USE OF TOTAL LIGHTNING LENGTHS TO ESTIMATE NO\textsubscript{x} PRODUCTION IN A COLORADO STORM

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ABSTRACT: We derive total components lengths based on the characteristics and angular locations of the VHF radiation detected by an interferometer. The method differentiates between negative leaders and fast negative processes and applies simple relationships from the physics of lightning to deduce the channel lengths of these components for both intra-cloud and cloud-to-ground lightning flashes. The studied storm produced over 5000 flashes with only 83 connecting to ground. The total component length of individual flashes retrieved varied from 0.02 to 474 km with an average value of 19 km. The sum of total channel lengths for all flash components for the 4 1/2 hour storm was estimated at 102,000 km. For flashes with duration >10 ms the length per flash was found to be related to the flash duration but with a lot of variation. The lightning channel lengths deduced from this work are used by Skamarock et al. [2002] to estimate NO\textsubscript{x} (= NO + NO\textsubscript{2}) produced by lightning in the 10 July 1996 storm.

INTRODUCTION

Thunderstorms vary widely over the globe and even regionally in terms of size, severity and lifetime. For example, much less lightning activity occurs in storms over the oceans than for storms over land. Likewise lightning activity within individual storms can show large variability during the lifetime of a storm. In addition the large variability between individual flashes in terms of types, durations, number of components, currents and energies suggests that other properties than flash rate or flash count must be considered to investigate the production of nitrogen oxides (NO\textsubscript{x}) by lightning.

We report here estimate of flash length based on the VHF radiation recorded during the Stratosphere-Troposphere Experiment: Radiation, Aerosols, Ozone (STERAO-A) 10 July 1996 storm with the Office National d'Études et de Recherches Aérospatiales (ONERA) VHF lightning mapping system. NO\textsubscript{x} production per flash and per unit lightning channel length has then been deduced from measured NO\textsubscript{x} values in the anvil and from a cloud simulation of the storm [Skamarock et al., 2002]. In addition the present study provides additional information on lightning characteristics for the studied storm.

METHOD

The ONERA lightning mapping system was deployed during the STERAO-A experiment to record the lightning activity [Dye et al., 2000]. The lightning mapper was composed of two independent interferometers (ST1 and ST2) sensing the VHF radiation at 114 MHz with 23-µs time resolution [Laroche et al., 1994]. Defer et al. [2001] present a detailed analysis of the lightning activity for the studied storm recorded on July 10, 1996. Based on the flash-by-flash analysis performed for the studied storm [Defer et al., 2001] we estimate the length of flash components by associating VHF sources (recorded by a single station) in components. Then according to the duration of the component a simple relation is applied to estimate the component length (radiating in the VHF domain) [Defer and Dye, 2003]. A detailed description of the method can also be found at the following URL: http://www.mmm.ucar.edu/science/sterao/sterao.html.

Kitagawa and Brook [1960] report some of the best information on the statistical difference between intracloud (IC) and cloud-to-ground (CG) flashes in terms of time between successive leader pulses (pulse intervals) and durations of leaders. They reported that for leaders of CG flashes the pulse interval indicative of individual steps in the leader had a mean of 80 µs with some up to 250 µs. For leaders of IC flashes they found that pulse intervals extended over a very broad range with a mean of about 650 µs. In our parameterization two VHF sources are assumed to belong to the same component if the interval between those two sources is less than 2 ms.

When VHF sources are associated in components we apply a criteria on the component duration in order to determine its type. Kitagawa and Brook [1960] reported that less than 10% of the CG leaders had a duration less than 10 ms while less than 2% of the IC leaders lasted less than 50 ms. Richard et al. [1986] reported leader duration for both IC and CG lightning including preliminary breakdown ranging from 10 to a few hundreds of milliseconds. For fast processes Proctor [1981] reported Q noise durations ranging from 10 µs to 2 ms while Richard et al. [1986] using 1 µs time resolution reported durations ranging from 10 µs to 1 ms. Based on these results we have considered flash components with durations <2 ms as fast processes, otherwise the component is considered to be a negative stepped leader.
Negative leaders are often branched and propagate by steps. VHF pulses are thought to be associated with the motion of the tip of the discharge [Proctor, 1981; Rhodes et al., 1994]. Electric field measurements show intervals ranging from 5 to 20 µs during stepped leaders [Krider and Radda, 1975; Krider et al., 1977]. Similarly, a wide range of variation has been reported for the step length. Uman [1987] gives step lengths of approximately a few tens of meters. More recently Chen et al., [1999] recorded lengths ranging from 8 to 20 m for downward negative stepped leaders. In our parameterization, we arbitrarily assume that only 1 step occurred during each 23-µs window and we further assume that the step is 20 m long and constant. The total length of leaders is then deduced by multiplying the number of VHF sources recorded during the leader process by the step length.

From careful scrutiny of results we noted that sometimes when the initial leader process was intermittent and of short duration (i.e. similar in behavior to fast processes), our criteria identified it as a fast process. This behavior could be the result of weak, undetected radiation by a leader or perhaps from short attempted leaders. Since lightning is initiated by a negative stepped leader process, we treated isolated or short trains of VHF sources recorded before any identified leaders as part of the leader process.

