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Multi-Year Lightning Impulse Charge Moment Change Measurements in the United States

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***Abstract*— We report and analyze several years of lightning impulse charge moment change (iCMC) measurements obtained from an automated, real time lightning charge moment change network (CMCN). The CMCN combines U.S. National Lightning Detection Network (NLDN) lightning event geolocations with extremely low frequency (<1 kHz) data from two stations to provide iCMC measurements across the entire United States. About 5 million lightning events per year are measured by the CMCN. We present the statistical distributions of iCMC versus polarity, including corrections for the detection efficiency of the CMCN versus peak current. For all positive strokes, there is a boundary near 20 C km that separates seemingly distinct populations of high and low iCMC strokes. We also explore the geographic distribution of high iCMC lightning strokes. High iCMC positive strokes occur predominantly in the northern midwest portion of the U.S., with a secondary peak over the gulf stream region just off the U.S. east coast. High iCMC negative strokes are also clustered in the midwest, although somewhat south of most of the high iCMC positive strokes. Among other applications, this network is useful for the nowcasting of sprite-producing storms and storm regions. The presented results summarize and extend those described by Cummer et al. [*J. Geophys. Res.*, 2013].**

Keywords—charge transfer, charge moment change

I. INTRODUCTION

Automated and geographically extensive remote measurements of lightning parameters are a valuable class of tool in lightning research. The most widely estimated parameter, aside from location and polarity, is return stroke peak current, which can be remotely estimated from the low frequency radiation [Cummins et al. 1998] from lightning. Another parameter that can be measured from electromagnetic fields long distances from the lightning stroke is charge moment change (CMC), which is the product of charge transfer and the vertical distance over which that charge is transferred (and thus the units are coulomb-kilometers or C km). CMC can be remotely estimated from extremely low frequency (ELF, 3–3000 Hz) radiation [Jones and Kemp, 1971; Burke and Jones, 1996; Huang et al., 1999; Cummer and Inan, 2000], and has proven important for understanding the origins of lightning-driven high altitude electric breakdown in the form of sprites [Pasko et al., 1997], is linked to heating and damage at a lightning contact point [Rakov and Uman, 2003], and may also be connected to forest fire ignition [Latham and Schlieter, 1989].

Here we report and analyze multiple years of measurements from an automated, real time lightning Charge Moment Change network (CMCN). The CMCN contains only two sensor stations, but because of the long reach of ELF measurements, lightning in most of the US is measured. By design the CMCN uses lightning geolocations from the US National Lightning Detection Network (NLDN) operated by Vaisala, Inc. The presented results summarize and extend those described by Cummer et al. [2013].

II. CMCN SYSTEM

The CMCN is presently composed of two sensor stations. One operates near Duke University in North Carolina at 35.975° N latitude and –79.100° E longitude, and the other at Yucca Ridge near Fort Collins, Colorado at 40.668° N latitude and –104.937° E longitude. These two sites have proven sufficient to provide meaningful measurements over most of the continental United States.

Each site contains two orthogonal induction magnetic field sensors (built by Quasar Federal Systems, Inc.) with a gain of 0.3 V/nT that measure the horizontal vector magnetic field from lightning discharges. These sensors have a flat response from about 2 Hz to 25 kHz and thus measure the very low frequency (VLF, 3–30 kHz) and ELF emissions. The two systems have different trigger thresholds (2.0 nT at Duke and 3.3 nT at YRFS, not time-varying) that reflect the different noise and background thunderstorm environments, and this does influence the distribution of lightning strokes measured by each system. However, highly energetic lightning strokes are the primary focus of this analysis, and these generally have a sufficient amplitude to trigger the sensors regardless of distance or the system details.

For every CMCN trigger with a corresponding NLDN lightning location and peak current above 10 kA magnitude, the system computes the azimuthal magnetic field waveform by appropriately rotating the two orthogonal signals and filters the data to yield a <1 kHz signal for each stroke to be processed. This signal and the known propagation distance are used to compute the vertical impulse charge moment change (iCMC) using a version of the regularization-based technique described in detail by Cummer and Inan [2000].

III. Results

We now present an analysis of the 13.6 million lightning events whose iCMC was measured by the CMCN during the initial August 2007 to July 2010 analysis period. Of these, NLDN reported that approximately 12.1 million were negative polarity, 1.4 million were positive polarity, 13.1 million were cloud-to-ground (CG), and 455,000 were in-cloud (IC). Recall that the processing threshold of 10 kA filters out the majority of IC events.

