DEMETER Satellite Observations of Lightning-Induced Electron Precipitation Events

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Motivation

Earth's magnetosphere is occupied by high-energy particles trapped within the Earth's magnetic field. The particle energies range from hundreds of keV to hundreds of MeV. Such energetic particles introduce a hazard for satellite instruments and astronauts. With an increasing number of satellites in the inner magnetosphere and potential tourists traveling to space, the need to understand the dynamics of respective environments is also increasing. In this work, we focus on the influence of lightning on electron precipitation from the Earth's magnetosphere.

Introduction

Lightning-induced electron precipitation

The particles are trapped within the Earth's magnetic field forever unless they interact, e.g. with waves. Such particle populations are called Van Allen radiation belts. A possible way of losing these particles is via lightning-induced electron precipitation (LEP) events.

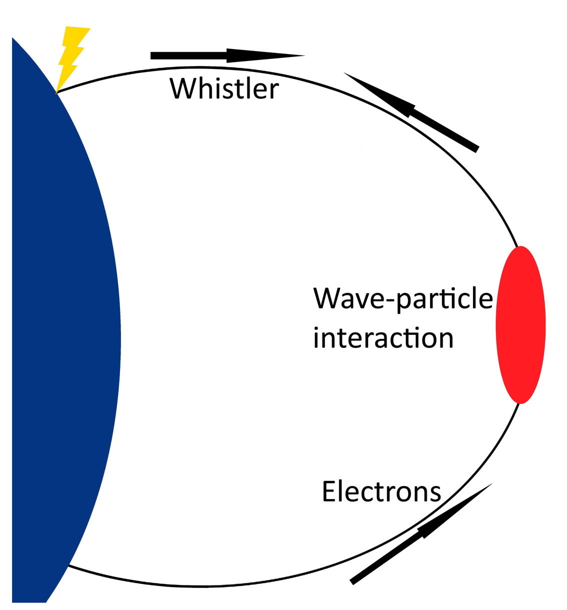

Figure 1. An overview of the LEP event.

