Middle Atmospheric Ionization During Solar Proton Events in WACCM-D and Riometer Observations

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Introduction

Solar proton events (SPEs) cause large-scale ionization in the middle atmosphere leading to ozone loss and changes in the energy budget of the middle atmosphere. The accurate implementation of SPEs and other particle ionization sources in climate models is necessary to understand the role of energetic particle precipitation in climate variability. We use riometer observations from 16 riometer stations and the Whole Atmosphere Community Climate Model with added *D* region ion chemistry (WACCM-D) to study the spatial and temporal extent of cosmic noise absorption (CNA), the effect of geomagnetic cutoff on the CNA, and the ability of WACCM-D to reproduce the magnitude and time behavior of observed CNA during 62 solar proton events from 2000 to 2005.

Observational Data and WACCM-D

- Riometer data from two arrays of riometers; seven Sodankylä Geophysical Observatory (SGO) wide-beam riometers and two imaging riometers (Longyearbyen and Kilpisjärvi) in northern Europe and seven GO-Canada riometers in Canada.
- Observational data averaged to one hour time resolution. 27 events removed from SGO data in the winter months of 2000 to 2003 due to unknown radio interference.

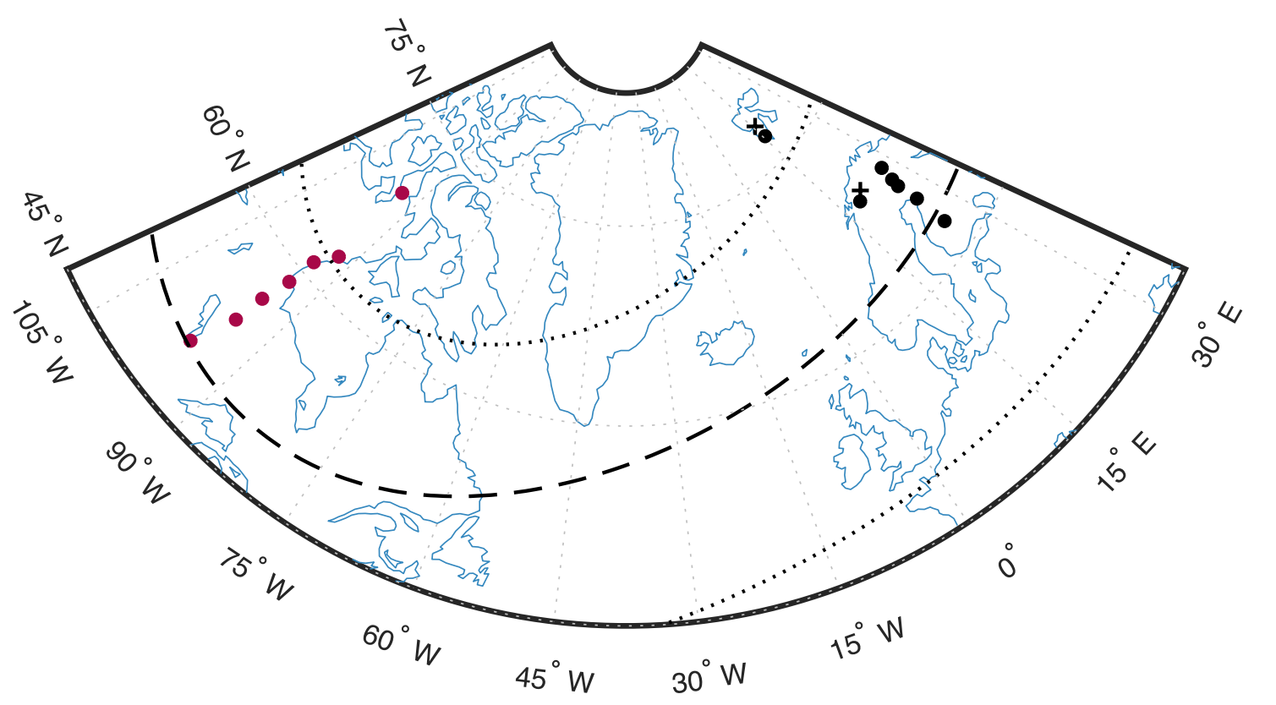

Figure 1: The used riometers (red dots: GO-Canada, black dots: SGO, black plus signs: imaging riometers) and CGM lat limits for SPE (dashed line) and MEE (dotted lines) ionization used in WACCM-D.

