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On remote measurements of lightning return stroke peak currents

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ABSTRACT

Return-stroke peak current is one of the most important measures of lightning intensity needed in different areas of atmospheric electricity research. It can be estimated from the corresponding electric or magnetic radiation field peak. Electric fields of 89 strokes in lightning flashes triggered using the rocket-and-wire technique at Camp Blanding (CB), Florida, were recorded at the Lightning Observatory in Gainesville, about 45 km from the lightning channel. Lightning return-stroke peak currents were estimated from the measured electric field peaks using the empirical formula of Rakov et al. (1992) and the field-to-current conversion equation based on the transmission line model (Uman and McLain, 1969). These estimates, along with peak currents reported by the U.S. National Lightning Detection Network (NLDN), were compared with the ground-truth data, currents directly measured at the lightning channel base. The empirical formula, based on data for 28 triggered-lightning strokes acquired at the Kennedy Space Center (KSC), tends to overestimate peak currents, whereas the NLDN-reported peak currents are on average underestimates. The field-to-current conversion equation based on the transmission line model gives the best match with directly measured peak currents for return-stroke speeds between $c/2$ and $2c/3$ (1.5 and 2×10^8 m/s, respectively). Possible reasons for the discrepancy in the peak current estimates from the empirical formula and the ground-truth data include an error in the field calibration factor, difference in the typical return-stroke speeds at CB and at the KSC (considered here to be the most likely reason), and limited sample sizes, particularly for the KSC data. A new empirical formula, $I = -0.66–0.028rE$, based on data for 89 strokes in lightning flashes triggered at CB, is derived.

1. Introduction

Lightning can be defined as a transient, high-current (typically tens of kiloamperes) electric discharge in the atmosphere whose length is measured in kilometers. All processes comprising lightning are associated with the motion of electric charges and, hence, produce electric and magnetic fields. By measuring these fields one can estimate various lightning parameters, such as electric current, charge transfer, etc. (see, for example, Kodali et al. (2005) and Qie et al. (2009)), needed in different areas of atmospheric electricity research. One of the most important lightning parameters, which is used as a measure of intensity of its component strokes, is the return-stroke peak current.

There have been many attempts to infer lightning return stroke currents from remotely measured (essentially radiation) electric and magnetic fields (e.g., Norinder and Dahle, 1945; Uman and McLain, 1970; Uman et al., 1973a,b; Dulzon and Rakov, 1980; Krider et al., 1996; Cummins et al., 1998; Rachidi et al., 2004). Such "remote" measurements are model dependent and, therefore, inferior to direct measurements.

Abbreviations: CB, Camp Blanding; EF, Empirical Formula; KSC, Kennedy Space Center; LOG, Lightning Observatory in Gainesville; NLDN, U.S. National Lightning Detection Network; TL, Transmission Line.

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Table 1
Summary of triggered lightning events recorded at LOG in 2008–2010.

Events	2008	2009	2010	2008-2010
Number of flashes recorded at LOG	4	15	9	28
Number of LOG-recorded flashes suitable for present analysis [a]	3	11	8	22
Number of strokes recorded at LOG [b]	17	41	31	89

[a] Excluding one flash for which no directly-measured currents are available and one flash without return strokes.
[b] Excluding 15 strokes for which no directly-measured currents are available.

However, they remain attractive because they allow one to acquire a large (statistically significant) sample over a relatively short period of time for lightning events that are not influenced by tall strike objects that are usually required for direct measurements. There have been also studies in which lightning peak currents are related to close (within tens to hundreds of meters) electric and magnetic fields (e.g., Rubinstein et al., 1995; Rakov et al., 1998; Jhavar, 2005; Yang et al., 2010). The use of such close fields, dominated by their static components, for inferring causative currents is outside the scope of the present paper.

Estimation of lightning return stroke peak currents from measured electric or magnetic fields requires a field-to-current conversion procedure. Lightning locating systems, such as the U.S. National Lightning Detection Network (NLDN), implement one such procedure. The NLDN uses an empirical formula, based on triggered-lightning data, to estimate the return-stroke peak current from the measured magnetic field peaks and distances to the strike point reported by multiple sensors. The conversion procedure includes compensation for the field attenuation due to its propagation over lossy ground (Cummins and Murphy, 2009).

