Bulletin of the American Meteorological Society

WMO World Record Lightning Extremes: Longest Reported Flash Distance and Longest Reported Flash Duration

--Manuscript Draft--

Manuscript Number:	BAMS-D-16-0061
Full Title:	WMO World Record Lightning Extremes: Longest Reported Flash Distance and Longest Reported Flash Duration
Article Type:	Article
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Manuscript Classifications:	1.052: Europe; 1.096: North America; 3.224: Lightning; 5.076: Instrumentation/sensors; 9.008: Anomalies
Abstract:	A World Meteorological Organization weather and climate extremes committee has judged that the world's longest reported distance for a single lightning flash occurred with a horizontal distance of 321 km (199.5 mi) over Oklahoma in 2007, while the world's longest reported duration for a single lightning flash is an event that lasted continuously for 7.74 seconds over southern France in 2012. In addition, the committee has unanimously recommended amendment of the AMS Glossary of Meteorology definition of lightning discharge as a "series of electrical processes taking place within 1 second" by removing the phrase "within one second" and replacing with "continuously." Validation of these new world extremes (a) demonstrates the recent and on-going dramatic augmentations and improvements to regional lightning detection and measurement networks, (b) provides reinforcement regarding the dangers of lightning, and (c) provides new information for lightning engineering concerns.
Author Comments:	Email (August, 2015) from Jeff Rosenfeld to me (Randy Cerveny), regarding eventual

	submission of this article to BAMS: It's great to hear from you. I hope all is well. That sounds like a great article--interesting extreme that I suppose was not possible until the modern era of lightning detection systems and satellite observing. BAMS would be a great place for the article. If you're thinking of submitting it, please go ahead and basically send what you just sent to me within the online Editorial Manager manuscript tracking system, so that we can assign a number for it and keep tabs on it. --Jeff On Tue, Aug 18, 2015 at 1:55 PM, Randall Cerveny <cerveny@asu.edu> wrote: Hi, Jeff, I have put together another blue-ribbon WMO evaluation weather extremes committee that is in the final stages of evaluating two lightning weather extremes. I am wondering if BAMS would be interested in publishing our findings?
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WMO World Record Lightning Extremes:
Longest Reported Flash Distance and Longest Reported Flash Duration

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Capstone Statement: A World Meteorological Organization committee has judged that the world's longest reported distance for a single lightning flash occurred with a horizontal distance of 321 km (199.5 mi) over Oklahoma in 2007, while the world's longest reported duration for a single lightning flash is an event that lasted continuously for 7.74 seconds over southern France in 2012.

Abstract. A World Meteorological Organization weather and climate extremes committee has judged that the world's longest reported distance for a single lightning flash occurred with a horizontal distance of 321 km (199.5 mi) over Oklahoma in 2007, while the world's longest reported duration for a single lightning flash is an event that lasted continuously for 7.74 seconds over southern France in 2012. In addition, the committee has unanimously recommended amendment of the AMS *Glossary of Meteorology* definition of lightning discharge as a "series of electrical processes taking place within 1 second" by removing the phrase "within one second" and replacing with "continuously." Validation of these new world extremes (a) demonstrates the recent and on-going dramatic augmentations and improvements to regional lightning detection and measurement networks, (b) provides reinforcement regarding the dangers of lightning, and (c) provides new information for lightning engineering concerns.

1. Introduction and Suggested Modification of "Lightning Flash" Definition

Dramatic augmentations and improvements to lightning remote sensing techniques have allowed the detection of previous unobserved extremes in lightning occurrence. As part of the ongoing work of the World Meteorological Organization (WMO) Commission for Climatology (CCl) in detection and documentation of global weather extremes (e.g., El Fadli et al. 2013), a critical evaluation of two recent lightning extremes has been undertaken. These two extremes are: (1) the world's longest detected distance for a single lightning flash, and (2) the world's longest detected duration for a single lightning flash. Specifically, a WMO CCl evaluation committee has adjudicated that the world's longest detected distance for a single lightning flash occurred over a horizontal distance of 321 km (199.5 mi) using a maximum great circle distance between individual detected VHF lightning sources. The event occurred on 20 June 2007 across parts of Oklahoma. They accepted the world's longest detected duration for a single lightning flash is a single event that lasted continuously for 7.74 seconds on 30 August 2012 over parts of southern France. It should be noted that, as with all WMO evaluations of extremes (e.g., temperature, pressure, wind, etc.), the proposed extremes are identified based on only those events with available quality data and brought to the WMO's attention by the meteorological community. It is possible, indeed likely, that greater extremes can and have occurred. For example, it is likely that the current highest recorded wind gust extreme of 113.2 m s^{-1} (253 mph; 220 kt) [Barrow Island Australia, 1055 UTC 10/4/1996] can be exceeded by winds in a tornado or similar phenomena. However, the Australian wind gust has been the highest recorded event placed before the WMO for adjudication. When higher extreme events are effectively recorded and brought to the attention of the WMO, subsequent evaluations of those extremes can occur.

A critical element in the discussion of these extremes is the fundamental definition of a lightning flash. The American Meteorological Society (AMS) *Glossary of Meteorology* (American Meteorological Society 2015) defines a lightning flash as "a transient, high-current electric discharge with path lengths measured in kilometers" while a lightning discharge is defined (American Meteorological Society 2015) as "the series of electrical processes taking place within 1 s by which charge is transferred along a discharge channel between electric charge centers of opposite sign within a thundercloud (intracloud flash), between a cloud charge center and the earth's surface (cloud-to-ground flash or ground-to-cloud discharge), between two different clouds (intercloud or cloud-to-cloud discharge), or between a cloud charge and the air (air discharge). It is a very large-scale form of the common spark discharge. A single lightning discharge is called a lightning flash."

Debate on an updated precise definition of a lighting flash was initiated by the committee and through the review process. Specifically, after careful deliberation by the WMO evaluation committee, comprised in part of international users and operators of lightning locating systems (LLS), the unanimous consensus was that this lightning discharge definition has not been adapted to fit with physical characteristics and processes as revealed by modern technologies. At this time, the committee recommends only small revisions to the AMS *Glossary of Meteorology* definitions to bring the definition to more current conformance with improved technologies.

For the broad meteorological community, it is useful to review a few relevant features of lightning formation. This discussion generally follows materials from Rakov and Uman (2007), WMO (2014), Albrecht et al. (2014), and UCAR MetEd (2016). A lightning flash is initiated through the occurrence of bi-directional leaders between two oppositely charged regions of a cloud. Lightning initiates at altitudes colder than freezing where a mixture of hail particles called graupel, supercooled water droplets, and various forms of ice crystals occur in the presence of an updraft. The updraft separates the different charges associated with these variably sized particles resulting in initiation of a lightning event. Negative stepped leaders move downward in steps of around 50 meters that can be detected by high-speed cameras and through the high-frequency radio emissions received by ground-based detection networks such as a Lightning Mapping Array (LMA).

For simplicity and because 90 percent of lightning strikes are of this type, consider the typical phenomenology of a negative cloud-to-ground (CG) flash. As a negative stepped leader approaches the ground, positive charges are induced at the ground and by tall conducting features, thereby maintaining the electrical potential between leader and ground. The electric potential difference between a downward-moving stepped-leader tip and ground is probably on the order of tens of megavolts. This allows an upward streamer of positive charge to develop from tall plants, artificial structures, or from flat ground or water surfaces. Typically, an LMA misses these upward streamers near the surface of the earth because they occur at a lower altitude than the detection network's line of sight. Streamers have less light emission and lower conductivity, current, and temperature than leaders.

When the stepped leader is within 30 to 50 meters of the ground, it makes contact with the upward streamer that is closest in space to the downward stepped leader. This connection completes the electrical circuit and the downward return stroke begins, in which negative charge flows down to the ground. The first return-stroke current measured at ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The leading edge of the return stroke moves upward as the negative charge is drained from the cloud. During the return stroke, the moving electrical charge radiates electromagnetic fields detected by ground-based sferics networks, an intense optical pulse (flash of light) detectable by satellite sensors, intense heating (~30,000 K) and rapid expansion of air (pressure of 10 atmospheres or more) creating acoustic shock waves (thunder) and the formation of nitrogen oxides.

However, the above discussion should not be construed as suggesting that a ground stroke (CG) alone is what produces light output from flashes and that and that it is the dart leader / return stroke process associated with CGs which drives channel extension. Many of the same basic extension and illumination processes take place with ICs and CCs (IntraCloud and Cloud-to-Cloud) as well. The ground strike example is a special case that fits in the general framework. This understanding is critical with regard to the future Geostationary Lightning Mapping (GLM) technology when space-based optical lightning detection will add to the current LMA and other ground-based networks (such as described in this study) that do not use any optical light.

If sufficient charge remains in the cloud, there is a short (~40 millisecond) pause before another negatively charged leader (the "dart leader") begins moving towards the surface. Like the stepped leader, the dart leader can be detected by an LMA. As the dart leader nears the surface, a second return stroke is generated that is generally detectable by ground-based systems. This cycle of dart leaders and return strokes continues until the channels cease growing within the cloud. The whole process normally lasts only a few hundred milliseconds. However, many lightning flashes have been detected, measured and evaluated in recent years with durations exceeding one second (e.g., Lang et al. 2010, Bruning and Thomas 2015, Montanyà et al. 2014). Consequently, the committee concluded that the phrase "within 1 second" within the *AMS Glossary of Meteorology* is no longer valid. Improved detection of long duration and long distance, particularly the horizontal part of lightning flash extremes, indicates that evaluation of lightning flashes of longer than one-second duration is now possible. Therefore, the committee for the WMO Archive of Weather & Climate Extremes evaluation has unanimously suggested amendment of the definition of lightning discharge by removing the phrase "within one second" and replacing with "continuously."

