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Lightning Effects in the Ionosphere Over The Arecibo Observatory

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Abstract

In the last couple of decades, substantial research has been dedicated to understanding the coupling between atmospheric regions. Research on transient luminous events (TLEs) appeared and quickly intensified with the promise of TLEs serving as an optical remote sensing tool of the mesosphere and lower ionosphere. However, to date it remains challenging to obtain quantitative estimates of electron density changes in the ionospheric D region due to underlying lightning and thunderstorms. Arecibo's incoherent scatter radar (ISR) capabilities for measuring ionospheric electron density with high resolution (300-m spatial resolution in the present study), combined with its tropical location in a region of high lightning incidence rates, indicate a potentially transformative pathway to address this problem. Through a systematic survey, we show that sudden electron density changes registered by Arecibo's ISR during thunderstorm times are on average different than the ones happening during fair weather conditions (driven by other external factors). Electron density changes happening coincidentally with lightning activity have typical amplitudes of 10–90% between 80–90 km altitude, and in a selected number of cases can be reasonably correlated to underlying lightning activity.

1 Introduction

The edge of space, the lower ionosphere marks the interface between the neutral and ionized portions of the Earth's atmosphere. The electron density content in this region — known as the D region — plays an important role in long-range radio communications by being the "lid" in the the waveguide that traps low frequency electromagnetic waves. Leveraging this concept, remote sensing with ELF/VLF electromagnetic waves has been a widely-employed technique to probe the high variability of this region [1]. The dominant sources of variability in the D region are understood to come from above, such as photoionization from solar UV radiation, electron precipitation from the radiation belts, meteor ablation, etc [2]. However, underlying thunderstorms can also potentially alter the electronic conductivity in the lower ionosphere due to penetration of thunderstorm [3] and lightning [4, 5, 6] quasi-electrostatic fields causing electron heating and electron-impact ionization, or due to thunderstorm-originated gravity waves that can modulate the local electron density [7]. Here, we search for potential evidence of the former mechanism.

In this work, we present a systematic survey of lightning-induced electron density changes in the lower ionosphere over the Arecibo Observatory (18.35° N, 66.75° W, −46.7° dip latitude), in Puerto Rico. This location is ideal for this type of study because Arecibo hosts the most comprehensive suite of instruments to probe the ionospheric electron density (including the incoherent scatter radar used here), and also because of the high occurrence of tropical storms accompanied by lightning, common to the Caribbean region. Despite these reasons, to the best of our knowledge, the only previous attempt to carry out such study was undertaken over 20 years ago [8], well before the latest radar upgrades [9], and leading to inconclusive results. In this conference presentation, we will show a systematic survey that demonstrates that electron density changes of ∼50% are regularly recorded in the ISR data in correlation with strong lightning activity in underlying thunderstorms.

2 Datasets

In this analysis we look at the two datasets:

1. Geolocation and peak current information provided by Vaisala's GLD360 global lightning detection network. GLD360 has a location accuracy of the order of 5 km and 70% detection efficiency for cloud-to-ground lightning strikes [10].

2. Vertical profiles of electron density probed with Arecibo's 430 MHz incoherent scatter radar (ISR) [9]. The electron density profiles used in this study have 300-m spatial resolution and are taken typically every minute (see Figure 1a).

For the sake of brevity, in this summary paper, we focus our analysis on 69 hours of approximatelly-continuous data acquisition by the ISR starting on November 04, 2013 20:00 UTC. In the conference presentation, we will show a comprehensive analysis that encompasses a number of overlaps between ISR and GLD360 data, totaling hundreds of hours.

