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Lightning-Induced Energetic Electron Precipitation Observed in Long-Term DEMETER Spacecraft Measurements

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Abstract

We use low-altitude DEMETER spacecraft measurements obtained between 2006 and 2010, complemented by WWLLN lightning location data, to investigate the importance of lightning-generated whistlers for the energetic electron precipitation from the Van Allen radiation belts. We focus, in particular, on the United States region, where there is a significant seasonal variation in the occurrence of lightning. We show that both the precipitating electron fluxes and very low frequency wave intensities correlate well with the total lightning occurrence in the region. We further demonstrate that lightning-induced electron precipitation is more significant during the nighttime than during the daytime, and during periods of low geomagnetic activity compared to periods of high geomagnetic activity.

1. Introduction

Lightning is a source of electromagnetic waves that propagate inside the Earth-ionosphere waveguide. These waves can also penetrate the ionosphere and propagate through the magnetosphere either in ducted mode (along the magnetic field line) or nonducted mode [1]. Such waves are called whistlers. They span over a larger frequency range but tend to be best pronounced approximately between 500 Hz and 12 kHz at L-shells between 2 and 3 [2]. Upon reaching the equatorial region of the radiation belts, whistlers may effectively interact with trapped energetic electrons. During these interactions, the electron pitch-angles can be considerably altered, and the electrons can move into the loss cone [3]. Consequently, each lightning may potentially increase precipitating electron fluxes. This effect is known as lightning-induced electron precipitation (LEP) [4, 5, 6,].

LEP effects were studied both using individual LEP events [4, 5, 6] and statistical methods [7, 2, 8]. One possible approach is to study a long-term relation between the number of lightning in a certain region and precipitating flux over the same region. Such a study was performed for the U.S. region using nighttime DEMETER spacecraft measurements between the years 2006 and 2008, comparing the data measured during August (high number of lightning) and December (low number of lightning) [7]. It showed that the electron flux measured over the U.S. region is significantly larger during August than during December, indicating the overall importance of lightning for electron precipitation. However, the possible effect of the geomagnetic activity and its peak in mid-September was not considered. In the present study, we use 5 years of DEMETER data and a direct comparison with lightning occurrence rates and the Dst geomagnetic index to overcome this issue.

2. Data

The primary data sources for this work are the French micro-satellite DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) and the WWLLN (World Wide Lightning Location Network) database of lightning locations.

DEMETER (2004-2010) had an original altitude of about 710 km, which was decreased to about 660 km in December 2005. For this reason, only data from the years 2006-2010 are used in the present study. The orbit was Sun-synchronous (10:30/22:30 LT) [9]. Data obtained from two instruments onboard are used: the Instrument for Particle Detection (IDP) [10] and the electric field instrument (ICE) [11] in the VLF range (19.5 Hz to 20 kHz). Given the low altitude of the spacecraft and the IDP field of view, the measured energetic electron fluxes correspond to pitch angles close to the edge of the loss cone.

WWLLN has been monitoring global lightning activity since 2005. Using a network of ground-based sensors, the system triangulates the location of individual lightning. It is important to point out that not all lightning strikes are detected, and the detection efficiency has gradually increased over time as new ground-based stations are added to the network.

3. Results

Following the former study [7], we focus on the U.S. region (geomagnetic longitude 300° – 360°, L-shell between 2 and 3). This region is advantageous for two main reasons:

i) there is a large difference between the total number of lightning during the local summer and winter, which facilitates the studies of lightning-related phenomena, and ii) it is a region westward of the South Atlantic Anomaly [12], i.e., the drift loss cone has not yet been emptied, and there are many particles with pitch angles not too far from the bounce loss cone. We further distinguish between low ($\mathrm{Dst} > -20$ nT) and high ($\mathrm{Dst} < -20$ nT) geomagnetic activity.

Following the Sun-synchronous DEMETER orbit, we consider only lightning occurring in the region of interest during the "daytime" (from 9:30 to 11:30 LT) and during the "nighttime" (from 21:30 to 23:30 LT). In order to account for the increasing WWLLN detection efficiency, we multiply the number of lightning detected in earlier years by a year-dependent factor, so that the total number of lightning in each year is the same as in 2010. The resulting time dependence of the total number of lightning with a one-month time resolution is depicted in Figures 1 to 4 by the black or white curves, separately for the daytime (panels a) and nighttime (panels b).