In addition, committee members suggest that the definition of a lightning flash should state that a flash is a three-dimensional phenomenon with channels that propagate both vertically and horizontally and that "along a discharge channel" be modified to "along discharge channels" to better conform to complex discharges that involve multiple charge regions and connection channels. Fundamentally, the potential presence of related upper-atmosphere discharges, forced by large charge moment change (e.g., sprites), may have to be incorporated into a broader future discussion of a precise lightning flash definition. For example, the atmospheric electricity community generally employs the term "flash" as the entire lightning discharge (breakdown, return strokes, dart and leaders, etc.) while the weather forecasting community commonly uses the more specific *AMS Glossary of Meteorology* definition of "the series of electrical processes" as associated with a "lightning discharge." At this time, however, the WMO committee recommends only two small revisions (employ 'continuously' rather than 'within 1 second' and "along discharge channels' rather than "along a discharge channel') to the AMS *Glossary* lightning definition to bring the definition to more current conformance with improved technologies and welcomes continued discussion of lightning definitions.

Given that amendment to the formal definition of a lightning flash, an analysis of the two different lightning extreme events (Oklahoma, 2007; France, 2012) have been put forth as extremes in lightning flash distance and duration respectively. Both of these events were detected with a Lightning Mapping Array (LMA; Rison et al. 1999). In the following discussion, the mention of specific companies or products does not imply that they are endorsed or recommended by WMO in preference to others of a similar nature which are not mentioned or advertised.

2. Lightning Mapping and Monitoring Technologies

The Lightning Mapping Array (LMA) is a time-of-arrival 3-D lightning mapping system developed by the New Mexico Institute of Mining and Technology (NMIMT). LMAs map lightning sources by receiving radiation produced in a specific VHF band as a flash develops.

Each LMA station records the arrival times and amplitudes of the peaks of impulsive VHF sources, recording at most one peak in a particular interval (80 μs for the data used here). Because negative leaders radiate much more strongly than positive leaders, an LMA having typical settings such as the LMAs providing data for this paper, primarily locates lightning channels from negative leaders, or from negative recoil events along positive leader channels. An LMA detects relatively few positive leaders directly. The positive electrical discharge is less impulsive and more continuous than a negative one. As a result, weaker and more frequent radiation emissions make it more difficult for multiple stations to detect the same pulse (MacGorman et al. 2008). Flashes commonly consist of tens to thousands of individual VHF sources. The design, operation, and accuracy of LMAs are given by Rison et al. (1999), Krehbiel et al. (2000), Thomas et al. (2004), and Chmielewski and Bruning (2016).

Locations of impulsive VHF sources are determined by firstly correlating the arrival times for the same event at multiple stations, then locating each source via a time-of-arrival (TOA) technique (Thomas et al. 2004). Because the VHF signal rates received by stations can be rapid enough that the time window for propagation across the array can contain multiple distinct combinations of received signals, it is necessary to determine which combination yields a reasonable solution for the time and location of the source. The Levenberg-Marquardt nonlinear inverse algorithm (Aster et al. 2013) is used to solve for multiple possible spatio-temporal location solutions, and then the chi-square (χ^2) goodness-of-fit value is minimized to find the most probable location. A source location with a very high χ^2 value (e.g., > 5) is unreliable. In addition, though a minimum of four stations is needed to locate the source of a VHF source from lightning in four dimensions (space and time), in practice it is preferable to have at least 6 or more stations detect a source in order to minimize the effect of noise in the retrievals. The influence on overall flash metrics (specifically, horizontal length and time duration), particularly thresholds on the number of stations providing data and the χ^2 value of the solution required to accept a VHF source as valid, will be discussed in more detail later.

VHF sources for each flash were manually isolated using the XLMA software developed at New Mexico Tech (Rison et al. 1999). Because the flashes in this study were very large, they spanned a substantial fraction of each LMA domain, and therefore were subject to highly variable source detection efficiencies (Thomas et al. 2004). Thus, it was deemed more accurate to use experienced scientific judgment to separate these flashes from other nearby flashes, rather than fixed thresholds on time and space parameters (e.g., maximum allowable time or distance between successive VHF sources; Fuchs et al. 2015). That is, while manually isolating each flash, the committee looked for spatial and temporal continuity in flash development, using a mixture of fixed and animated imagery to help inform decisions about which VHF sources to include. This manual analysis is a well-established technique in LMA-based research, and is highly desirable for case studies of complex individual flashes (e.g., Rison et al. 1999; Lang et al. 2011; van der Velde and Montanya 2013).

a) Oklahoma Network

The Oklahoman LMA (OKLMA) is operated by the University of Oklahoma, the NOAA National Severe Storms Laboratory (NSSL), and New Mexico Institute of Mining and Technology (NMIMT) (MacGorman et al. 2008). The performance of the OKLMA, particularly on the day of the lightning flash that concerns this study, was discussed in detail by Lang et al. (2010, 2011). According to that study, horizontal location accuracy for individual sources averaged about 0.5 km in the horizontal at 100 km range from the network centroid, and about 1.2 km at 200 km range. In the vertical the accuracies were 0.9 and 2.1 km, respectively. Though detection efficiency is expected to decrease with range starting from the center of the LMA (Boccippio et al. 2001), for the 20 June 2007 storm the source detection efficiency only became partially decorrelated from reflectivity structure beyond 120 km range (Lang et al. 2011). The flash in this study had sources ranging from 9 km to 206 km distance from network centroid. Based on this, as well as the results of Lang et al. (2010), we estimate a worst-case standard error of 1 km (rounded to the nearest km) in the horizontal for the sources in this flash. Furthermore, though we expect some potential sources were not detected at the longer ranges, improved detection would only have increased the measured length of the flash in question, not decrease it. On 20 June 2007, when the longest-length flash occurred, there were 11 of 12 OKLMA stations active.

b) Southern France Network

HyMeX (Hydrology cycle in the Mediterranean Experiment; http://www.hymex.org/) is a long-term multidisciplinary science project initiated by the French scientific community in 2007 (Drobinski et al. 2014; Ducrocq et al. 2014). A HyMeX science team dedicated to Lightning and Atmospheric Electricity deployed several observation systems for the first Special Observation Period (SOP1) from August to November 2012 in southeast France, one of the target areas of HyMeX (Defer et al. 2015). Among those instruments, several different LLS technologies were made available to record the total lightning activity in this region (Defer et al. 2014, Defer et al. 2015).

The HyMeX LMA (HyLMA) system consisted of 12 stations, lent to the campaign by Dr. Rich Blakeslee of NASA Marshall Space Flight Center (MSFC). It was deployed around Alès in the Cévennes Vivarais region by personnel from NMIMT and the Laboratoire d'aérologie in Toulouse. The average separation distance between each station was approximately 34 km in order to obtain high-resolution measurements inside the network. This region is surrounded by mountains, on top of which some stations were installed, up to an altitude of 1100 m MSL. With such conditions the HyLMA could cover an area of 150 km x 150 km and produce reliable and accurate measurements of source locations near the Mediterranean coast. However, the lines of sight of most of the stations to low-altitude lightning channels outside of the array were blocked by the mountainous terrain in southeastern France, so the HyLMA typically detected only the higher altitude lightning channels outside the array. The HyLMA stations were located in radio-frequency-quiet (RF-quiet) regions, mainly rural areas, and were solar powered and used broadband cell phone modems for communications.

Based on the network's configuration relative to the assumptions underlying the analysis of Thomas et al. (2004), we estimate that the HyLMA detected lightning inside the array with a location accuracy of about 10 m horizontally and 30 m vertically. HyLMA design was very similar to the system presented by Thomas et al. (2004), with 12 stations in HyLMA against 13 in the other study for comparable coverage. The average of the five closest sensor baselines was 34 km. Thus, this would suggest very similar performances for HyLMA. Because of the unusual phenomenology of thunderstorms in this region during 2012, the HyLMA located much of its detected lightning outside of the core of the array. However, location errors were estimated to be < 1 km at 200 km range from the network center.

Standard LMA products come with unadjusted χ^2 and assumed timing errors of 70 ns. Consequently, χ^2 is not perfect because the model does not perfectly match every type of breakdown process in lightning flashes. Therefore, members of the committee adjusted χ^2 based on XLMA-estimated timing errors of 45 and 30 ns for OKLMA and HyLMA LMAs, respectively (Thomas et al. 2004). Using Equation A2 of Thomas et al. (2004), the actual χ^2, for a system with a timing error of 35 ns and an assumed timing error of 70ns, is (χ_c^2 x 4) where χ_c^2 is the calculated value.

3. VLF/LF lightning Detection Networks

Most lightning monitoring groups around the world utilize VLF/LF lightning detection networks such as the National Lightning Detection Network (NLDN), a system that provides accurate data on the time, location, amplitude, and polarity of the individual return strokes in CG flashes, and also detects some IC strokes (Cummins et al. 1998b). System accuracy is high, as demonstrated, for example, in a comparative test of the NLDN with tower observations in Rapid City, South Dakota, USA (Warner et al 2012), in which a total of 81 upward flashes were observed from 2004–2010 using GPS time-stamped optical sensors, and in all but one case, visible flash activity preceded the development of the upward leaders. In that study, time-correlated analysis showed that the NLDN recorded an event within 50 km of towers and within 500 ms prior to upward leader development from the tower(s) for 83% (67/81) of the upward flashes. NLDN observations were available for the Oklahoma event.

In our study, the Southern France event discussed below employed the European Cooperation for Lightning Detection (EUCLID) system. EUCLID is network is a collaborative effort among national lightning detecting networks across Europe with the aim to identify and detect lightning over the entire European area. This cooperation was established in 2001 by six countries (Austria, France, Germany, Italy, Norway, and Slovenia) and subsequently other countries as Spain, Portugal, Finland, and Sweden also joined this cooperation.