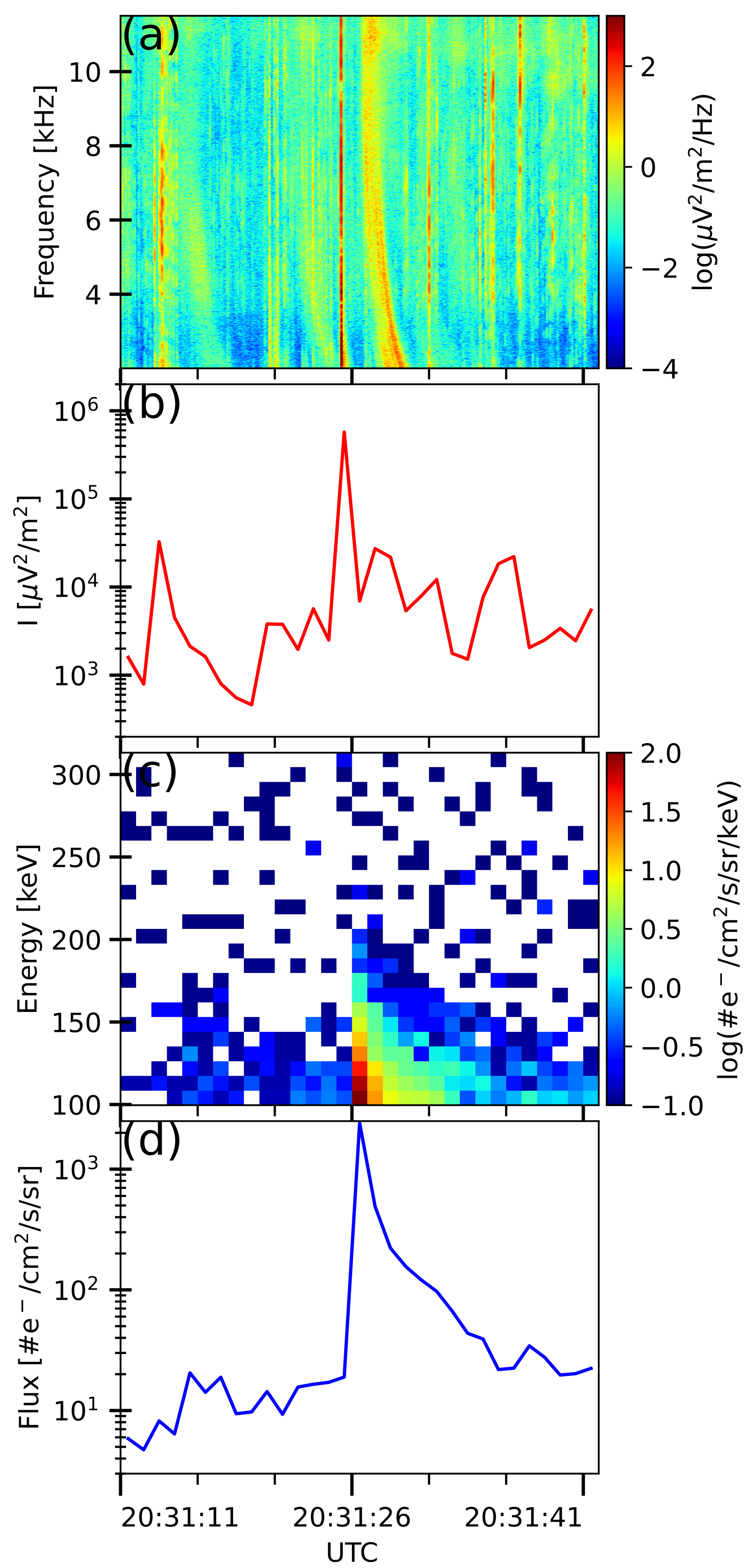

Figure 2. LEP event example from May 22, 2008

DEMETER

- Satellite orbiting Earth between 2004-2010
- Orbit only during local Day/Night (10:30/22:30 LT)
- We use IDP and ICE-VLF survey data between 2006 and 2010
- IDP — electron flux in loss cone with energies between 70 keV and 2.34 MeV with 4 s resolution
- ICE-VLF — power spectral density of electric field fluctuations in the VLF range with 2.048 s resolution

WWLLN

- World Wide Lightning Location Network
- Global network of VLF sensors
- Time-of-arrival method => Lightning locations and times
- Non-stable detection efficiency

LEP event detection

The goal is to detect events such as in Figure 2. We look for peaks in wave power and electron flux which occur approximately at the same time (shift between wave and electron flux peaks is allowed to be between -0.5 s and 1 s). Electric field power frequency range is between 2 and 11.5 kHz and precipitating electron flux energy range is between 100 and 300 keV.

The detection algorithm:

- We take 31 s long data intervals (1 s shift between each other).
- Compute integral wave power and electron flux.
- Compute median and standard deviations.
- If both integral wave power and integral electron flux exceed their respective medians by more than 2.25 times the standard deviation → potential LEP event.
- Finally manually verify potential events.

Final dataset consists of 440 LEP events. The geographic distribution is shown in Figure 3. Most events are above the U.S. East Coast.