Figures 1 and 2 show dependences of average DEMETER-measured electron fluxes at a representative energy of about 230 keV on L-shell and time during low and high geomagnetic activity, respectively. The resolution in L-shell is 0.05 and the resolution in time is one month. It can be seen that during the summer periods, when the number of lightning increases considerably, the energetic electron flux also increases over essentially the entire analyzed L-shell range. The effect seems to be arguably slightly stronger during the night than during the day, and the periodic annual variation is much better pronounced during the low geomagnetic activity than during the high geomagnetic activity.

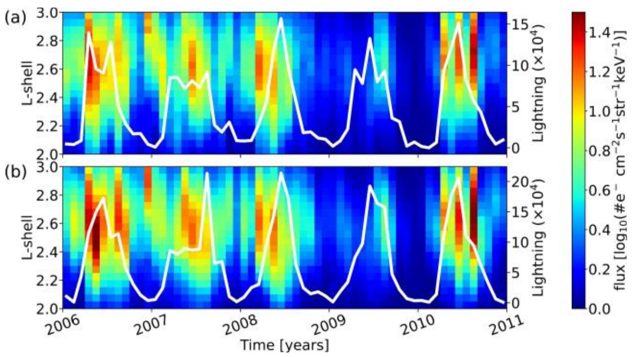

Figure 1. Time and L-shell dependence of IDP measured electron fluxes with an energy of 233.1 keV during low geomagnetic activity ($\mathrm{Dst} > \mathbf{-20}$ nT). (a) Day and (b) night measurements, averaged in monthly bins with a 0.05 L-shell resolution. The white curve represents the total number of lightning detected each month.

Hereinafter, we mostly focus on the measurements performed during periods of low geomagnetic activity, when lightning-related phenomena apparently dominate over other relevant effects.

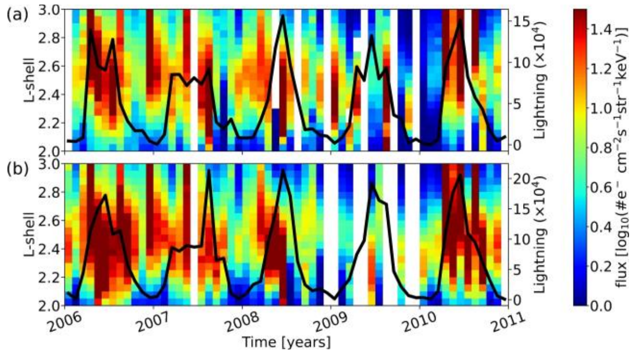

Figure 2. Time and L-shell dependence of IDP measured electron fluxes with an energy of 233.1 keV during high geomagnetic activity ($\mathrm{Dst} < \mathbf{-20}$ nT). The format is the same as in Figure 1.

Figure 3 shows the dependence of the average electron flux measured during the low geomagnetic activity in the L-shell range between 2 and 3 on energy and time. It can be seen that the aforementioned seasonal variation of the measured electron flux is identifiable over a rather broad range of electron energies.

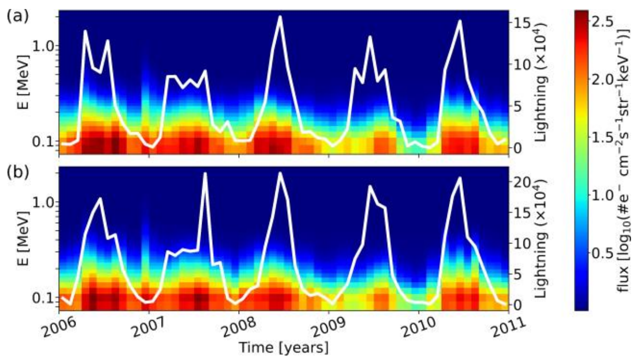

Figure 3. Time and energy dependence of IDP measured electron fluxes in the northern hemisphere during a low geomagnetic activity ($\mathrm{Dst} > \mathbf{-20}$ nT). (a) Day and (b) night measurements, averaged in monthly bins with 128 energy bins corresponding to the IDP survey mode resolution. The white curve represents the total number of lightning detected each month.

Given that the observed variations in the energetic electron precipitation are believed to be caused by lightning-generated electromagnetic waves, DEMETER wave measurements are further investigated. Figure 4 shows the average power spectral densities of electric field fluctuations during the periods of low geomagnetic activity as a function of frequency and time. A clear seasonal variation in wave intensities is observed, peaking in the summer and reaching minima in the winter. This pattern is particularly striking during the night when wave attenuation in the ionosphere is lower.