EUCLID is based on NLDN technology, combining both magnetic direction finding and TOA techniques as one, called IMPACT sensors (Cummins et al. 1998a), to locate return strokes or large current intracloud discharges in the VLF/LF range. This system has undergone multiple validation studies. Validation of the EUCLID network was primarily done with independent ground truth data; e.g., tower measurements, video, and field measurement data. Most of the validation in terms of location accuracy (LA) and detection efficiency (DE) was accomplished in Austria (Diendorfer et al. 2009; Diendorfer et al. 2010; Schulz et al. 2014) but an experiment in Belgium also occurred in 2011. The performance of EUCLID was estimated during the HyMeX SOP1 campaign based on high-speed video camera records and electric field measurements. The estimated DE of the network for negative CG flashes/strokes was 90%/87% and the DE for positive CG flashes/strokes was 87%/84%. Because the EUCLID performance suffered during the observation period due to the outage of a close sensor, the estimated DEs are lower than the performances measured in Austria and Belgium (Schulz et al. 2014). However, all sensors covering the HyMeX region were up and running when the flash under study occurred. EUCLID was then totally operational at that moment.

4. Longest Distance: 20 June 2007 Oklahoma USA

This extreme lightning event started around 06:07:22 UTC on 20 June 2007 and lasted 5.70 seconds over central Oklahoma in the United States (Fig. 1). Curve-fitting procedures (discussed below) give an east-west direction distance of 305 km, in the north-south direction a distance of 232 km, and in the vertical a distance of 17 km. A mosaic radar reflectivity plot at 1 km MSL, valid at 06:03 UTC on 20 June 2007shows the longest-length flash origin point as well as a plan projection of the VHF sources encompassing the flash (Fig. 2a). A plot of the spatiotemporal behavior of the flash can be seen in Fig. 3. The flash propagated from east to west, initiating in convection and moving into a region of stratiform precipitation. It lasted 5.70 seconds. While traveling toward the stratiform region during the first second, the flash descended in altitude as its negative leaders followed a downward-sloping upper positive charge layer (Lang et al. 2010). Between seconds 1 and 2, the flash turned back toward convection and sources rose in altitude (Fig. 3a). This meandering behavior (away and toward convection) continued over the next few seconds, leading to substantial source altitude variability. After 06:07:26 UTC, the flash remained mostly within the stratiform region of the storm and VHF sources became sparser. During its lifetime, the flash produced at least 9 positive CG strokes, 4 negative CG strokes, and 4 IC events, as NLDN (Fig. 3).

Figure 4a shows how VHF sources behaved in terms of time versus distance from the flash origin, defined as the median location of the first 10 sources. This visualization approach is useful for investigating the spatiotemporal continuity of lightning flashes, as well as diagnosing apparent leader speeds (van der Velde and Montanya 2013). Essentially, in this type of plot significant leaders show up as coherent lines of sources (e.g., between 0 and 1 seconds, and near 3 seconds, in Fig. 4a are good examples of this), with the line slopes providing rough estimates of leader speeds. Also, one would expect near-continuous activity that is approximately contiguous with range in a single flash. In the flash indicated in Fig. 4a, VHF activity was highly continuous in time and contiguous in range. After 4 seconds, activity became sparser deep into the stratiform region. However, there was never a gap longer than 77 ms between individual VHF detections, and these sources all occurred in close proximity to one another (with the exception of renewed activity near the flash origin after 4 s; Fig. 4). Moreover, at this long range, source detection efficiency would be expected to be reduced (Boccippio et al. 2001, Lang et al. 2010). For example, source powers (Fig. 4) average higher during the sparse period (seconds 4 to 5), especially beyond 250 km distance from flash origin. This suggests that only the strongest sources are being detected at these ranges. Regardless, the flash had already reached its maximum length by 4.75 s, before the longest temporal gap occurred. In addition, animations (available in the supplemental material) indicated spatiotemporal continuity in flash behavior throughout its duration.

Two sprites were observed from this flash. The first occurred at 6:07:26.364-.397 UTC, and the second, at 6:07:26.643-.660 (Lang et al. 2010, Lang et al. 2011). These were associated with two distinct parent +CGs that emanated from the flash in question. The first had a total charge moment change (CMC) of (at least) 650 C km, while the second had a total CMC of (at least) 236 C km. The CMC measurements came from the Charge Moment Change Network (CMCN) operated by Duke University (Cummer et al. 2013). These values were mainly associated with the return stroke. There is no available information on the continuing current contribution due to noise at the two CMCN sensor sites (one in North Carolina, one in Colorado). CMC information for any other CGs associated with this flash has not been analyzed. More information on the CMC network used to make these analyses can be found in Cummer et al. (2013), and additional information about CMC measurements on this day can be found in Lang et al. (2011).

The lightning event was produced in a warm-season mesoscale convective system (MCS) that formed under a large 500-hPa ridge (Fig. 5a) with a shortwave evident at 700-hPa using the 20th Century Reanalysis (Version 2; Compo et al. 2011). This MCS was a symmetric leading-line/trailing stratiform MCS. According to Lang et al. (2010), its size and infrared satellite brightness temperature characteristics qualified it as a mesoscale convective complex (MCC; Maddox 1980). The period encompassing the production of the flash in question was characterized by a convective line that was weakening and a stratiform region that was still intensifying, as the embedded secondary convection and the horizontal area of weak reflectivity in the stratiform region both were increasing (Lang et al. 2010).

This MCS produced 282 observed transient luminous events (TLEs) over a four-hour period (Lang et al. 2010). Around the time of the flash's occurrence, convection in the leading line of the MCS was inferred from lightning to have normal-polarity tripolar charge structures, with upper-level positive charge (<−40°C), midlevel negative charge (−20°C), and low-level positive charge near the melting level (Lang et al. 2010). Notably, the stratiform region featured a downward-sloping upper positive charge region that was spatially connected to upper-level convective positive charge, a common pattern in MCSs that have been studied with LMAs and similar sensors (e.g., Ely et al. 2008, van der Velde et al. 2014).

The critical concern addressed by the committee with regard to the Oklahoma lightning extreme event involved the method for accessing projected-to-ground horizontal distance. In unanimous consensus, the committee noted that a precise method for determining flash length is critical because differing methods can result variation in flash length estimates.

In evaluation of the Oklahoma lightning extreme, four different methods were discussed and evaluated. Two of these methods, however, are mathematically equivalent. Specifically, the methods used were calculation of flash distance through (a) the major axis of the ellipse fitted to the convex hull (Fitzgibbon et al. 1996, Bruning and Thomas 2015), (b) the maximum great circle distance between individual LMA sources (Haversine method) or the maximum great circle distance between individual convex hull vertices (these are mathematically equivalent), and (c) the square root of the convex hull area (or its characteristic length scale). The analyses were conducted using a variety of minimum station numbers and maximum χ^2 values (Uman 2001), as seen in Fig. 6. Minimum station number refers to the minimum number of LMA stations that must detect a VHF source for it to be included in the dataset, and maximum χ^2 value refers to the maximum error associated with its location solution for a VHF source to be included in the dataset. As either of these parameters are relaxed (e.g., fewer stations or higher χ^2 allowed for a solution), the number of available VHF sources in a flash dataset will grow, leading to bigger, longer-lived flashes. However, relaxing these thresholds can lead to more noise in the dataset. Doing the opposite can remove good data. Thus, researchers have sought to balance these competing concerns in LMA analyses, and Fig. 6 demonstrates how this balancing act can affect outcomes in this study.

Although LMAs have well-documented error statistics (e.g., Thomas et al. 2004, Lang et al. 2010, Chmielewski and Bruning, 2016) for characterizing individual sources, much less work has been conducted in terms of derived flash properties. Method selection can make a large difference in distance determination, as do station requirements and χ^2. The variability in length can be tens of kilometers. Merits and disadvantages can be advanced for each method. For example, with regard to the ellipse method, (a) the method may be needlessly complicated, and (b) the ellipse could be sensitive to the geometry of the flash orthogonal to the longest dimension. Conversely, the method of ellipse fitting to the convex hull vertices may be less sensitive to LMA network effects such as differing numbers of stations.

After discussion, the committee unanimously recommended that, for flashes mapped by an LMA, the flash length be computed as the maximum great circle distance between the extreme VHF sources, minus the uncertainty in the measurement (twice the standard error, due to subtracting from both ends). The computation of each VHF source included in a flash must be derived from a) detections by at least seven (7) stations and b) must have an adjusted χ^2 of no more than five since, as stated earlier, a source location with a very high χ^2 value (e.g., > 5) is unreliable. This ratio of station number to χ^2 was chosen to optimize and balance good sources versus noise for large, long-lived mesoscale flashes that experience a variety of LMA network characteristics due to their large size (e.g., they are so big they can exist both within the network core as well as at long distance from the core). Additionally, sequential points in a flash must occur within reasonable spatial and temporal proximity of other points in the flash; however, no rigid thresholds for spatiotemporal continuity were used since source detection efficiency variability can lead to incorrect outcomes, particularly when dealing with large flashes (e.g., Fig. 4). Instead, committee members used their scientific judgment when assessing the spatiotemporal behavior indicated in the figures and animations of these flashes. The committee also noted a caveat that it may be necessary, when using new lightning mapping technologies, to reexamine the criteria for determining what detections to include in a flash, although the method for computing the distance as the great circle distance minus twice the standard error likely would remain the same. Consequently, the committee strongly recommends that both the specific criteria for including detections by a new technology in a single flash and, if a method different from a great circle method is employed, the specific method of distance calculation must be identified in professional discourse of the distance spanned by a flash.

Given a selection of 7 stations and χ_c^2 of 5, the maximum great circle distance (Haversine method) for the 20 June 2007 (06:07:22 UTC) flash between two sources is 323 km, minus 2 km (standard error) , resulting in 321 km. This distance of 321 km (199.5 mi), recorded on 20 June 2007 (06:07:22 UTC), is thereby deemed acceptable as the WMO's official "Longest Distance" record lightning extreme for the globe (Fig. 1).