Model data from WACCM-D [*Verronen et al.*, 2016]:

- WACCM-D run with specified dynamics and spans from the Earth's surface to about 140 km.
- Ionization sources: Hourly SPE ionization rates [*Jackman et al.*, 2005] applied uniformly poleward of 60° geomagnetic latitude (CGM lat) based on GOES, medium-energy electrons (MEE, 30-1000 keV) with a daily resolution [*van de Kamp et al.*, 2016], and standard WACCM ionization sources for solar EUV, auroral electrons, galactic cosmic rays, and solar Lyman-α.
- Differential CNA calculated from model data for each riometer station, and integrated over the atmospheric column to produce modeled CNA with one hour time resolution.

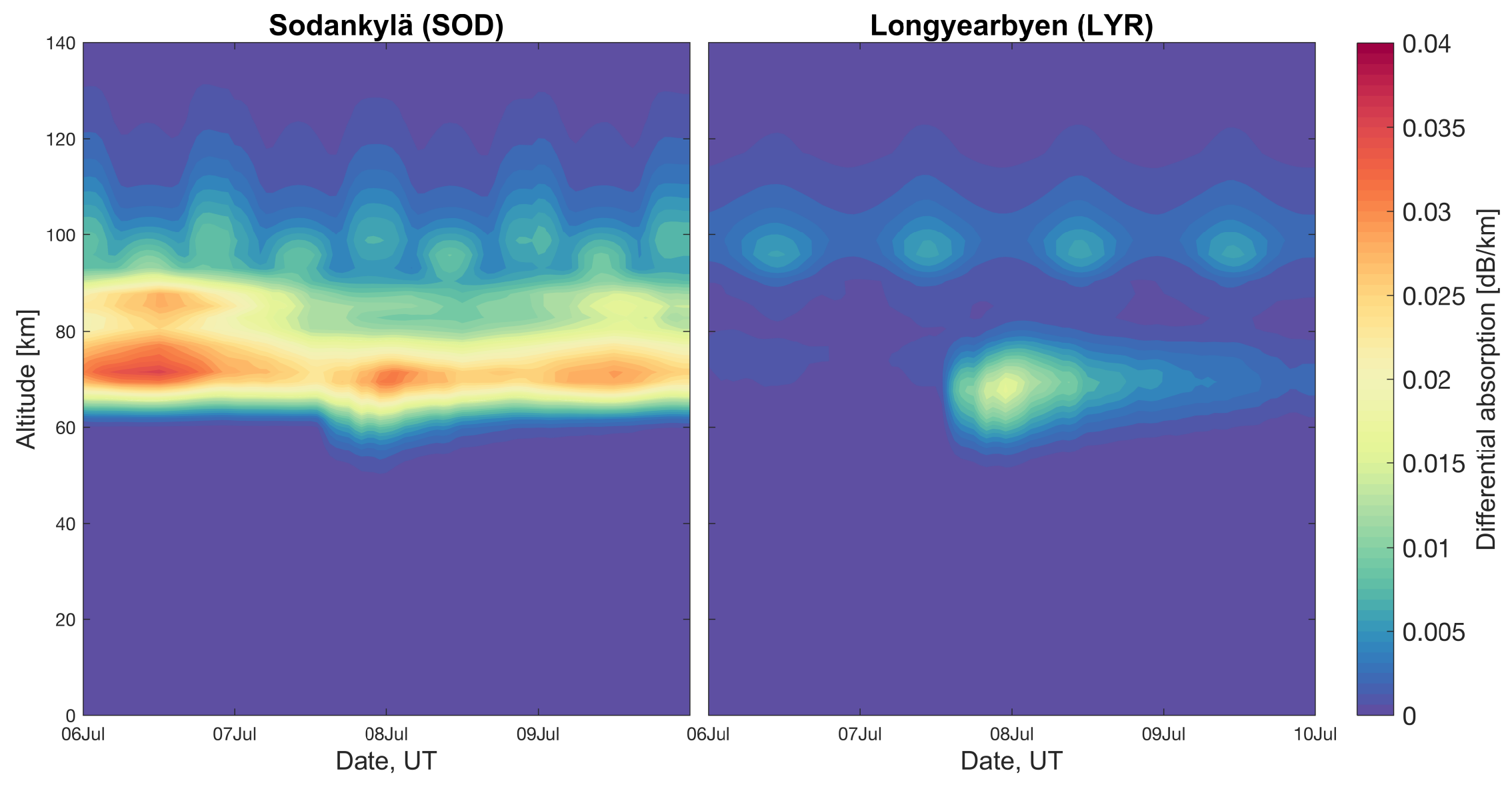

Figure 2: Modeled differential absorption during a weak SPE (7 July 2002, max 22 pfu).

Solar Zenith Angle and Geomagnetic Latitude

Comparison of modeled and observed CNA as a function of solar zenith angle, χ, and CGM lat:

- The Field-of-view (FoV) of each riometer assumed to be ±0.5° in CGM lat.
- Data binned to 5° solar zenith angle bins and median CNA calculated for each bin with more than ten data points (15 to 268 data points in the remaining bins).
- Overlapping FoVs (in CGM lat) averaged.

Findings:

- WACCM-D underestimates CNA in sunlit conditions and overestimates CNA in dark conditions poleward of 70° CGM lat.
- Increasing difference equatorward of about 66° CGM lat due to MEE overestimation and gradual geomagnetic cutoff effect.
- Twilight transition more abrupt and at larger χ values in WACCM-D than in observations.
- Main geomagnetic cutoff effect at 62° to 63° CGM lat in observations.