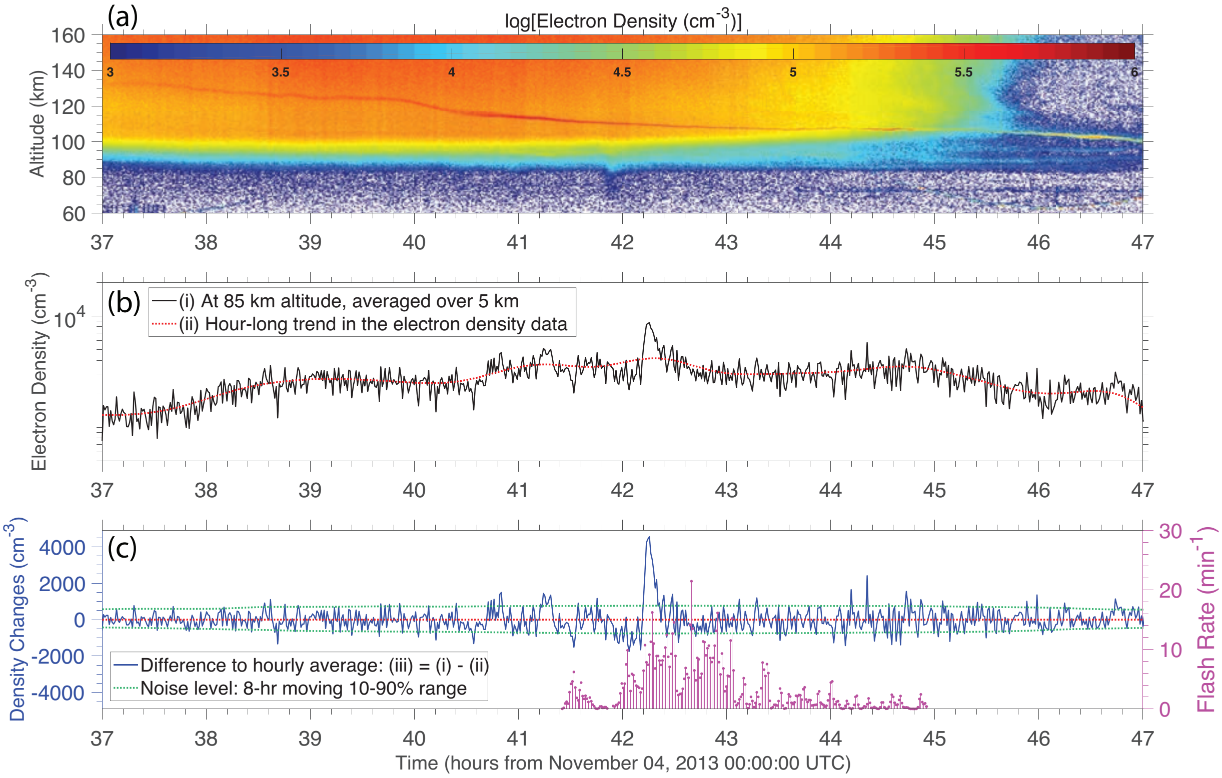

Figure 1. (a) Logarithm of electron density data (in cm^{-3}) as a function of altitude and time. (b) Electron density time series at 85 km altitude. Curve (i) shows data averaged over a ± 2.5 km altitude range, and curve (ii) shows the data further smoothed with an hour-long moving average. (c) Electron density changes (left-hand-side vertical axis), and flash rate (right axis). Curve (iii) is simply the difference between curves (i) and (ii). Panel (c) also shows the noise level (green dashed curve), defined as 10–90 percentile changes in an 8-hr-long moving window. The salient electron density change happened during a thunderstorm around 2:00 PM local time.

3 Methodology

Figure 1a shows the (logarithm of) electron density as a function of altitude and time. Any potential sudden change in electron density due to underlying lightning activity is masked by the inherent variations with altitude and time, which span 3 orders of magnitude in the figure. Curves (i)–(iii) are constructed to alleviate this problem. Curve (i) in Figure 1b shows the time series of electron density at 85 km altitude (averaged over a 5-km window around this altitude). Curve (ii) is an hour-long moving average of this time series. Finally, taking the difference between the two, shown as curve (iii) in Figure 1c, we start seeing minute-long electron density changes at a given altitude as spikes in the time series. We consider a modification to be significant if it is above the noise level, defined as the 10th (negative noise level) and 90th (positive) percentile in an 8-hr moving window, shown as a green dashed curve in Figure 1c.

On the right-hand-side axis, Figure 1c also shows the lightning flash rate activity nearby the Arecibo Observatory. The sudden electron density increase (the big spike right after 42 hs) is coincident with a nearby thunderstorm, which happened between 1:30 to 5:30 PM local time. In this work we use a custom measure of flash rate determined from a 3-step process. First, we correct for the distance to the observatory using the known decrease of the lightning electromagnetic wave amplitude with distance [11, 12]. Second, we correct for peak current, normalizing all flashes to a typical peak current of 20 kA [13]. Third, we bin the flash rate in a histogram that is temporally aligned to the electron density profiles' time stamp.