We first examine the distribution of NLDN-reported peak current for the 13.6 million events (both IC and CG) processed by the CMCN in the three-year analysis window. The top panel of Figure 1 shows the distributions for positive and negative polarity events. As expected, these peak current distributions contain fewer low peak current events than the distributions of peak current of all NLDN-measured events. However, despite the low detection efficiency at low NLDN peak current, the distributions show that the CMCN measured many lightning events across the entire range of peak current, and the full distribution of lightning events that occur in the US have been extensively sampled. Even for the lowest values (10--20 kA), the CMCN still measured approximately 2 million events. The bottom panel of Figure 1 shows the computed detection efficiency (DE) of the CMCN system as a function of NLDN peak current. DE is defined as the ratio of detected and processed lightning events to the total number of NLDN-detected events. The analysis that follows includes a correction for the limited detection efficiency of smaller peak current lightning.

Figure 2 shows the corrected distributions of CMCN-measured impulse charge moment change (iCMC) for all lightning events during the three-year analysis window. Positive and negative polarity events are again separated. Almost the entire corrected negative iCMC distribution and the upper end of the corrected positive distribution are well-fit with log-normal functions (see Cummer et al. [2013] for details). However, there is a excess of small iCMC (+5 to +70 C km) positive events that cannot be fit with a log-normal distribution that also fits the high end of the distribution. The iCMC distribution in events identified by the NLDN as +IC

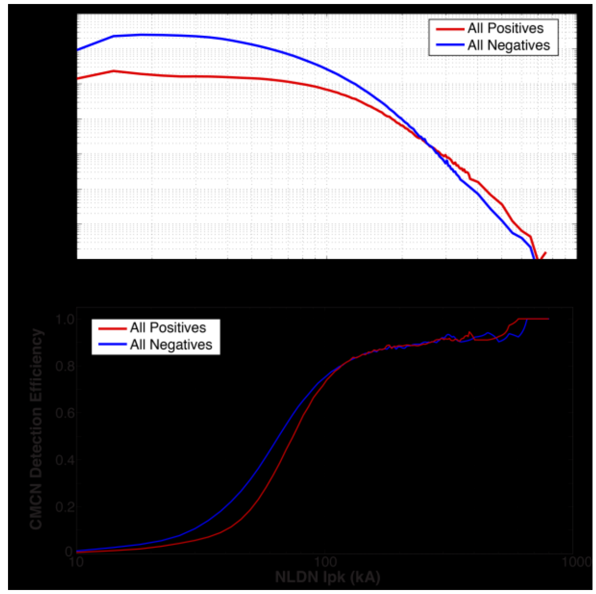

Fig. 1. Top: Distributions of NLDN-reported peak current for all CMCN-processed lightning events in a 3 year analysis window. Bottom: Detection efficiency (DE) of the CMCN versus NLDN peak current. DE drops with peak current because of the amplitude-dependent triggering of the CMCN. Figure adapted from Cummer et al. [2013].

shown in the figure does exhibit an excess of small iCMC events, but still about half of the observed small iCMC positive events are classified as CG. Also, while approximately 10% of the high iCMC positive events are classified as +IC by NLDN, it seems possible that these are in fact +CG strokes based on their high impulse charge transfer. This highlights the challenge of identifying IC and CG events, and also suggests that the measured iCMC may be able to provide additional information to better distinguish IC and CG events.

Figure 3 shows the same corrected positive and negative iCMC distributions as cumulative distribution functions (CDFs) that focus on the high iCMC portion of the distributions to highlight the occurrence rate of these unusually strong lightning flashes. These are relative frequencies within each polarity. For example, negative strokes with iCMC

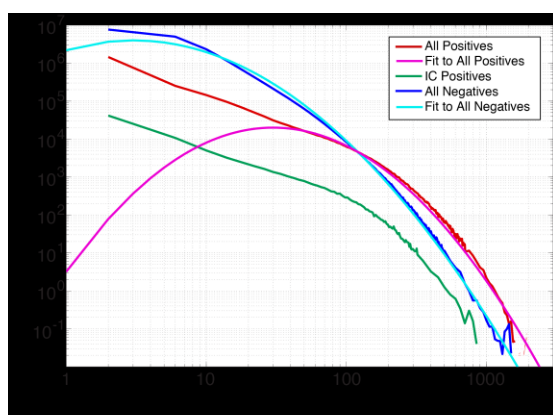

Fig. 2. Corrected statistical distributions of iCMC in all lightning events during the 3 year analysis window. Plotted separately are the measured distributions for all positive, all negative, and all positive IC events. Also shown are log-normal fits to the corrected positive and negative distributions. Figure adapted from Cummer et al. [2013].