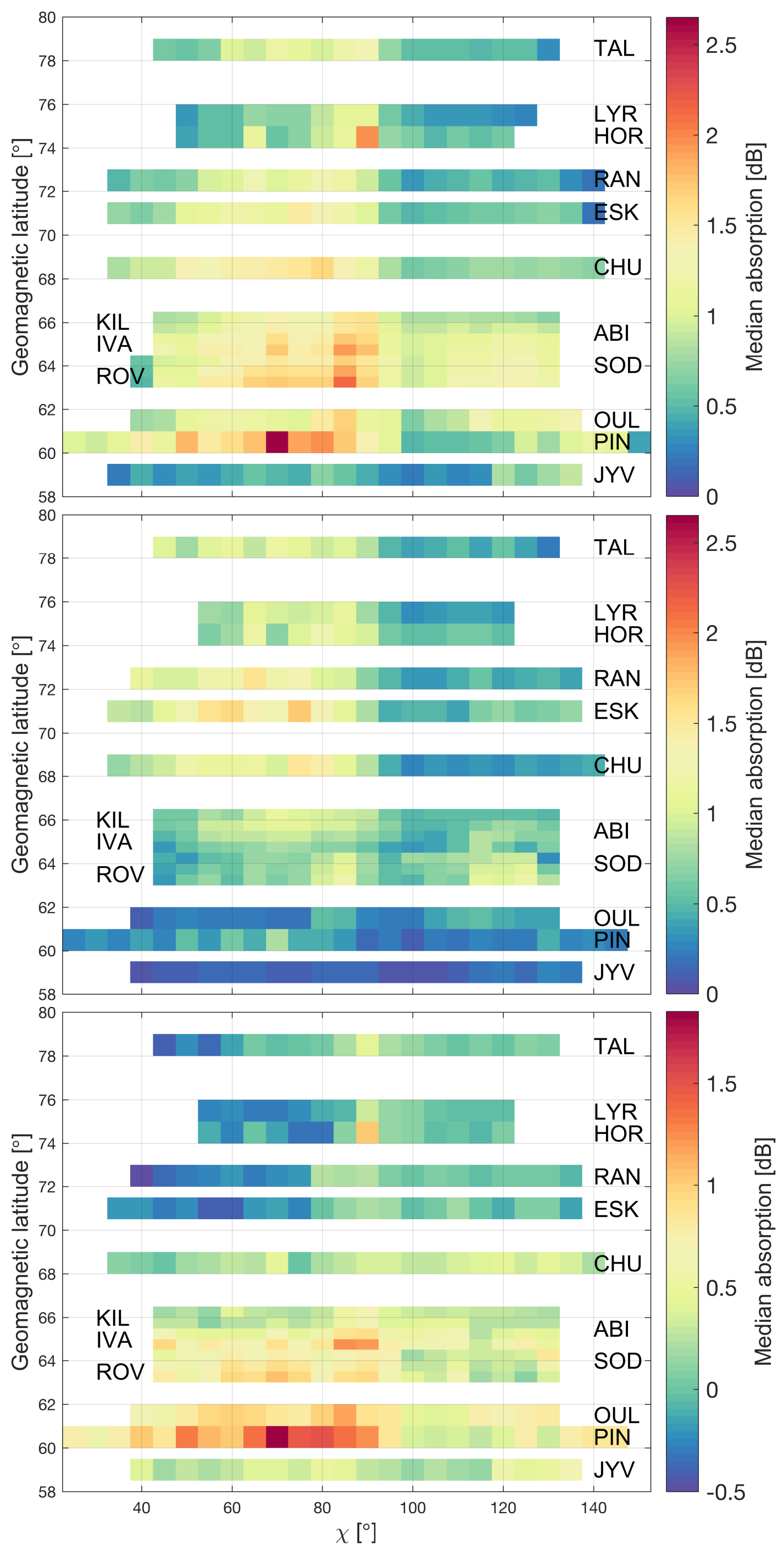

Figure 3: Median CNA from WACCM-D (top) and observations (middle), and the difference between WACCM-D and observations (bottom).

References:

Verronen, P. T. et al. WACCM-D - Whole Atmosphere Community Climate Model with D-region ion chemistry. *Journal of advances in Modeling Earth Systems*, 8(2):954-975, 2016

Jackman, C. H. et al. The influence of the several very large solar proton events in years 2000-2003 on the neutral middle atmosphere. *Advances in Space Research*, 35(3):445-450, 2005

van de Kamp, M. et al. A model providing long-term data sets of energetic electron precipitation during geomagnetic storms. *JGR: Atmospheres*, 121(20):12520-12540, 2016