Finally, we separate all electron density changes above the noise level and compare the ones that happen coincidentally with lightning activity to the ones that are not, and the principal findings are summarized in Section 4 below.

4 Results

For the 69 hours of data starting on November 04, 2013 20:00 UTC we have identified an average of 536 sudden electron density changes (or spikes) for each of the 435 altitude levels between 70 and 200 km, 17% of them happen coincidentally with lightning activity. The ones that happen in association with lightning tend to have a smaller magnitude than the ones that are not, i.e., that are likely driven by other external factors. Figure 2a shows the median magnitude of electron density changes (in %) as a function of altitude. Note that the curves account for both enhance-

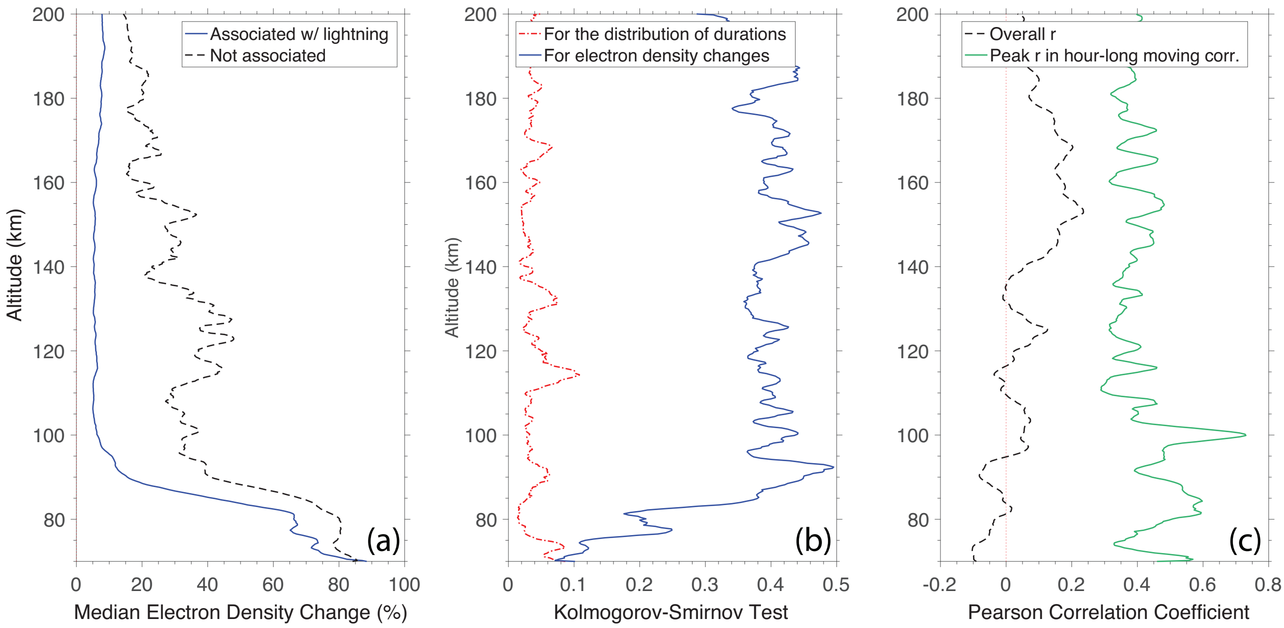

Figure 2. Vertical profiles summarizing the correlation between lightning activity and electron density changes. (a) Median electron density change (in %) as a function of altitude for events that happen simultaneously with lightning (solid line) and that are not associated with lightning (dashed). (b) Difference in the distribution of event durations and magnitudes (with and without lightning) as measured by the Kolmogorov-Smirnov test. (c) Pearson correlation coefficient for the whole time series (dashed curve) and its peak value in hour-long moving window (solid).

ments and depletions. Percent changes that happen coincidentally to underlying lightning activity tend to be very small at altitudes above 100 km, which corroborate with the idea of the forcing coming from a thunderstorm below. Figure 2b shows the Kolmogorov-Smirnov test comparing the distribution of percent electron density changes (solid line). They are substantially different at all altitudes, but the peak difference happens at around 90 km. The same test applied to the distribution of durations (in minutes) shows no substantial difference between the two (dot-dashed line in Figure 2b).