5. Longest Duration: 30 August 2012 Southern France

This particular lightning event was detected around 04:18:50 UTC on 30 August 2012 over Provence-Alpes-Côte d'Azur, France (Fig. 7) during the first Special Observation Period (SOP1) of HyMeX (Ducrocq et al. 2014).

At this time, strong thunderstorm activity was occurring in southern France as the result of a cold front passage associated with a deep trough. Analysis of the 500-hPa chart showed the axis of a trough extending through western France (Fig. 5b). Surface analysis by the UKMO indicated a surface front entering France from the northwest at 00 UTC, while surface station observations indicated substantial surface moisture in southern France with surface dew points ranging from 18°C to 22°C. Reflectivity from the Aramis (Bollene), France radar at 0.8° elevation angle, valid at 04:15 UTC on 30 August 2012 shows the origin point of the flash (set as the median of the first 10 sources) together with plan projection of the VHF sources encompassing the longest-duration flash, which occurred around 04:18:50 UTC(Fig. 2b).

The flash started in the main convective part of the storm, located around Pierrelatte (Drôme), and propagated into the trailing stratiform region to the southeast of the storm, similar to the the Oklahoma flash, toward Brignoles (Bouches du Rhône). Its centroid was located at about 44.0° N latitude, and 5.4° E longitude, and its horizontal length (great circle distance) was approximately 160 km using (as with the event in Oklahoma) LMA sources detected by at least seven stations and exhibiting a maximum χ^2 of 5.

The most active period of the storm was from about 01:00 to 02:30. By the time of the longest-duration flash at 04:18:50 the lightning activity had decreased significantly. Large long-duration flashes commonly occur in the later part of storms, as they enter the final dissipation stage (Albrecht et al. 2011, Peterson and Liu 2013). In this situation, there were approximately a dozen flashes with durations over two seconds, and there was a five-second flash that occurred at about 04:35:00. The HyLMA sources for this flash are shown in Fig. 8. However, at times within the stratiform region, the France flash accessed multiple, vertically stacked charge layers (e.g., Stolzenburg et al. 1998). The most dramatic example of this was around 04:18:57.5, when new breakdown along a flash channel, which started just before 04:18:57 (see the downward leader in Fig. 8a), eventually accessed three distinct charge layers (made most apparent by the dark red sources in Fig. 8e).

Two key concerns regarding this particular flash under investigation was whether it was one continuous event and whether there was more than one flash. Reanalyses by individual evaluation committee members all reached consistent conclusions. As Fig. 4b indicates, there was a clear, continuous sequence of leaders (i.e., distinct lines of sources) and other VHF activity during the lifetime of the flash, with no significant temporal gap. In addition, the flash was nearly contiguous with range from the initiation location. The presence of low-power (< 10 dBW) sources even at long ranges indicated that source detection efficiency for the HyLMA was good enough to provide a nearly complete VHF-based view of the flash.

Analysis of HyLMA data for this flash indicated that application of a variety of χ^2, station number, and altitude criteria did not drive the duration below 7.74 seconds. For example, in Fig. 6d there is little to no change in flash duration across a wide range of χ^2 values for a required minimum of 7 or 8 stations. Even application of very strict criteria ($\chi_c^2 < 0.5$, stations = 9 minimum, only altitudes below 15 km MSL considered), that more than quartered the available source numbers, did not decrease the duration. Relaxing the station criterion to 6 actually lengthened the flash to 8 seconds, but this was likely due to the addition of noise.

The second question of flash separation (e.g., is there one flash or more) is a more difficult one to answer definitively, and depends on how a lightning flash is precisely defined. Consider a flash in a small storm - it might start with in-cloud breakdown, then a leader to ground, followed by a return stroke. After a short pause of a few milliseconds, a new leader develops which may start at a location a few kilometers from the start of the original leader, and may propagate back towards the starting point of the original leader, or may propagate in another direction - perhaps upwards into the upper positive charge region in a hybrid flash. Since the second leader was induced by the field changes from the first leader/return stroke, both leaders are considered to be part of the same flash. For the southern France flash under discussion here, the new activity starting at about 0.6 seconds (see the supplementary material for a detailed animation) likely was induced by the field changes from earlier activity, not by the slow field buildup due to charge separation processes. Because this is a large stratiform region of charge which extends over hundreds of kilometers, the subsequent activity starts a few tens of kilometers away, as compared to a smaller storm, when the subsequent activity will be only a km or so from the original activity.

Fundamentally, a definitive discussion as to how long of a pause and how much separation in distance is needed in determining whether there is one flash or more. Before total lightning mapping, systems such as the NLDN (which locates primarily return strokes) would classify return strokes which were separated by half a second or so in time, and tens of kilometers in distance, as separate flashes. With VHF lightning mapping systems, such strokes are often seen as part of the same flash, as it propagates over tens of km with a duration of several seconds through a large stratiform region. If early activity induces subsequent breakdown in the same charge region, this should all be considered as one flash. In smaller storms the separation in distance will be small; in a large stratiform charge region, the separation in distance can be rather large. Consequently, for this investigation, the consensus of the committee was that there was one single flash with a duration of 7.74 seconds. That lightning flash which was recorded on 30 August 2012 (beginning approximately 04:18:50 UTC) is thereby deemed acceptable as the WMO's official "Longest Duration" record lightning extreme for the globe (Fig. 7).

During this long-lasting flash, the EUCLID system detected a total of 8 CG return strokes and 4 IC pulses. Since these events are associated with large vertical current discharges radiating in the LF, these data are complementary to the VHF data from the HyLMA dedicated to the detection of weaker phenomena such as leaders. Three positive IC pulses were detected at the very beginning of the flash between 04:18:50.260 and 04:18:50.263, and were related to the preliminary breakdown process in perfect agreement with the VHF data. Then, the first two +CG strokes occurred, with one (+14 kA) occurring at 04:18:50.480 immediately followed by the second one (46 kA) after a delay of 102 ms and at a distance of 25 km to the east. Another sequence of two +CGs occurred again around 04:18:52, with the second in the pair occurring 125 ms later and 21 km farther south. The first return stroke in this pair exhibited a peak current of +82 kA and the second was estimated to be +32 kA. The distance in sequence from the first to the second was 26 km, comparable to the distance separating the two strokes in each pair. At 04:18:53.294, EUCLID recorded a –CG of about -15kA, which was the first negative discharge in the flash. The analysis of the waveform parameters of this particular stroke shows the system might have misclassified an IC pulse. However, it is interesting to note this -CG was located near the last +CG, which had occurred about 400 ms earlier. This might be a signature of a bipolar lightning flash (Rison et al. 2016). About two seconds later, a single +CG stroke (+19 kA) was detected at a distance of 60 km from the previous discharge, toward the southeast. Finally, EUCLID observed a last sequence of negative discharges consisting of two -CG strokes followed by a negative IC pulse.

It is interesting to note this long-lasting event is not associated with observed TLEs, despite it having produced several strong positive return strokes along its path. A total of three low-light cameras located in southern France and northeast Spain covered the area of concern. They were all operational and events were recorded during the following night between the 30th and 31st of August, but no event could be found at the time of the flash of interest in the TLE database observations, meaning no observations were made.

6. Conclusions

An evaluation committee for the WMO CCl has established two new records of lightning extremes: (1) the world's longest detected distance spanned by a single lightning flash, and (2) the world's longest detected duration for a single lightning flash. As part of that evaluation and through the review process, debate on an updated precise definition of a lighting flash was initiated by the committee. Specifically, after careful deliberation by the WMO evaluation committee, composed in part of international users and operators of lightning locating systems (LLS), the unanimous consensus was that this lightning discharge definition has not been adapted to fit with modern technologies in lightning detection, monitoring and mapping. At this time, the committee recommends only small revisions to the AMS *Glossary of Meteorology* definitions to bring the definition to more current conformance with improved technologies (employ 'continuously' rather than 'within 1 second' and "along discharge channels' rather than "along a discharge channel').

Consequently, the WMO CCl evaluation committee has judged that the world's longest detected distance spanned by a single lightning flash is 321 km (199.5 mi) along the maximum great circle joining outermost pairs of VHF sources. The event occurred on 20 June 2007 across parts of Oklahoma. Additionally, the committee unanimously recommended that, for flashes mapped by an LMA, the flash length be computed as the maximum great circle distance between the extreme VHF sources, minus the uncertainty in the measurement (twice the standard error, due to subtracting from both ends). The world's longest detected duration for a single lightning flash is 7.74 seconds for an event that occurred on 30 August 2012 over parts of southern France, It should be noted that, as with all WMO evaluations of extremes (e.g., temperature, pressure, wind, etc.), the proposed extremes are identified based on only those events with available quality data and brought to the WMO's attention by the meteorological community. When higher extreme events are effectively recorded and brought to the attention of the WMO, subsequent evaluations of those extremes can occur. With regard to the lightning extremes discussed below, it is possible that the occurrence of Mesoscale Convective Systems (MCSs) in locations such as Argentina and Congo Basin (e.g., Zipser et al. 2006 and Albrecht et al. 1016) may produce more extreme lightning. Additionally, extreme duration/distance lightning over oceans has been observed from satellites (Peterson and Liu 2013).

Validation of these new world lightning extremes (a) demonstrates the recent and on-going dramatic augmentations and improvements to regional lightning detection and measurement networks, (b) provides reinforcement to lightning safety concerns (e.g., Walsh et al. 2013) that lightning can travel large distances and so lightning dangers can exist even long distances from the parent thunderstorm, and (c) for lightning engineering concerns.