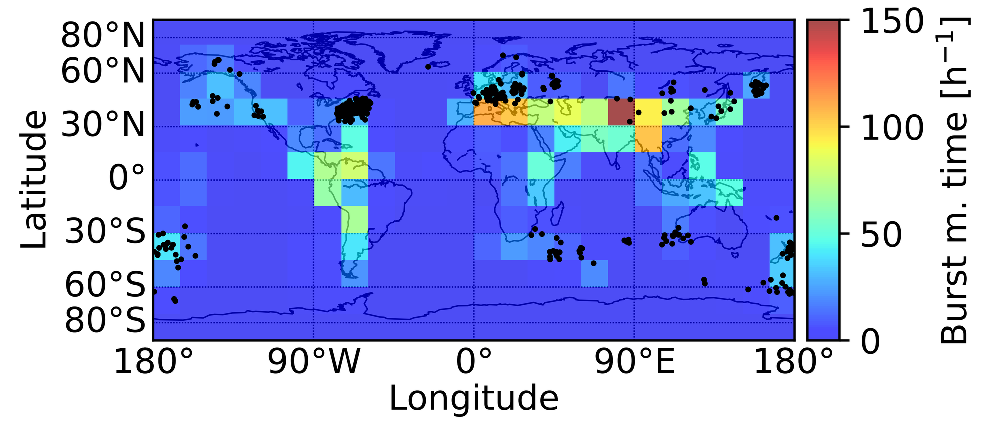

Figure 3. Global LEP event distribution

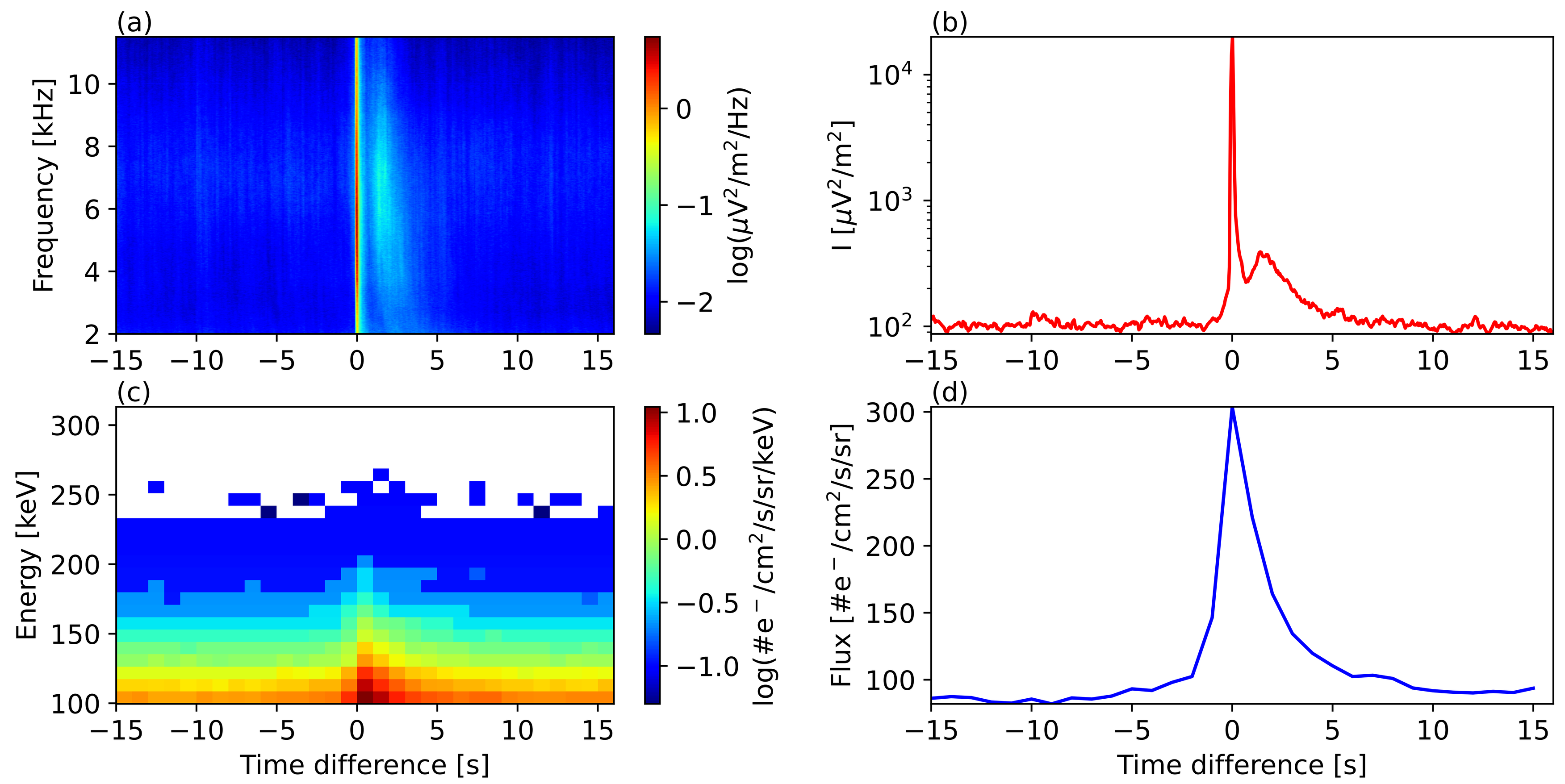

Figure 4. Median time dependencies of identified LEP events. (a) Electric field PSD spectrogram. (b) Electric field power at 2–11.5 kHz. (c) Precipitating electron flux (energy–time). (d) Flux time series at 100–300 keV.

Figure 4 shows the median characteristics from superposed epoch analysis of all 440 LEP events:

- Clear low-dispersion whistler in the center of (a,b) followed by weaker high-dispersion whistler (reflection).
- The LEP-related flux increase up to 200 keV and spread over several seconds.