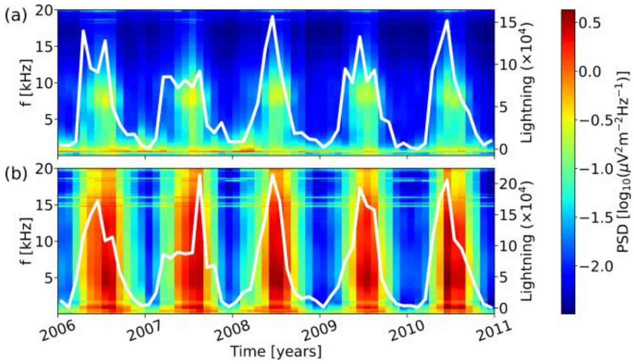

Figure 4. Time and frequency dependence of ICE measured wave intensities during a low geomagnetic activity ($\mathrm{Dst} > -\mathbf{20}$ nT). (a) Day and (b) night measurements, averaged in monthly bins with a 19.53 Hz resolution. The white curve represents the total number of lightning detected each month.

In order to further demonstrate the relation between the lightning occurrence and precipitating electron fluxes, and to determine the most affected electron energies, the respective correlation coefficients are analyzed in Figure 5. It shows Spearman's rank correlation coefficients between the monthly total number of lightning and the corresponding average electron fluxes as a function of electron energy. The blue/red curves correspond to the periods of low/high geomagnetic activity, and the dashed/solid curves correspond to the daytime/nighttime measurements. The energy range of the IDP instrument extends up to about 2 MeV. However, the correlation coefficients at energies above approximately 1 MeV drop down to 0, so that the energies beyond 1 MeV are not displayed. Otherwise, significant correlations are observed across a broad range of energies, peaking at about 150-200 keV. Moreover, the correlation values tend to be somewhat larger during the night and periods of low geomagnetic activity, in agreement with the aforementioned results.

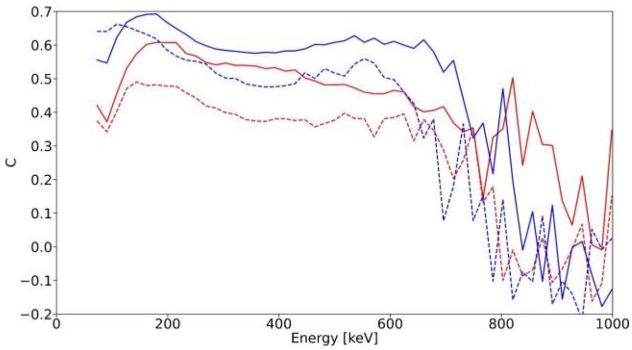

Figure 5. Spearman's rank correlation coefficients between the monthly total number of lightning and total precipitating electron flux at L-shells between 2 and 3 as a function of electron energy. The red/blue lines represent high/low geomagnetic activity, and the solid/dashed lines correspond to night/day measurements.

4. Discussion

The WWLLN detection efficiency has improved over the years, which we need to account for when determining the total number of lightning in each month. Unfortunately, there is no information about the detection efficiency for the earlier years. The normalization is thus achieved by assuming that the detection efficiency does not change during a single year and that the total number of lightning each year is the same. This necessarily introduces some errors in the number of lightning considered, particularly during the earlier years analyzed. However, as it is the seasonal variation of the lightning occurrence rather than the exact number of lightning, these potential errors do not significantly affect the results obtained.

The analysis itself is then based on a global comparison of the monthly-averaged lightning activity and monthly-averaged precipitating fluxes/wave intensities over a rather large geographic region. When shortening the considered time interval, the results are essentially conserved, and the seasonal variation is still apparent, but the overall correlation between the number of lightning and the precipitating fluxes decreases. This is a consequence of the situation becoming noisier, with the number of lightning and measured fluxes oscillating considerably. This indicates that the electron fluxes are controlled by many other factors on top of the lightning activity. However, it is also a consequence of the fact that no other pairing of the lightning and spacecraft measurements is done apart from the rather broad geographic and temporal constraints. Despite these limitations, the used approach turns out to be very effective in assessing the overall lightning-related effects on the energetic electron precipitation.

Our results show that the lightning-induced electron precipitation is more significant during the night than during the day. This is in agreement with the lightning-related wave intensities being considerably larger during the night than during the day [8], resulting from the lower nighttime ionospheric attenuation.

More importantly, our results reveal the overall annual periodicity in precipitating energetic electron fluxes, clearly demonstrating that this variation is due to changes in lightning occurrence rather than geomagnetic activity. This conclusion is further supported by analyzing periods of low and high geomagnetic activity separately, showing that the effect not only persists but also intensifies during geomagnetically quiet periods. This can be understood in terms of the relative importance of lightning-related effects. During periods of low geomagnetic activity, both the wave intensity and precipitating fluxes are strongly controlled by lightning activity, as other possible factors become comparatively weaker. On the other hand, during geomagnetically active periods, other factors become much more significant and eventually dominate.