Rakov et al. (1992) proposed the following empirical formula (EF) (linear regression equation) to estimate the return-stroke peak current, I_{EF}, from the initial (essentially radiation) electric field peak, E, and distance, r, to the lightning channel:

$$I_{EF} = 1.5 - 0.037rE \tag{1}$$

where I_{EF} is in kA and taken as negative, E is positive and in V/m, and r is in km. Eq. (1) was derived using data for 28 triggered-lightning strokes acquired by Willett et al. (1989) at the Kennedy Space Center (KSC), Florida. The fields were measured at about 5 km and their initial peaks were assumed to be pure radiation. The currents were directly measured at the lightning channel base. The field propagation path was over brackish water, so that propagation effects due to ground losses were minimal. Eq. (1) is expected to be applicable for distances at which the initial electric field peak is essentially radiation and field propagation effects are negligible. Lin et al. (1979) reported that normalized field peaks were typically attenuated by 10% in propagating over 50 km in Florida. For our field measurements, the distance from lightning channel was 45 km. At this distance the field is dominated by its radiation component and the propagation effects should not be significant.

Lightning peak currents can also be estimated using the radiation-field-to-current conversion equation based on the transmission line (TL) model (Uman and McLain, 1969), which is given by:

$$I_{TL} = \frac{2\pi\varepsilon_0 c^2 r}{v} E \tag{2}$$

where ε_0 is the permittivity of free space, c is the speed of light, and v is the return-stroke speed (assumed to be

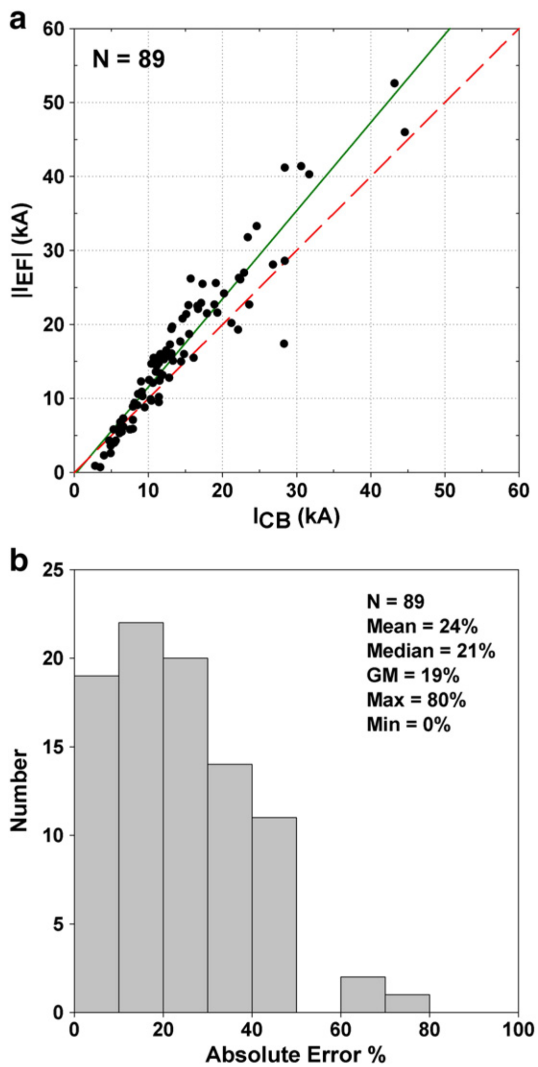

Fig. 1. (a) Magnitude of peak current estimated from the empirical formula of Rakov et al. (1992) (I_{EF}) vs. directly-measured peak current (I_{CB}). The solid green line is the best (least squares) fit to the data, while the broken red line represents the ideal situation when $|I_{EF}| = I_{CB}$. (b) Histogram of absolute errors in estimated peak current from the empirical formula, given as a percentage of the directly measured Camp Blanding current ($\Delta I_{EF}\% = 100\ \Delta I_{EF}/I_{CB}$, where $\Delta I_{EF} = I_{EF} - I_{CB}$). Corresponding statistics are also given. The GM was computed excluding two zero values.