My minor comments and suggested edits are listed below the major comments. In conclusion, I recommend a major revision of the paper, with the authors addressing my main comments and minor points, before the paper is considered further for publication in *ANGEO.*

Major comments

1. Temperature changes. Although the superposed epoch analysis (SEA, Figure 3) shows the lowest temperature (~198 K) coinciding with the time of (superposed) event onset, the ~20 K decrease is from a peak (~221 K) occurring immediately before onset which is not discussed. Furthermore, the temperature plots for individual events show instances before event onsets where temperature changes of 20 K or more occur in the absence of EPP. Therefore, I am unconvinced from the results presented that observed temperature changes can be linked to EPP occurrences. I recommend that the discussion and conclusions are revised to better

describe Figures 2 and 3, and the challenge of distinguishing EPP-temperature correlations from other variability clearly presented. A more rigorous statistical analysis of the temperature variations e.g., SEA of OH airglow temperatures for randomly selected periods *not* associated with EPP, would also help. I also question why, for the events (seventh and ninth) with the highest precipitating electron fluxes at onset, is no discernible temperature change found?

2. Sudden stratospheric warmings (SSWs). Two of the events (#2 and #10) follow within a week of major SSWs (https://csl.noaa.gov/groups/csl8/sswcompendium/majorevents.html) that would have strongly affected the northern hemisphere mesopause region including above Svalbard. Although gravity wave effects on winter mesopause temperatures are considered, the authors should discuss potential effects of these two SSWs as well as more general variability due to planetary waves, atmospheric tides, and the polar vortex that, as recent work shows (e.g., Harvey, V. L., Randall, C. E., Goncharenko, L., Becker, E., & France, J. (2018). On the upward extension of the polar vortices into the mesosphere. *Journal of Geophysical Research: Atmospheres, 123,* 9171– 9191. https://doi.org/10.1029/2018JD028815), extends well into the mesosphere.

<u>Minor comments</u>

Abstract

- Line 1. ‘Energetic Particle Precipitation’ should be ‘Energetic particle precipitation’.
- Line 5. ‘spectrum of the OH airglow’. The region of the spectrum and OH band system should probably be stated here. The location of the OH spectrometer should also be given in the Abstract.
- Line 5. ‘EISCAT’ needs to be defined.
- Line 9. ‘Most of our 10 electron precipitation events are associated with a temperature decrease of 10–20 K’. The exact number of events showing a temperature decrease needs to be stated. Perhaps ‘our’ should be changed to ‘the selected’, or similar- and an indication given of how the 10 events were selected.
- Line 16. ‘conclude that this type of particle precipitation event’. What type of particle precipitation event is being referred to here?
- Line 17. ‘if the lifetime of the precipitation was much longer than that of a typical EPP event found in this study’. The duration of a typical event in this study needs to be stated.

1. Introduction

- Line 21. The definition ‘EPP’ needs to be added after the first use of ‘energetic particle precipitation’ here, rather than on line 26.
- Line 27. Define ‘NOAA POES’.
- Line 28. Define ‘TIMED’. The TIMED instrument needs to be stated.
- Lines 34–35. ‘was observed due to precipitation of 250–800 keV protons (an intense solar proton event).’ The date(s) of the intense solar proton event should be added.
- Line 26. ‘The rotational hydroxyl (OH) airglow temperature’ should probably be ‘The hydroxyl (OH) airglow rotational temperature’.
- Lines 33–34. ‘at 85–90 km, only a minor cooling of 3–4 K’. In what way is 3–4 K only a minor cooling? Does this relate to the SABER instrument measurement accuracy or background quiet-time temperature fluctuations? It should be made clear here, and elsewhere in the paper, what constitutes a significant temperature change at the mesopause region e.g., due to EPP.
- Line 41. Clarify what is meant by ‘largest magnetic deflection’.

- Line 43. Clarify what is meant by ‘activity’. Geomagnetic activity?
- Line 63. ‘The results showed that the mesopause temperature from October to February…’ It should be made clear that the results are for the northern hemisphere. Presumably the same might be the case for the southern hemisphere winter months?
- Lines 65–66. ‘They concluded on a temperature change of about 4 K per 100 solar flux units (SFU) of the F10.7 radio flux.’ Is this temperature change associated with solar UV variability during the solar cycle or EPP? The following sentence suggests that EPP effects are another matter, but earlier in the paragraph solar activity is mentioned in terms of Ap. The effects on the mesopause of changes in solar activity – strongly indicated by F10.7 - and geomagnetic activity - indicated by Ap - need to be clearly distinguished.

2. Instrumentation

2.1 EISCAT Svalbard Radar

- Line 83–84. ‘D-region altitudes.’ The D-region isn’t yet mentioned. Suggest either include some words about the D-region or change to ‘mesopause altitudes’.

2.2 Ebert-Fastie airglow Spectrometer

- Line 91. ‘rotational OH(6–2) band’. More correctly, the OH(6–2) band is a rovibrational, or rotation-vibration band. However, it is probably correct to say that *rotational* temperatures are derived by analysing the P-branch lines of the band system.
- Line 92. ‘at Svalbard latitudes (78.2° N)’ should be ‘at the Svalbard latitude (78.2° N)’.
- Lines 93–94. ‘The spectral resolution of the OH(6–2) band is 0.4 nm.’ It needs to be made clear that this is the resolution of the spectrometer measurement. The true linewidth of the OH airglow lines will be much narrower.
- Line 94. ‘several scans are averaged’. Please state exactly how many scans are averaged. If half hour averaging is used, I would say that is going to be rather more scans than ‘several’.
- Line 95. ‘Most earlier studies use 1-hour averages. In this study, half-hour averaging is used’. Presumably 1-hour averages were chosen to reduce signal-to-noise in the airglow spectra to an acceptable level. What is the consequence on signal-to-noise, and temperature determinations, of the shorter, 30 minute averages used in this study?
- Line 99. ‘An oxygen auroral emission line at 844.6 nm’. It should be made clear that the auroral emission is from *atomic* oxygen.
- Lines 104–105. ‘at the event selection state. Once the events were selected’. It needs to be clarified what are the events being selected?
- Line 109. Clarify what is meant by ‘The error bars shown in this study represent the standard deviations (STD) over the averaged time’. How can standard deviations over the averaged time be determined from, as suggested earlier, averaged spectra?