Key takeaways

- Lightning play a significant role in electron precipitation from radiation belts.
- LEP events occur mostly above the U.S. East Coast and Europe.
- Respective wave powers and electron fluxes are systematically higher during the night (lower ionosphere attenuation).
- Total electron precipitation from isolated LEP events seems insufficient to explain the observed summer-winter differences (possible importance of non-ducted whistlers).
- The results can be found at Linzmayer et al. (2025), DOI: 10.1029/2024JA033639

Average wave and electron spectra

The average event spectra are determined as the average differences between the event peak (0.1 s for waves and 3 s for fluxes) and the corresponding background values.

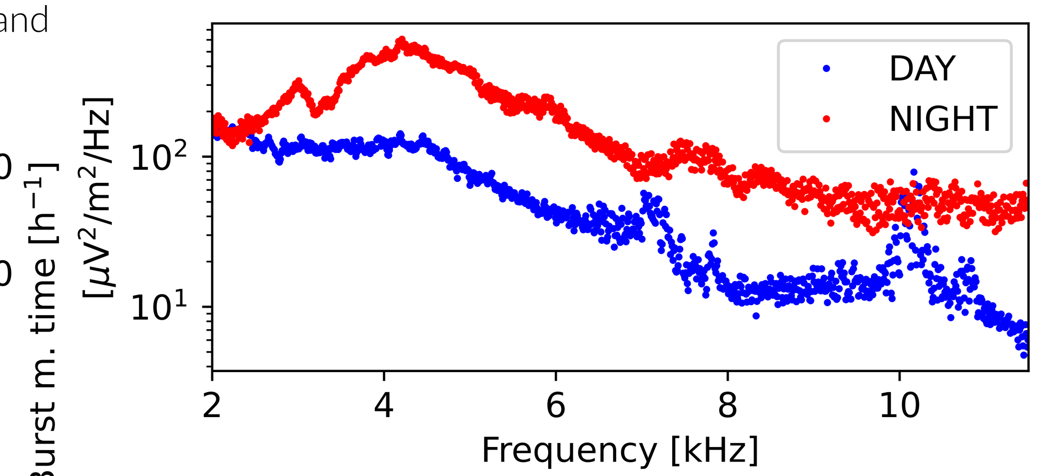

Figure 5. Average 0.1 s wave spectrum.

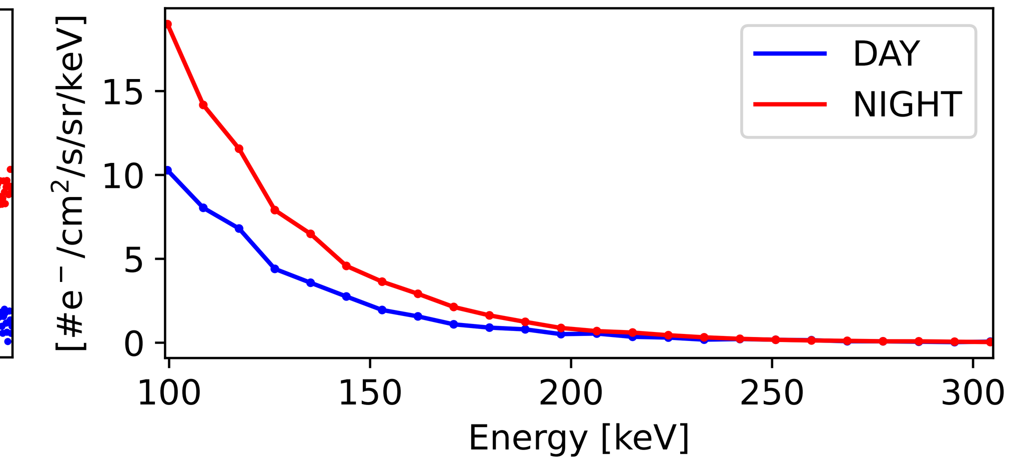

Figure 6. Average 3 s electron spectrum.

- Shapes of the spectra are rather similar for daytime and nighttime for both the waves and fluxes. However, the respective intensities are larger during the night.

Summer-winter difference estimation

Finally, we investigate whether it is possible to explain the summer-winter differences in DEMETER survey data above U.S. region as the cumulative effect of numerous isolated LEP events. We assume the following: i) each lightning stroke results in a LEP event, ii) duration of LEP event is 0.1 and 3 s for waves and electron fluxes, respectively, and iii) each lightning stroke homogeneously affects a circular area with radius of 1,000 km.