7. Acknowledgements

The OKLMA data for the Oklahoma lightning flash were provided by NOAA NSSL and by NOAA/NESDIS grant L2NSR20PCF. The CG lightning stroke data over Oklahoma were provided by Vaisala. Walt Lyons and Thomas Nelson of FMA Research, Inc. made the sprite observations for the Oklahoma flash. The CMC data were provided by Steven Cummer of Duke University. Analysis of the OKLMA data was performed using NMIMT's XLMA software (ftp://zeus.nmt.edu/thomas/) as well as Dr. Eric Bruning's lmatools package (https://github.com/deeplycloudy/lmatools). All datasets for the Oklahoma event are available upon written request to Dr. Timothy Lang of NASA MSFC (timothy.j.lang@nasa.gov). A special thanks to PEACH, the Atmospheric Electricity component of HyMeX project, the French program MISTRALS, ALDIS and Météorage that supported both field operation and data analysis. The HyLMA deployment and operation were supported by the ANR IODA-MED project and the HyLMA sensors were provided by NASA. The Authors are grateful to all PEACH field participants, the HyMeX Operation Center Directors, Forecasters and Administrators, the research team of New Mexico Tech, François Malaterre (Météorage), Georg Pistotnik (ESSL), and Jean-François Ribaud (Météo France) for their support during the field campaign. Oscar van der Velde programmed the time vs. distance graph that helped identify the continuous sequence and polarities of lightning leaders with the LMA data. Timothy Lang was funded by Defense Advanced Research Project Agency (DARPA) Nimbus program, National Science Foundation (NSF) Physical Meteorology program via grants ATM-0649034 and AGS-1010G6S7, and NASA Lightning Imaging Sensor (LIS) project. Manola Brunet was funded by the European Union-funded project Uncertainties in Ensembles of Regional Reanalyses (UERRA, FP7-SPACE-2013-1 Project No. 607193). Joan Montanyà was funded by the Spanish

Ministry of Economy and Competitiveness (MINECO) AYA2011-29936-C05-04 and ESP2013-48032-C5-3-R. We deeply appreciate the extremely useful comments by Ed Zipser, M.J. Peterson, Rachel Albrecht and Eric Bruning.

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Figure Captions

Figure 1. Linear representation of the Oklahoma flash event for 20 June 2007 (06:07:22 UTC) using the maximum great circle distance method described in the text, WMO evaluated "Longest Distance Lightning Flash" event.

Figure 2. (a) Mosaic radar reflectivity at 1 km MSL, valid at 06:03 UTC on 20 June 2007. Also shown is a plan projection of the VHF sources encompassing the longest-length flash, which occurred around 06:07:22 UTC on this day. See Lang et al. (2010) for more details about this multi-radar mosaic product. Flash origin is set as the median of the first 10 sources. (b) Reflectivity from the Aramis (Bollene), France radar at 0.8-degrees elevation angle, valid at 04:15 UTC on 30 August 2012. Ground clutter has not been edited from these data. Also shown is a plan projection of the VHF sources encompassing the longest-duration flash, which occurred around 04:18:50 UTC on this day. Flash origin is set as the median of the first 10 sources.

Figure 3. Characteristics of the Oklahoma flash event for 20 June 2007 (06:07:22 UTC). a) Time-height (km MSL) evolution with color variations indicating time intervals, b) Longitude (deg) / Altitude (km MSL) plot, c) Altitude (km MSL) /frequency diagram, d) Latitude/longitude plot time-sequenced flash event, and e) Altitude (km, MSL) / Latitude (deg) plot. Also shown on most panels are locations and times of NLDN-detected ICs, positive CGs, and negative CGs.

Figure 4. Time vs. horizontal distance as a function of power (dBW) showing the lightning event of 20 June 2007 (6:07:22 UTC) in Oklahoma (a) and the lightning event of 30 August 2012 (4:18:50 UTC) in southern France (b). For interpretation of the time vs. distance plot see van der Velde and Montanyà (2013).

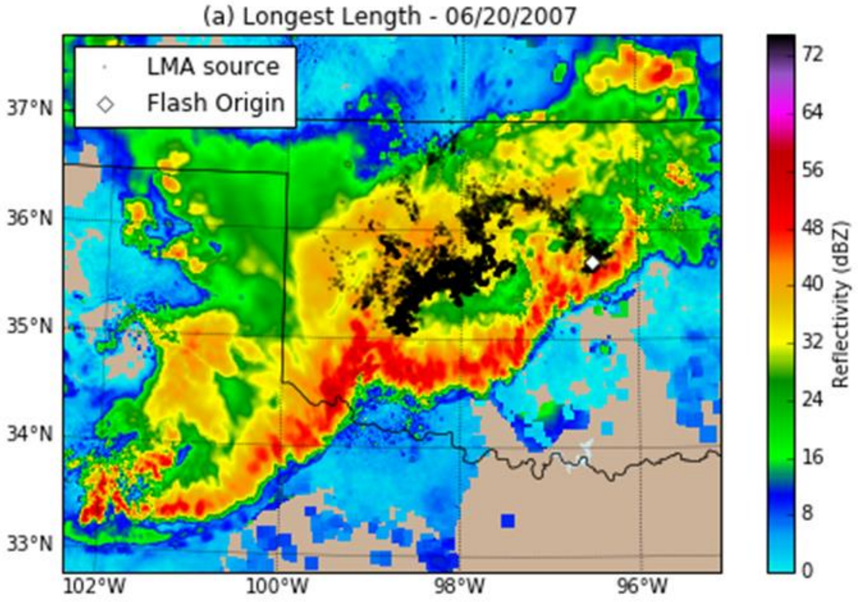
Figure 5. 20th Century Reanalysis (v2) of the 500 hPa height in meters over a) North America on 20 June 2007 (6 UTC) and b) Europe on 30 Aug 2012 (6 UTC).

Figure 6. Computation of the flash length using the four different methods discussed in the text for a variety of stations and χ^2 values for the Oklahoma flash event for 20 June 2007 (06:07:22 UTC). Colors are used for minimum number of stations (blue, 6; green, 7; red, 8). (a) Ellipse method. (b) Maximum distance between individual two sources or xaximum distance between convex hull vertices, which are mathematically equivalent. (c) Characteristic length scale of the convex hull. (d) Comparison of flash durations for the France flash event for 30 August 2012 (04:18:50 UTC), for a variety of station number and χ^2 thresholds. The 7- and 8-station curves largely overlap.

Figure 7. Linear Representation of the southern France flash event for 30 August 2012 (4:18:50 UTC) using the maximum great circle distance method described in the text. This is the WMO-evaluated "Longest Duration Lightning Flash" event.

Figure 8. Characteristics of the southern French flash event of 30 August 2012 (4:18:50 UTC). a) Time-height (km MSL) evolution with color variations indicating time intervals, b) Longitude (deg) / Altitude (km MSL) plot, c) Altitude (km MSL) /frequency diagram, d) Latitude/longitude plot time-sequenced flash event, and e) Altitude (km, MSL) / Latitude (deg) plot. Also shown on most panels are locations and times of EUCLID-detected ICs, positive CGs, and negative CGs.

Figure 1. Linear representation of the Oklahoma flash event for 20 June 2007 (06:07:22 UTC) using the maximum great circle distance method described in the text, WMO evaluated “Longest Distance Lightning Flash” event.



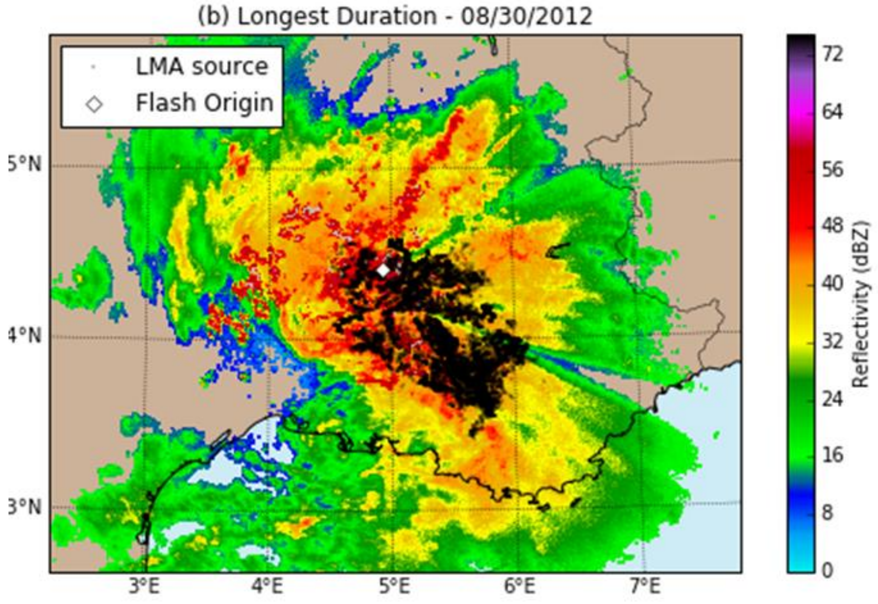


Figure 2. (a) Mosaic radar reflectivity at 1 km MSL, valid at 06:03 UTC on 20 June 2007. Also shown is a plan projection of the VHF sources encompassing the longest-length flash, which occurred around 06:07:22 UTC on this day. See Lang et al. (2010) for more details about this multi-radar mosaic product. Flash origin is set as the median of the first 10 sources. (b) Reflectivity from the Aramis (Bollene), France radar at 0.8-degrees elevation angle, valid at 04:15 UTC on 30 August 2012. Ground clutter has not been edited from these data. Also shown is a plan projection of the VHF sources encompassing the longest-duration flash, which occurred around 04:18:50 UTC on this day. Flash origin is set as the median of the first 10 sources.