Figure 2c shows the Pearson correlation coefficient (r) between the entire time series of absolute electron density changes and lightning flash rate (i.e., for all the time instants when there is coincidence in both). The overall value of r is rather small for all altitudes (see the dashed curve in Figure 2c). On the other hand a moving correlation with an hour-long window indicates higher levels of correlation, as shown by the solid curve in the same figure. The maximum values are $r = 0.75$ at 100 km and 0.6 at 80–85 km. The information on this last graph was used to identify the large electron density change highlighted in Figure 1c, which has a magnitude of $\sim$100%, larger than the typical $\sim$50% for this altitude range (Figure 2a).

5 Summary and Outlook

In this summary paper, we have shown that electron density changes of $\sim$50% are regularly detected at 85 km altitude coincidentally with underlying lightning activity. These electron density changes have a different distribution of magnitudes in comparison to the ones happening during fair weather conditions (i.e., with no lightning).

In the conference presentation, we will show an extensive systematic survey of electron density changes coincident with lightning activity, highlighting the potential of Arecibo's incoherent scatter radar as a tool to quantify the coupling between thunderstorms and the middle and upper atmosphere.

6 Acknowledgements

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References

[1] U. S. Inan, S. A. Cummer, and R. A. Marshall, "A survey of ELF and VLF research on lightning-ionosphere

interactions and causative discharges," *J. Geophys. Res.*, vol. 115, 2010.

[2] C. G. M. Brum, M. A. Abdu, I. S. Batista, A. J. Carrasco, and P. M. Terra, "Numerical simulation of nighttime electron precipitation in the lower ionosphere over a sub-auroral region," *Adv. Space Res.*, vol. 37, no. 5, pp. 1051–1057, 2006.

[3] V. P. Pasko, U. S. Inan, and T. F. Bell, "Ionospheric effects due to electrostatic thundercloud fields," *J. Atmos. Solar-Terr. Phys.*, vol. 60, no. 7-9, pp. 863–870, 1998.

[4] V. P. Pasko, "Recent advances in theory of transient luminous events," *J. Geophys. Res.*, vol. 115, JUN 16 2010.

[5] C. L. da Silva and F. T. São Sabbas, "Consequences of the application of the streamer fluid model to the study of the sprite inception mechanism," *Adv. Space Res.*, vol. 51, no. 10, pp. 1902–1915, May 2013.

[6] X.-M. Shao, E. H. Lay, and A. R. Jacobson, "Reduction of electron density in the night-time lower ionosphere in response to a thunderstorm," *Nat. Geosci.*, vol. 6, no. 1, pp. 29–33, JAN 2013.

[7] E. H. Lay, X.-M. Shao, A. K. Kendrick, and C. S. Carrano, "Ionospheric acoustic and gravity waves associated with midlatitude thunderstorms," *J. Geophys. Res.*, vol. 120, no. 7, pp. 6010–6020, 2015.

[8] R. L. Showen and A. Slingeland, "Measuring lightning-induced ionospheric effects with incoherent scatter radar or with cross-modulation," *J. Atmos. Solar-Terr. Phys.*, vol. 60, no. 7, pp. 951–956, 1998.

[9] B. Isham, C. A. Tepley, M. P. Sulzer, Q. H. Zhou, M. C. Kelley, J. S. Friedman, and S. A. González, "Upper atmospheric observations at the Arecibo Observatory: Examples obtained using new capabilities," *J. Geophys. Res.*, vol. 105, no. A8, pp. 18 609–18 637, 2000.

[10] R. K. Said, M. B. Cohen, and U. S. Inan, "Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations," *J. Geophys. Res.*, vol. 118, no. 13, pp. 6905–6915, 2013.

[11] R. E. Orville, "Calibration of a magnetic direction finding network using measured triggered lightning return stroke peak currents," *J. Geophys. Res.*, vol. 96, no. D9, pp. 17 135–17 142, Sep. 1991.

[12] C. L. da Silva, R. A. Merrill, and V. P. Pasko, "Mathematical constraints on the use of transmission line models to investigate the preliminary breakdown stage of lightning flashes," *Radio Sci.*, vol. 51, no. 5, pp. 367–380, May 2016.

[13] V. A. Rakov and M. A. Uman, *Lightning: Physics and Effects*. Cambridge: University Press, 2003.