5. Conclusions

We used wave and energetic particle measurements performed by the low-altitude DEMETER spacecraft between 2006 and 2010, complemented by the WWLLN lightning data, to systematically investigate their annual variations in the U.S. region. We showed that during the summer, when the number of lightning strikes increases considerably, both the VLF wave intensities and precipitating energetic electron fluxes also increase. A correlation analysis was employed to identify the most affected electron energy range. Finally, we showed that the effect is more pronounced during the night than during the day and during geomagnetically quiet periods rather than during geomagnetically active periods.

6. Acknowledgements

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References

[1] Helliwell, R. A. (1969), Low-frequency waves in the magnetosphere, *Rev. Geophys.*, 7(1, 2), 281–303, doi:10.1029/RG007i001p00281

[2] Záhlava, J., Němec, F., Santolík, O., Kolmašová, I., Hospodarsky, G. B., Parrot, M., et al. (2019). Lightning contribution to overall whistler mode wave intensities in the plasmasphere. *Geophysical Research Letters*, 46, 8607–8616. https://doi.org/10.1029/2019GL083918

[3] Inan, U. S., M. Walt, H. D. Voss, and W. L. Imhof (1989), Energy spectra and pitch angle distributions of lightning-induced electron Precipitation: Analysis of an event observed on the S81-1(SEEP) satellite, Journal of Geophysical Research, 94(A2), 1379–1401, doi: 10.1029/JA094iA02p01379

[4] Inan, U. S., D. Piddyachiy, W. B. Peter, J. A. Sauvaud, and M. Parrot (2007), DEMETER satellite observations of lightning-induced electron precipitation, Geophys. Res. Lett., 34, L07103, doi:10.1029/2006GL029238

[5] Voss, H., Imhof, W., Walt, M. *et al.* Lightning-induced electron precipitation. *Nature* 312, 740–742 (1984). doi:10.1038/312740a0

[6] Voss, H. D., M. Walt, W. L. Imhof, J. Mobilia, and U. S. Inan (1998), Satellite observations of lightning-induced electron precipitation, *Journal of Geophysical Research*, 103(A6), 11725–11744, doi:10.1029/97JA02878

[7] Gemelos, E. S., U. S. Inan, M. Walt, M. Parrot, and J. A. Sauvaud (2009), Seasonal dependence of energetic electron precipitation: Evidence for a global role of lightning, Geophys. Res. Lett., 36, L21107, doi:10.1029/ 2009GL040396

[8] Němec, F., O. Santolík, M. Parrot, and C. J. Rodger (2010), Relationship between median intensities of electromagnetic emissions in the VLF range and lightning activity, J. Geophys. Res., 115, A08315, doi:10.1029/2010JA015296

[9] Cussac T., M. A. Clair, P. Ultré-Guerard, F. Buisson, G. Lassalle-Balier, M. Ledu, C. Elisabelar, X. Passot, N. Rey, The Demeter microsatellite and ground segment, Planetary and Space Science, Volume 54, Issue 5, 2006, Pages 413-427, doi:10.1016/j.pss.2005.10.013

[10] Sauvaud J.A., T. Moreau, R. Maggiolo, J.-P. Treilhou, C. Jacquey, A. Cros, J. Coutelier, J. Rouzaud, E. Penou, M. Gangloff, High-energy electron detection onboard DEMETER: The IDP spectrometer, description and first results on the inner belt, Planetary and Space Science, Volume 54, Issue 5, 2006, doi: 10.1016/j.pss.2005.10.019.

[11] Berthelier J.J., M. Godefroy, F. Leblanc, M. Malingre, M. Menvielle, D. Lagoutte, J.Y. Brochot, F. Colin, F. Elie, C. Legendre, P. Zamora, D. Benoist, Y. Chapuis, J. Artru, R. Pfaff, ICE, the electric field experiment on DEMETER, Planetary and Space Science, Volume 54, Issue 5, 2006, doi: 10.1016/j.pss.2005.10.016

[12] Sauvaud, J.-A., R. Maggiolo, C. Jacquey, M. Parrot, J.-J. Berthelier, R. J. Gamble, and C. J. Rodger (2008), Radiation belt electron precipitation due to VLF transmitters: Satellite observations, Geophysical Research Letters, 35, L09101, doi:10.1029/2008GL033194