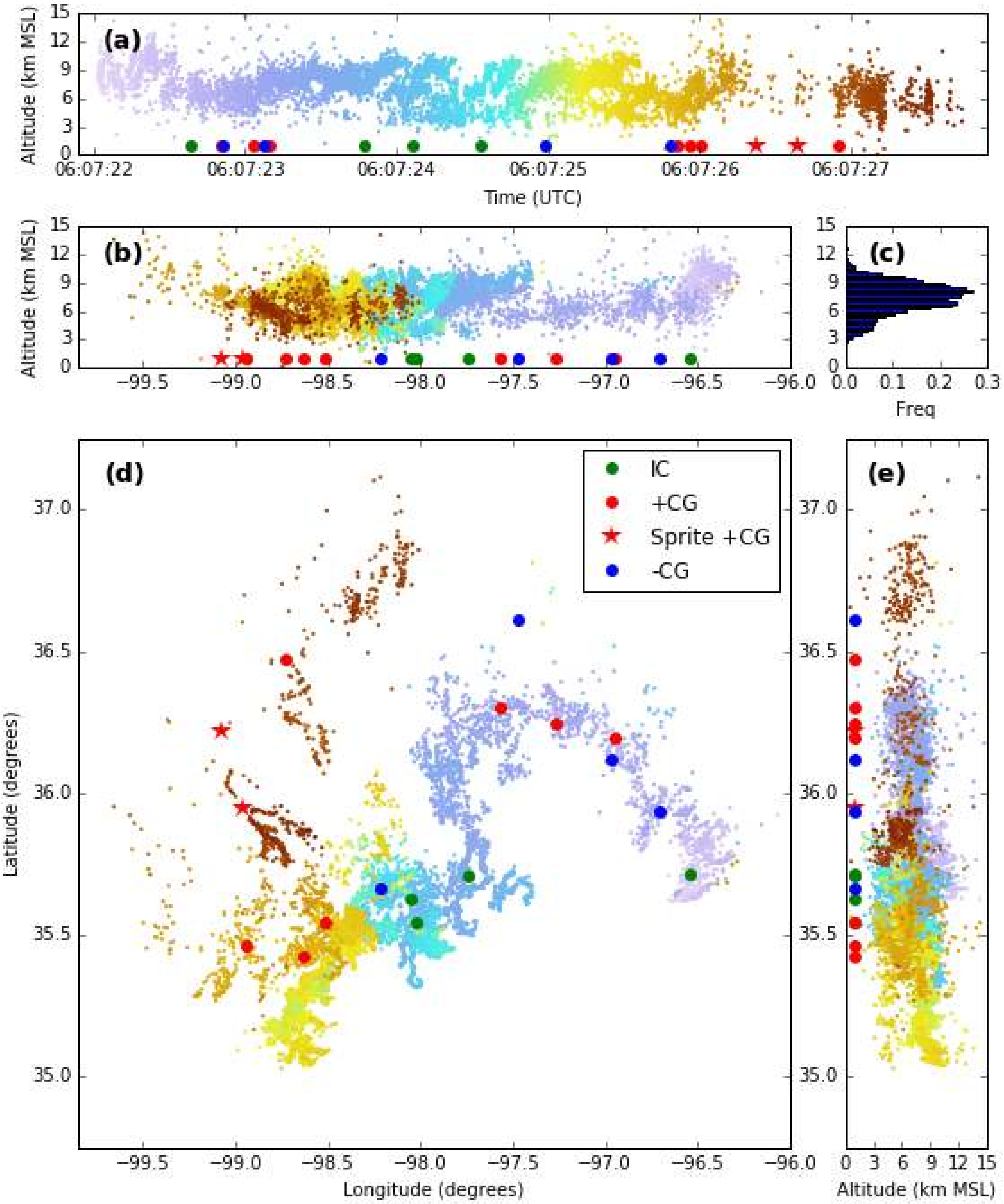


Figure 3. Characteristics of the Oklahoma flash event for 20 June 2007 (06:07:22 UTC). a) Time-height (km MSL) evolution with color variations indicating time intervals, b) Longitude (deg) / Altitude (km MSL) plot, c) Altitude (km MSL) /frequency diagram, d) Latitude/longitude plot time-sequenced flash event, and e) Altitude (km, MSL) / Latitude (deg) plot. Also shown on most panels are locations and times of NLDN-detected ICs, positive CGs, and negative CGs.

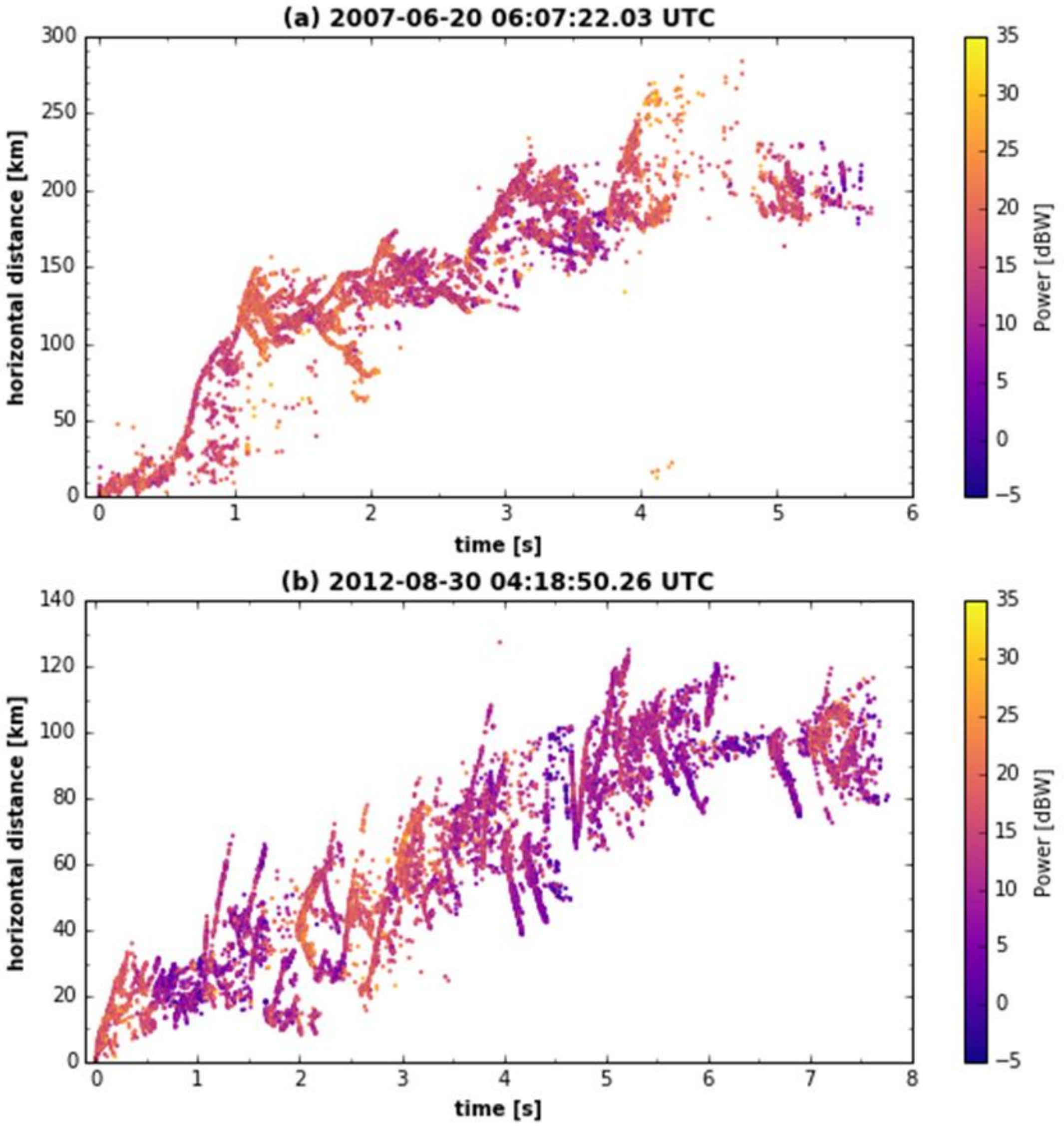


Figure 4. Time vs. horizontal distance as a function of power (dBW) showing the lightning event of 20 June 2007 (6:07:22 UTC) in Oklahoma (a) and the lightning event of 30 August 2012 (4:18:50 UTC) in southern France (b). For interpretation of the time vs. distance plot see van der Velde and Montanyà (2013).