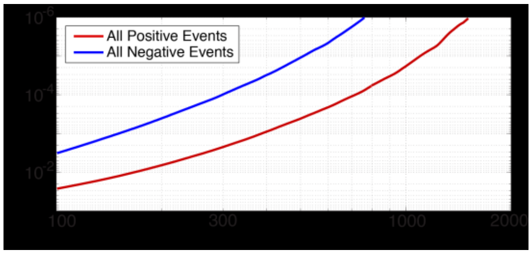

Fig. 3. Cumulative distribution functions (CDFs) of iCMC for positive and negative events based on the detection-efficiency corrected distributions, showing the fraction of observed lightning events that exceed a given iCMC value to highlight the relative occurrence rate of very high iCMC events. Figure adapted from Cummer et al. [2013].

exceeding roughly –750 C km are 10^{-6} of all negative strokes in the corrected dataset, and thus the distribution predicts that approximately 144 of these events occurred in the US in 36 months. Similarly, positive strokes with iCMC exceeding +1400 C km occurred at the same 10^{-6} relative rate and predicts about 27 of these events US in the 3 year window.

We now present and explore the geographic distribution of high iCMC events of positive and negative polarity. Thresholds of –200 and +300 C km are chosen so that roughly 50,000 events of each class were found in the first three years of data. The top panel of Figure 4 shows the smoothed distribution of all CMCN events with iCMC < –200 C km. These high charge transfer negative events are not strong enough to create sprites. There are concentrations of strong lightning in the Gulf Stream and Gulf of Mexico, but the highest concentration of high iCMC negative lightning occurs along a nearly vertical strip from western Missouri to western Arkansas. The highest iCMC negative events occur more frequently over land.

The bottom of Figure 4 shows the smoothed distribution for events with iCMC > +300 C km. We consider these ``likely'' sprite producers because the impulse CMC by itself reaches the empirical threshold for generating a sprite. The geographic peak of this distribution has a peak of about 0.01 strokes per km^2 per year from Iowa to northeast Oklahoma. But these very high iCMC events do occur regularly over a very wide portion of the United States, including the southeast (Mississippi, Alabama, etc.) where few efforts to observe sprites have been made.

IV. SUMMARY

We have analyzed multiple years of measurements of lightning impulse charge moment change (iCMC, defined as the lightning discharge charge moment change during the first two milliseconds after the discharge onset) containing millions of NLDN-detected events over the continental United States. These measurements of iCMC are generated from a real-time lightning charge moment change network that relies on NLDN lightning geolocations provided by Vaisala, Inc. and has been operating since 2007.

The real-time nature of the CMCN measurements will continue to be valuable in nowcasting the storms and locations within storms that are generating potentially sprite-producing lightning. Additionally, these measurements will enable addressing questions related to the link between meteorology and storm structure and high charge transfer lightning.

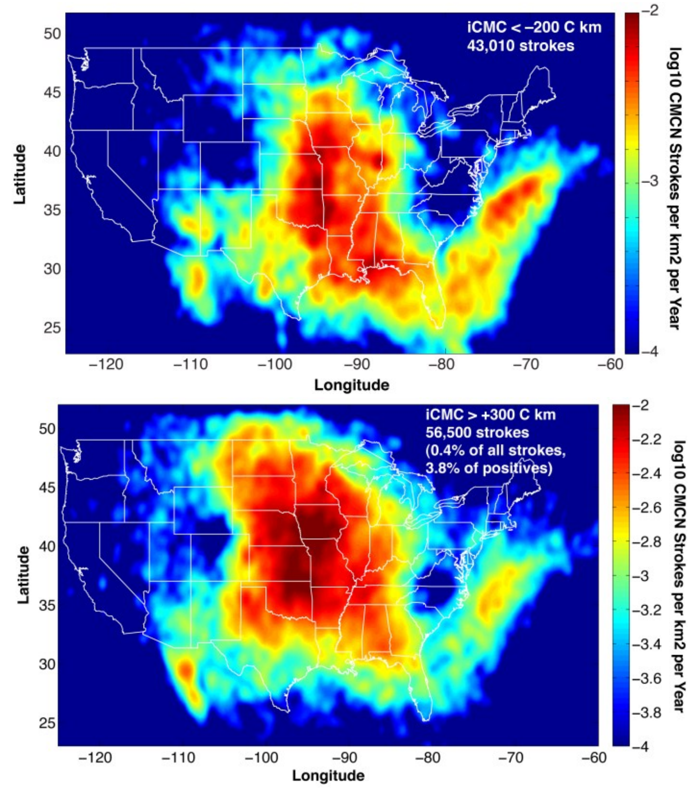

Fig. 4. Geographic distributions and rates of high iCMC negative and positive polarity events. Figure adapted from Cummer et al. [2013].

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