The ONERA interferometer records a second type of radiation which is associated with fast processes (dart leaders, K change processes). These events occur along part of, or sometimes along all of, the channels previously created by the positive and the negative leaders. Because altitude information of the VHF sources was not reliable and because these events exhibit the same type of radiation as sensed by the ONERA interferometer, we treat dart leaders and K change processes the same. Shaod and Krehbiel [1996] reported K changes propagating with speeds ranging from $10^6$ m s$^{-1}$ to 1-2 x $10^7$ m s$^{-1}$ and K bursts up to 5 x $10^7$ m s$^{-1}$. Proctor [1981] reported speeds from 2.5 x $10^6$ m s$^{-1}$ to 4.4 x $10^7$ m s$^{-1}$ with an average speed of 2.5 x $10^7$ m s$^{-1}$. Dart leader speeds have been measured ranging from 10$^6$ m s$^{-1}$ to 5 x 10$^7$ m s$^{-1}$ [Richard et al., 1986; Shaod and Krehbiel, 1996]. For the present study we assume that the fast processes propagate at the constant speed of 10$^7$ m s$^{-1}$ from their beginning to their end. We then estimate the length of fast processes by multiplying the number of VHF sources by the previous velocity and by the time resolution of the interferometer (23 µs).

Finally our representation does not specifically take into account the length of return strokes. VHF sources recorded during return stroke process are considered as part of the stepped or dart leaders. Because there were relatively few CG flashes for the studied storm this is not a large source of error. Finally, the positive leaders and positive strokes are not considered in the present parameterization because the interferometer does not detect them.

RESULTS

The ONERA lightning sensors recorded the entire life of the STERAO-A 10 July 1996 storm [Dye et al., 2000; Defer et al., 2001]. Figure 1a shows the total flash rate per 5 min period over the entire life of the storm. Figure 1b shows the CG/(IC+CG) ratio. The National Lightning Detection Network (NLDN) reported only 83 CG flashes while the ONERA system sensed 5428 flashes. Analysis of the flash duration, ranging from 23 µs to 1.8 s, reveals that 14% of the flashes lasted less than 1 ms. Figure 1c shows the ratio of short duration flashes. Roughly half of the flashes at 2315 UT lasted less than 1 ms. Length estimate of the entire flash components ranged from 0.02 up to 474 km with an average value of 19 km (Figure 1d). Interestingly the

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Figure 1. (a): total flash rate per 5 min; (b): CG flash ratio per 5 min; (c): short duration discharge ratio per 5 min; (d) flash length for entire life of the storm from ST1 data; (e): total flash length per 5 min for both ONERA stations; (f): average flash length per 5 min for both ONERA station.

Figure 2. (a): length distribution for all flashes from the data of the two ONERA interferometers; (b): length distribution of the negative and positive CG flashes based on ST1 data.

Figure 3. Flash length as function of the flash duration based on ST1 data.

Finally Figure 3 shows the total VHF length of individual flashes as a function of the flash duration measured at ST1. For short duration flashes, i.e., those <1 ms, the length does not exceed 1 km. Our method characterizes them as leader events. For flashes with durations >1 ms, the length estimates separate into two populations of flashes. The first population, with lengths mostly <3 km, is associated with flashes characterized by very little radiation. For these flashes, the ONERA system detected very few VHF sources even though the duration for some flashes extended up to almost half a second and the magnitudes of the detected radiation was strong. In the second population, the flashes are longer, exhibit more branching, contain many leaders and fast processes, and have many more VHF sources that are radiatively intense. For this population of flashes, the total VHF length increases when the duration increases. However, for a given duration the total VHF length varies over one order of magnitude, while for a given length, the flash duration varies over less than one order of magnitude. This suggests that different lightning flashes of similar duration do not exhibit either the same number of components, the same component duration or the same component extensions.
DISCUSSION

The present article synthesizes results of our investigation on flash component length based on the VHF radiation. For most of the flashes of the present study the flash component length does not represent the flash extension but the sum of all the lengths of the flash components. Of course our assumptions introduce uncertainties. Our results are highly dependent on relationships we applied, step lengths, intervals between steps and speeds of propagation of fast processes we considered. If we were trying to estimate lengths for only a few flashes a more comprehensive approach might be taken. But this seemed infeasible for studying flashes over the lifetime of a storm that lasted 4 1/2 hours and produced over 5000 lightning flashes. Another source of error is that the interferometer poorly detects positive discharge processes. We think that there is roughly a factor of 2 to 3 uncertainty in determination of total lightning component lengths using our method with the ONERA interferometer measurements made during STERAO-A. The technology of this instrument is now more than a decade old. If the newly developed time of arrival systems, such as that of Krehbiel [2001], were combined with a high time resolution interferometer system, more reliable estimates of total lightning lengths are possible.

The results from this study have been used by Skamarock et al. [2002] to examine NOx production per unit channel length for the 10 July 1996 storm. They used the results of a cloud simulation [Skamarock et al., 2000] to estimate the transport of NOx into the anvil from lower levels and uses in situ measurements of NOx [Dye et al., 2000] to determine the flux of NOx into the anvil. The estimates of flash length reported here are then combined with the flux of lightning produced NOx in the anvil to determine NOx produced per unit lightning channel length, produced per flash, and estimates of the total NOx potentially produced by the 10 July 1996 storm. The flux analysis revealed that 60% of the NOx transported in the anvil was produced by lightning. Finally the analysis yields a production rate of $10^{21}$ molecules NOx per meter of component channel (radiating in the VHF domain).

The present analysis shows that flash characteristics such as type, flash duration, component duration, number of components, and probably NOx production are highly variable from flash to flash. Further investigations in different locations on Earth are needed to characterize the flash population by the use of improved lightning mapping techniques. With additional field studies using in situ chemical and lightning measurements in thunderstorms and laboratory investigations of NOx production by different lightning components we can eventually reduce the uncertainty in estimates of the global production of NOx by lightning.

REFERENCES