Non-Linear Response

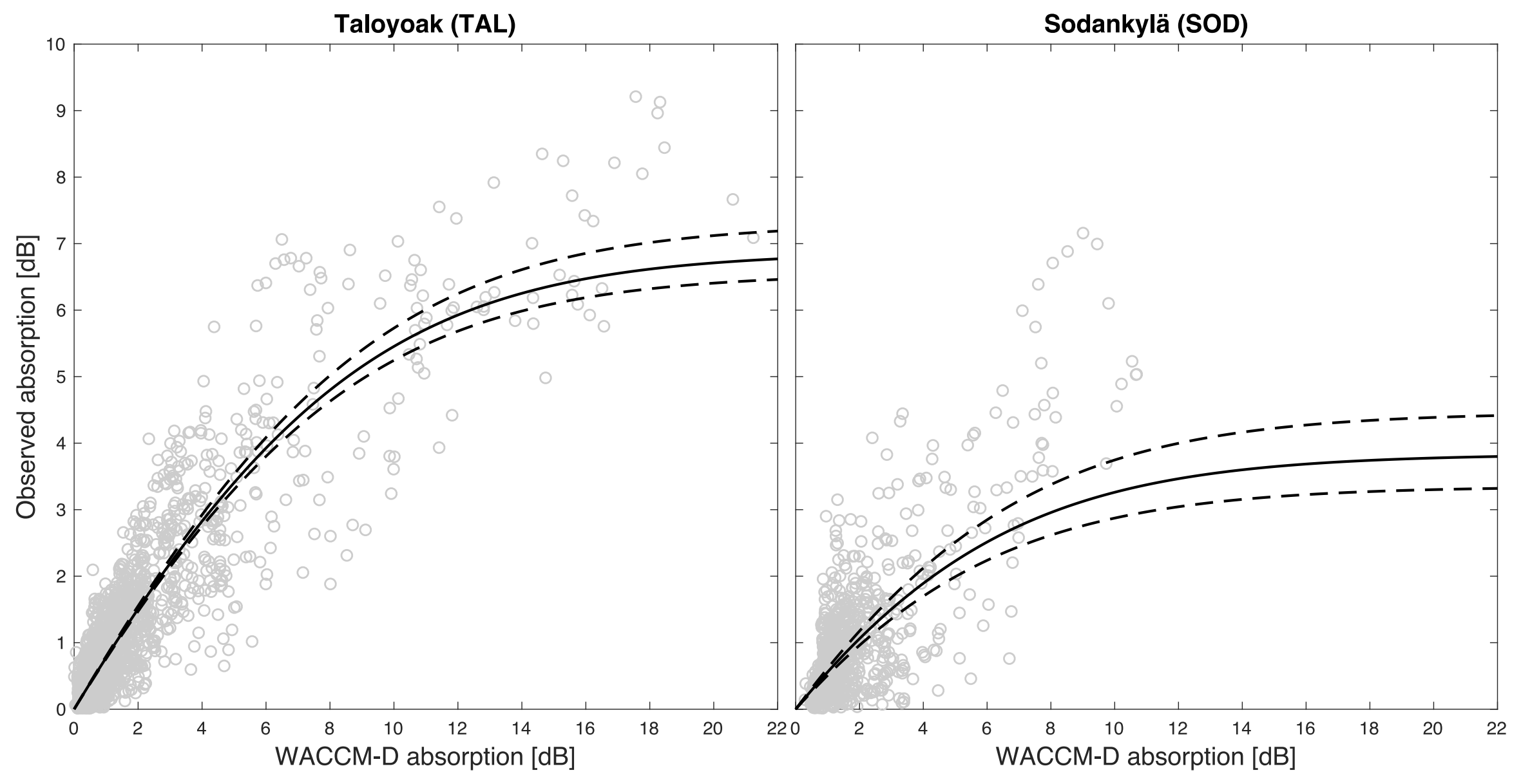

Figure 4: Modeled and observed CNA at Taloyoak (left panel) and Sodankylä (right panel) with fitted non-linear correction and 95% confidence intervals. TAL shown as an example of a good fit and SOD as an example of a poor fit of the correction method.

Observed wide-beam riometer CNA becomes non-linear at high absorption values. The imaging riometers were found to be linear. Suggestion for a correction method for the non-linearity:

$$A = 10 \cdot \log_{10}\left(\frac{1+1/R}{10^{-A_s/10}+1/R}\right),$$

where A is the observed absorption, A_s is the true absorption of the ionosphere, and R is the ratio between the wanted and unwanted radio noise. Using modeled CNA as the true absorption, and R as a fitted free parameter, the non-linearity of each riometer can be determined.