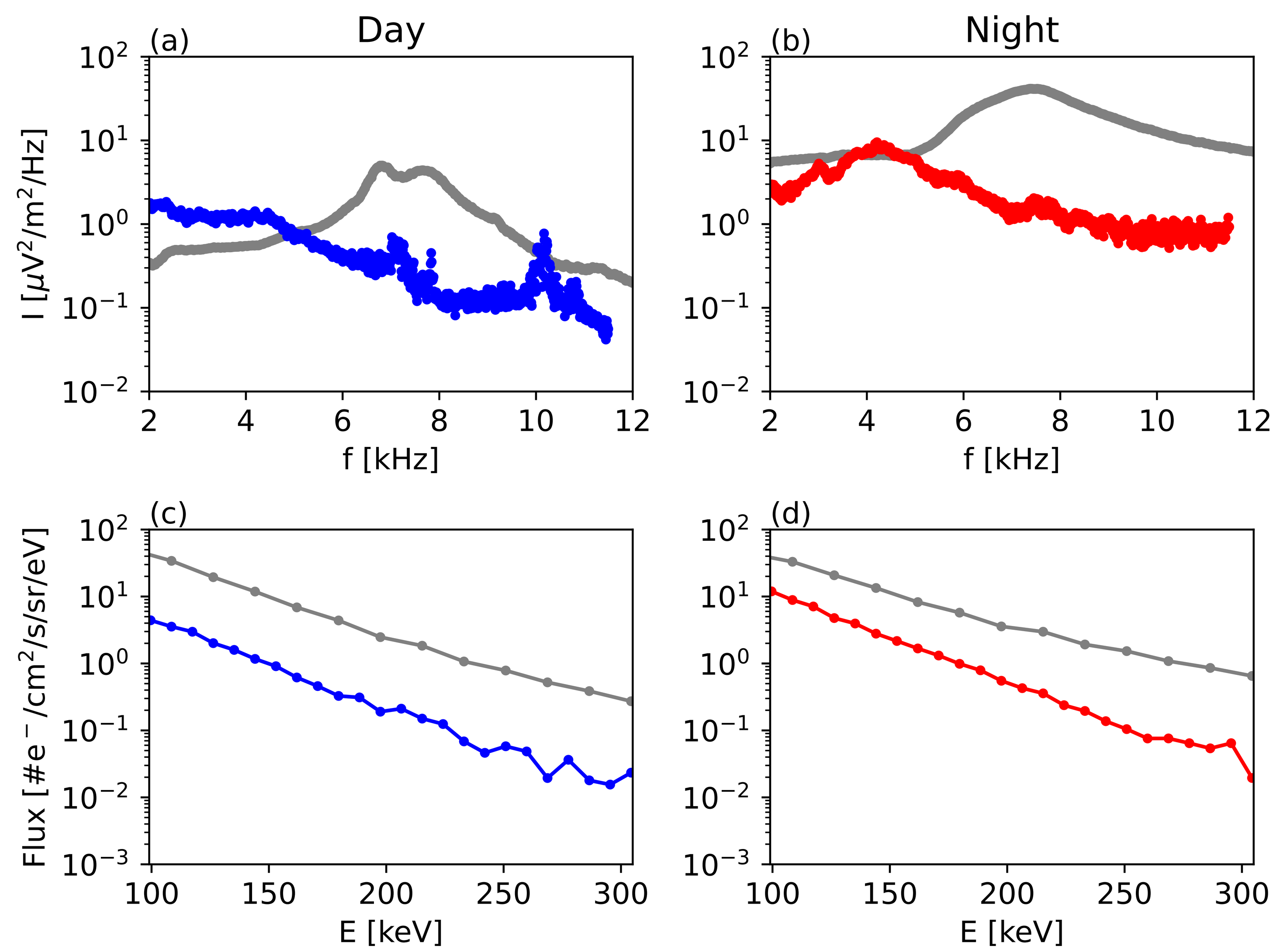

Figure 7. Comparison between observed (gray dots) and estimated (blue/red dots) summer-winter differences in daytime/nighttime wave intensities (first row) and electron fluxes (second row).

The resulting upper estimates of the cumulative effect of individual LEP events are calculated by multiplying the average wave/electron spectra, the summer-winter difference in the number of lightning strokes and the event duration. The estimates are further normalized to 1 s and the U.S. area. The summer-winter differences in wave intensities can, to certain extend, be explained by the LEP event cumulative effect. However, the difference in precipitated fluxes is notably larger.

We believe that the main issue lies in non-ducted whistlers not being considered in our analysis. The non-ducted whistlers reflect at lower hydrid frequency (above DEMETER). They would thus effect the wave measurements once, but contribute to electron precipitation possibly several times (during each equatorial crossing).

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