3. Data description and event selection

- Line 115. ‘These experiments provide a sufficient height resolution’. State what is a sufficient height (altitude) resolution.
- Line 119. ‘from 1 March 2007 to 29 February 2008 (Blelly et al., 2010). This year includes 8784 hours in the ipy experiment mode.’ Which year is being referred to here?
- Line 121. ‘The total of 1388 hours of ESR data between 2008–2019 were analyzed in more detail.’ In more detail than what? Also, ‘were’ refers to the total and therefore should be ‘was’.

- Line 126. Perhaps the model atmosphere used could be stated / referenced?
- Line 129. Why were the altitude ranges 87–90 km and 91–94 km chosen? Perhaps the electron densities at lower altitudes (i.e., <87 km), overlapping the lower region of the OH airglow layer, are too noisy?
- Lines 131–132. Suggest change 'based on an earlier study by Cresswell-Moorcock et al. (2013). The onset is found by a sudden increase of the electron density (median value) by a factor of 5 over 5 minutes.' to 'based on an earlier study by Cresswell-Moorcock et al. (2013), in which onsets were found as sudden increases of electron density (median value) by a factor 5 over 5 minutes.' This then makes it clear what was done previously, compared to the following sentences that describe what was done in this study.
- Line 145. 'which where' should be 'which were'.
- Line 147 and Figure 1. 'The electron density during the radar run on 6 January 2019 from 16:00 UT to 22:00 UT is shown in Figure 1'. It should be pointed out here and in the Figure 1 caption that this example is the tenth event (#10) in the Results section. The lower panels of Figure 1 show essentially the same data as the corresponding plots in Figure 2 for that event, but with different (perhaps better) axis ranges. The temperature and intensity panels could be removed from Figure 1 and the text incorporated in the discussion of the tenth event (lines 222–226).
- Line 148. The electron density at the lower part of the ionosphere'. Please state the altitude range that is meant here.
- Lines 148–149. 'electron density … was low (mainly below 10^{10} m^{-3}) but abruptly increased at the EPP onset time.' Is the low electron density value for quiet-time conditions before EPP increases, and how abruptly does it increase?
- Line 150. What might be causing the large temperature variations (~20 K) in the hours before EPP onset?
- Line 154. 'During this experiment the radar was pointed to zenith, which is aligned with the spectrometer field-of-view.' This sentence is unnecessary since it has already been stated that the radar and spectrometer are collocated with overlapping views.
- Lines 155–156. I cannot see a missing temperature data point in Figure 1. What is the time of the missing measurement or data point?

4. Results

- Line 174. 'The electron precipitation lasts for about 30 min.' should be 'The increased precipitating electron flux lasts for about 30 min.' or similar.
- Line 176. 'relative OH(6–2) band intensity is 148 before the event and only slightly diminishes to 129 over the EPP onset'. Rather than terms such as 'only slightly', it would be better in the description of each event to quantify the change e.g., as a percentage decrease / increase.
- Line 184. 'The soft precipitation'. In what way is the precipitation soft? Since it is detected at 87–90 km, the electron precipitation could be described as harder than for events where it is detected higher up at 91–94 km.
- Line 195. 'stays slightly elevated'. State the value of the electron density that is slightly elevated.
- Line 213. Suggest change 'The light precipitation' to 'This modest increase in precipitating flux' or similar.
- Lines 229–235. The results section discusses correlations between electron density and airglow temperature / intensity in Figure 3. Regression lines for the data need to be added to the scatter plots and the correlation values stated.

5. Discussion

- Line 245. ‘10 degrees’ should be ’10 K’. Rather than ‘often larger…’, it should be stated for exactly how many events the temperature change was larger than 10 K.
- Lines 247–248. ‘the fast temperature decrease and equally quick recovery shown by the superposed epoch analysis (bottom left panel of Figure 3) would not be seen as a change in hourly or daily averaged epoch’. I agree that daily averaged epochs are unlikely to show the temperature decrease, but hourly averages may do so. Suggest the authors either remove the statement about hourly data or substantiate the claim e.g., by showing the 30-minute data smoothed to hourly averages.

6. Conclusions

- Line 302. Suggest change ‘downward temperature decrease by 5–10 K/km at the airglow altitude’ to ‘decreasing temperature of 5–10 K/km over the airglow altitude range’, or similar.
- Line 310–311. ‘Energetic electron precipitation’ is defined as ‘EPP’ whereas that abbreviation was used previously (lines 1 and 26) for ‘energetic particle precipitation’.
- Line 317. ‘only a few decrease’. I think this should be ‘only a few degrees’.

Figure 1

- The upper altitude of the electron density panel should be set at 160 km as there are no plotted data higher up.

Figure 2

- The colour bars of the electron density panels are missing titles.
- The vertical axis limits of the electron density, temperature, and intensity panels need to be adjusted to more clearly show the plotted data without significant white space, and without clipping the error bars.

Figure 3 caption

- ‘The lower percentile for intensity (is) 35%.’ Why is the lower percentile set at 35% rather than 25% as for temperature?
- ‘Each 30 min epoch time bin contains 6–10 temperature (intensity) values.’ Why does the number of values in each bin vary between 6 and 10?