Observed and Modeled CNA in Example Events

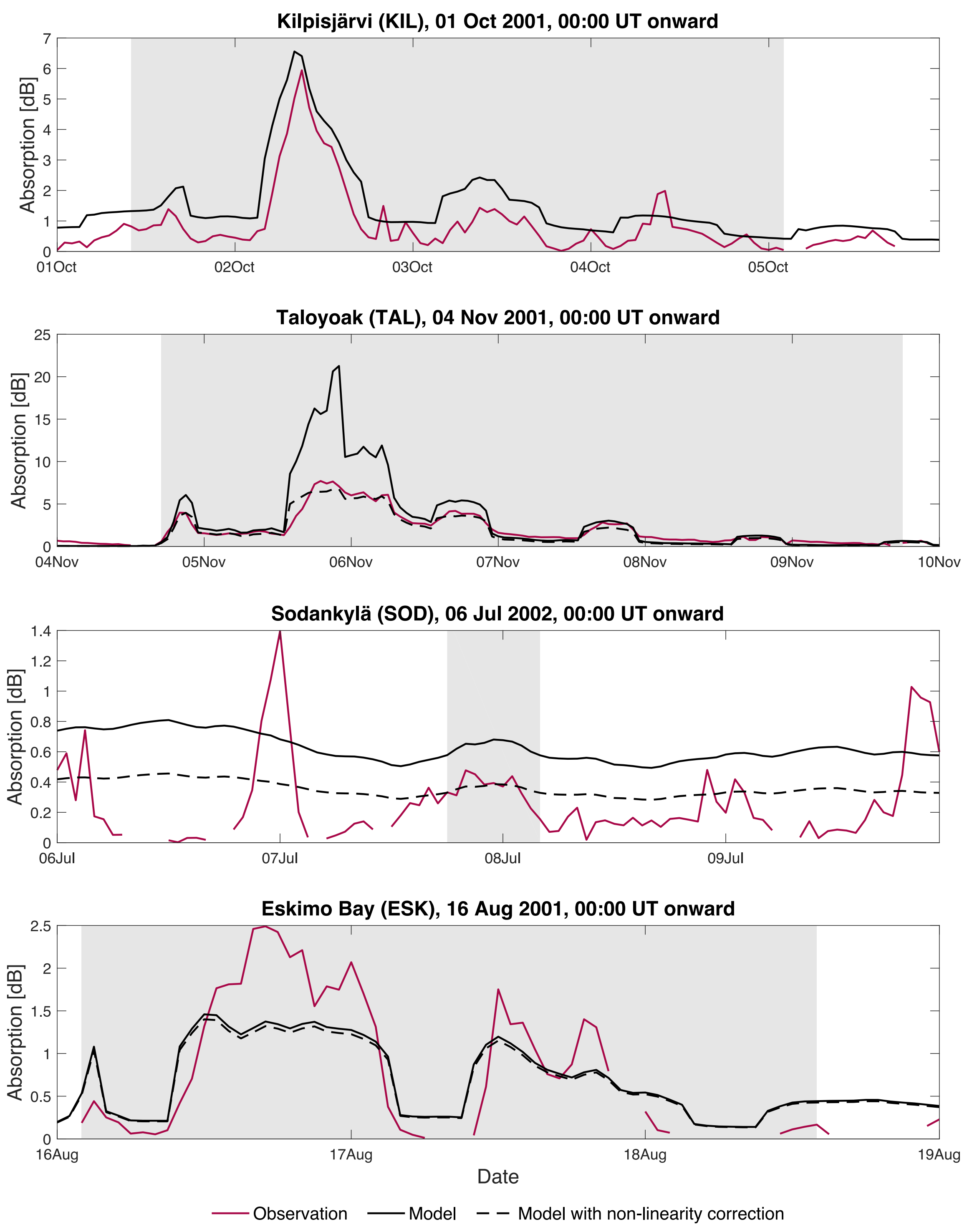

Figure 5: Examples of modeled and observed CNA during four SPEs at four different stations. Solid black lines are modeled CNA values, dashed black lines are modeled CNA values with the non-linear correction applied, and the solid red lines are observations. Note, that the top panel does not have a non-linear response corrected line. The gray shaded areas indicate the time periods of the SPEs. The event in the third panel is also shown in the left panel of Figure 2.

Conclusions

We summarize the results of this study as follows:

1. Poleward of ~66° CGM lat, average absolute difference between model and observations <0.5 dB varying with solar zenith angle and station.

2. Equatorward of ~66° CGM lat, the average difference increases with decreasing latitude from about 0.5 dB to 1 dB due to the daily zonal mean MEE forcing and the uniform proton forcing.

3. CNA overestimated by WACCM-D in twilight conditions due to the used Earth shadow implementation.

4. More investigations are required to explain the underestimation of CNA in sunlit conditions poleward of ~66° CGM lat by WACCM-D in 18 events (see bottom panel of Figure 5).

5. Non-linearity correction works well at some of the stations, but is sensitive to data selection.

6. Spatial extent of CNA overestimated by about 2° to 3° CGM lat on average. Seems to decrease to about 1° geomagnetic latitude when data are limited to the extreme events.

The results presented here should be compared with comparison runs of the WACCM-D model with improved proton cutoff constraints and MLT-dependent MEE fluxes.

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