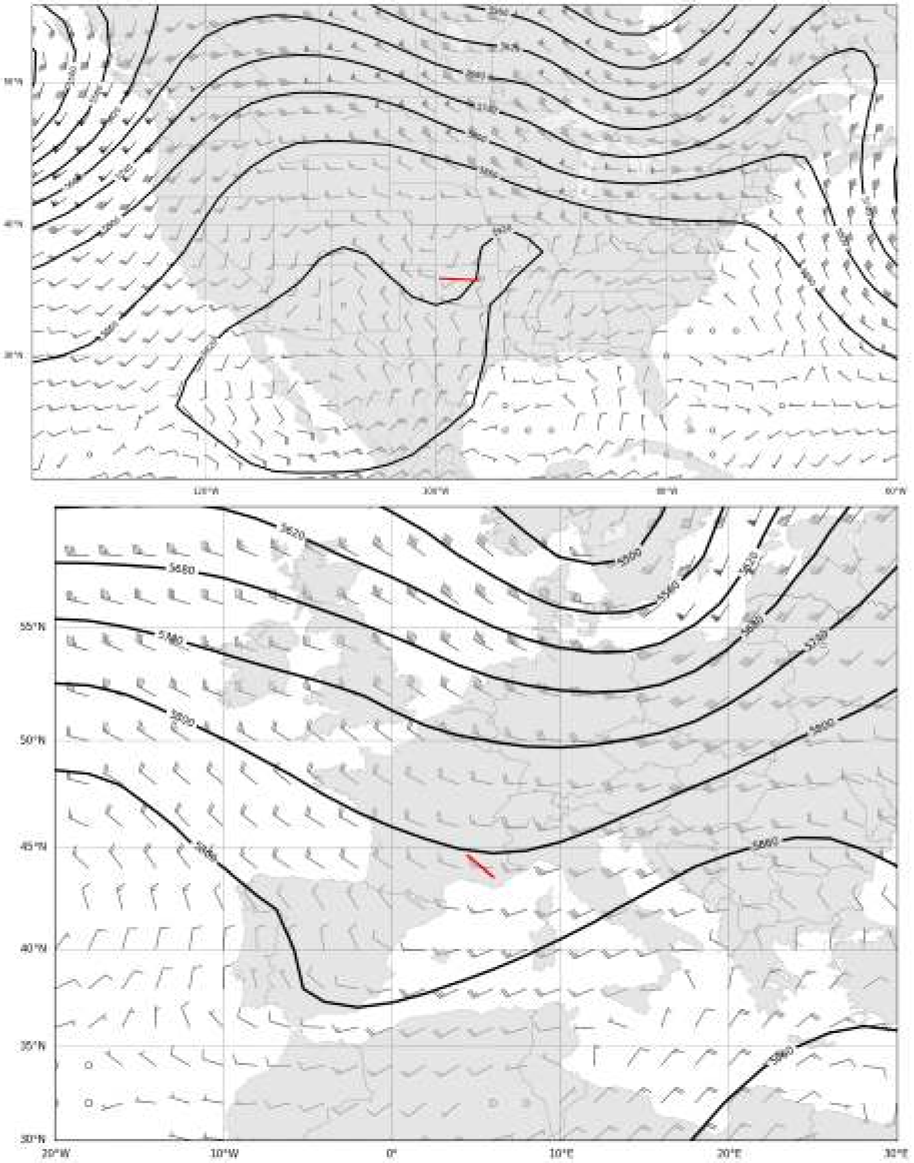


Figure 5. 20th Century Reanalysis (v2) of the 500 hPa height in meters over a) North America on 20 June 2007 (6 UTC) and b) Europe on 30 Aug 2012 (6 UTC).

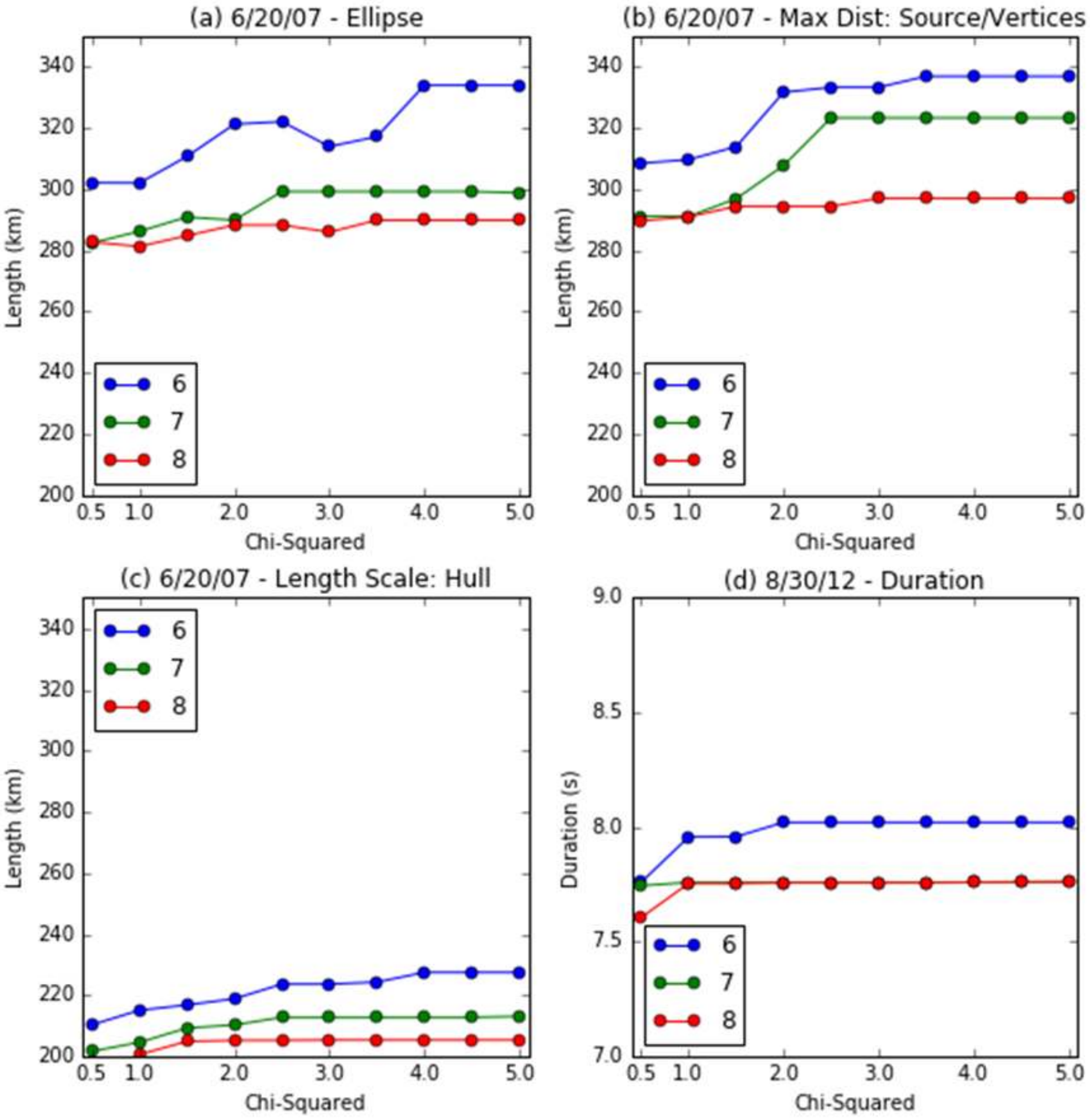


Figure 6. Computation of the flash length using the four different methods discussed in the text for a variety of stations and χ2 values for the Oklahoma flash event for 20 June 2007 (06:07:22 UTC). Colors are used for minimum number of stations (blue, 6; green, 7; red, 8). (a) Ellipse method. (b) Maximum distance between individual two sources or xaximum distance between convex hull vertices, which are mathematically equivalent. (c) Characteristic length scale of the convex hull. (d) Comparison of flash durations for the France flash event for 30 August 2012 (04:18:50 UTC), for a variety of station number and χ2 thresholds. The 7- and 8-station curves largely overlap.

Figure 7. Linear Representation of the southern France flash event for 30 August 2012 (4:18:50 UTC) using the maximum great circle distance method described in the text. This is the WMO-evaluated "Longest Duration Lightning Flash" event.

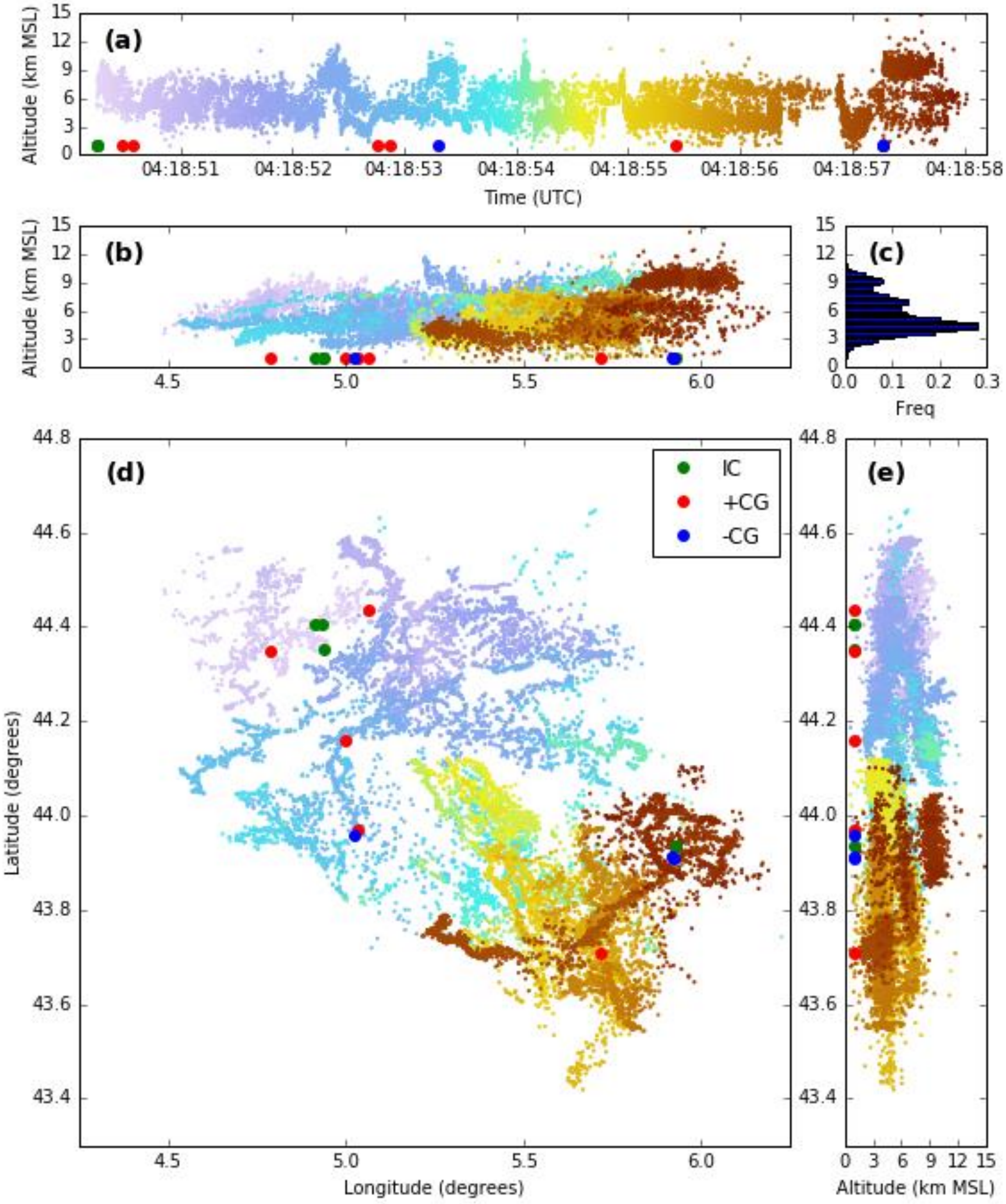


Figure 8. Characteristics of the southern French flash event of 30 August 2012 (4:18:50 UTC). a) Time-height (km MSL) evolution with color variations indicating time intervals, b) Longitude (degree) Altitude (km MSL)$^{-1}$ plot, c) Altitude (km MSL) /frequency diagram, d) Latitude/longitude plot time-sequenced flash event, and e) Altitude (km, MSL) / Latitude (deg) plot. Also shown on most panels are locations and times of EUCLID-detected ICs, positive CGs, and negative CGs.

Supplemental Animation

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Supplemental Material

anim_120830_duration.gif

Supplemental Animation

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Supplemental Material

anim_070620_length.gif

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Editor Comments	Our Response
This is an unusual situation. You and your coauthors are to be commended for submitting a revised manuscript that is responsive to the comments and suggestions of all 3 reviewers. It is also unusual for all 3 reviewers to identify themselves. All reviewers agree with me that the latest revision is considerably improved from the one that they reviewed. However, two of them still find several significant issues that they believe must be attended to, and I agree with them, and at their request will send them your next revision to them for a second review. Accordingly, in spite of the improvements you have made, I am considering this version to require some revisions that I will call "major" although certainly less so than the original submission.	We have made the additions & modifications requested by the reviewers. We thank the editor and the reviewers for their great comments – we firmly believe that this article will actually be a major research article often cited in the future … and we therefore thank all involved for their hard work.
Please pay particular note to Reviewer 2's offer to work with you to cause a suitably revised definition of a lightning flash to be suggested to the Glossary of Meteorology.	Yes, after publication of this article, the members of this WMO committee have agreed without dissent to work with Eric Bruning on a revised AMS lightning definition
Reviewer #1: General comments:	
The authors addressed most of the reviewers' major remarks properly, but a few remains. My recommendation is "minor revision", however the authors should pay attention to item #3 below which was not fully addressed in this new version of the manuscript but it is fairly easy to incorporate, as well as all other remarks.	
Major remarks:	
1. L 102-133: The explanation of all the processes involved in a cloud-to-ground lightning is now very well detailed. While reading your text, it promptly reminded of MetEd's text (which I suggested in the first place). So I went back to that MetEd's module* and watched it all over again. It turns out that the words and a few phrases used in this manuscript were sometimes too similar to that used at MetEd. It might be	Although the original discussion was based on several sources, you are correct that the core was from the MetEd module. We had one of co-authors (not associated with those paragraphs originally) rewrite them in the following fashion: **For simplicity and because 90 percent of lightning strikes are of this type, consider the typical phenomenology of a negative cloud-to-ground (CG) flash. As a negative stepped leader approaches the ground, positive charges are induced at the ground and by tall conducting features, thereby maintaining the electrical potential between leader and**

only my first impression and I kindly ask that the editor do the same (watch the videos in Steps 1 to 7 of the link below) and check if this text is okay or if it has too many similarities to the videos and it should be rewritten. (*https://www.meted.ucar.edu/goes_r/glm/navmenu.php?tab=1&page=2-2-0&type=flash)	**ground. The electric potential difference between a downward-moving stepped-leader tip and ground is probably on the order of tens of megavolts. This allows an upward streamer of positive charge to develop from tall plants, artificial structures, or from flat ground or water surfaces. Typically, an LMA misses these upward streamers near the surface of the earth because they occur at a lower altitude than the detection network's line of sight. Streamers have less light emission and lower conductivity, current, and temperature than leaders.** **When the stepped leader is within 30 to 50 meters of the ground, it makes contact with the upward streamer that is closest in space to the downward stepped leader. This connection completes the electrical circuit and the downward return stroke begins, in which negative charge flows down to the ground. The first return-stroke current measured at ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The leading edge of the return stroke moves upward as the negative charge is drained from the cloud. During the return stroke, the moving electrical charge radiates electromagnetic fields detected by ground-based sferics networks, an intense optical pulse (flash of light) detectable by satellite sensors, intense heating (~30,000 K) and rapid expansion of air (pressure of 10 atmospheres or more) creating acoustic shock waves (thunder) and the formation of nitrogen oxides.** **However, the above discussion should not be construed as suggesting that a ground stroke (CG) alone is what produces light output from flashes and that and that it is the dart leader / return stroke process associated with CGs which drives channel extension. Many of the same basic extension and illumination processes take place with ICs and CCs (IntraCloud and Cloud-to-Cloud) as well. The ground strike example is a special case that fits in the general framework. This understanding is critical with regard to the future Geostationary Lightning Mapping (GLM) technology when space-based optical lightning detection will add to the current LMA and other ground-based networks (such as described in this study) that do not use any optical light.** **If sufficient charge remains in the cloud, there is a short (~40 millisecond) pause before another negatively charged leader (the "dart leader") begins moving towards the surface. Like the stepped leader, the dart leader can be detected by an LMA. As the dart leader nears the surface, a second return stroke is generated that is generally detectable by ground-based systems. This cycle of dart leaders and return strokes continues until the channels cease growing within the cloud. The whole process normally lasts only a few hundred milliseconds. However, many lightning flashes have been detected, measured and evaluated in recent years with durations exceeding one second (e.g., Lang et al. 2010, Bruning and Thomas 2015, Montanyà et al. 2014). Consequently, the committee concluded that the phrase "within 1 second" within the AMS Glossary of Meteorology is no longer valid. Improved detection of long duration and long distance, particularly the horizontal part of lightning flash extremes, indicates that evaluation of lightning flashes of longer than one-second duration is now possible. Therefore, the committee for the WMO Archive of Weather & Climate Extremes evaluation has unanimously suggested amendment of the definition of lightning discharge by removing the phrase "within one second" and replacing with "continuously."**

2. L 143-156: Thanks for pointing out the differences in the "flash" terminologies! :)	Yes, as Reviewer #2 points out the definitions are somewhat complex but we have addressed to some degree those complexities
3. L 165-291: I still have concerns about the structure of Section 2: a) This sections' title is "Lightning Mapping Technology", so it is about the Oklahoma and Southern France LMAs, and the subsection "c. The EUCLID system" is not a mapping network.	We have renamed the section “Lightning Monitoring and Mapping Technologies”
b) NLDN description and performance are not addressed at all, which is also a network used here and very well documented. Not mentioning NLDN characteristics give the false impression of highlighting EUCLID and then we are again on that political issue of maintaining WMO isonomy.	We have added a discussion of the NLDN and EUCLID as a new section after discussion of the Oklahoma and French networks
Suggestions: create another section like "VLF/LF technology" and move "c. The EUCLID system" to this section and include NLDN description/performance in the same manner as EUCLID. A paragraph is sufficient for NLDN due to the very well documentation that this network has.	We have addressed both the NLDN system (first) and then the EUCLID (second, moving it per the reviewer’s suggestion into a new section). **Most lightning monitoring groups around the world utilize a form of the National Lightning Detection Network (NLDN), a system that provides accurate data on the time, location, amplitude, and polarity of the individual return strokes in CG flashes (Cummins et al. 1998b).System accuracy is high, as demonstrated, for example, in a comparative test of the NLDN with tower observations in Rapid City, South Dakota, USA (Warner et al 2012), in which a total of 81 upward flashes were observed from 2004–2010 using GPS time-stamped optical sensors, and in all but one case, visible flash activity preceded the development of the upward leaders. In that study, time-correlated analysis showed that the NLDN recorded an event within 50 km of towers and within 500 ms prior to upward leader development from the tower(s) for 83% (67/81) of the upward flashes.** **In our study, the Southern France event discussed below employed the European Cooperation for Lightning Detection (EUCLID) system. EUCLID is network is a collaborative effort among national lightning detecting networks across Europe with the aim to identify and detect lightning over the entire European area. This cooperation was established in 2001 by six countries (Austria, France, Germany, Italy, Norway, and Slovenia) and subsequently other countries as Spain, Portugal, Finland, and Sweden also joined this cooperation.** **EUCLID is based on NLDN technology, combining both magnetic direction finding and TOA techniques as one, called IMPACT sensors (Cummins et al. 1998a), to locate return strokes or large current intracloud discharges in the VLF/LF range. This system has undergone multiple validation studies. Validation of the EUCLID network was primarily done with independent ground truth data; e.g., tower measurements,**

	video, and field measurement data. Most of the validation in terms of location accuracy (LA) and detection efficiency (DE) was accomplished in Austria (Diendorfer et al. 2009; Diendorfer et al. 2010; Schulz et al. 2014) but an experiment in Belgium also occurred in 2011. The performance of EUCLID was estimated during the HyMeX SOP1 campaign based on high-speed video camera records and electric field measurements. The estimated DE of the network for negative CG flashes was 90%/87% and the DE for positive CG flashes/strokes was 87%/84%. Because the EUCLID performance suffered during the observation period due to the outage of a close sensor, the estimated DEs are lower than the performances measured in Austria and Belgium (Schulz et al. 2014). However, all sensors covering the HyMeX region were up and running when the flash under study occurred. EUCLID was then totally operational at that moment.
4. Finally, in corroboration to Reviewer #3 comments, in the beginning of the text, the authors comment on the very true possibility of greater extremes that may exist and that it is a matter of them being reported to WMO (L 76-81). They also give the example of wind gust fronts reports. It is important to discuss where lightning extremes are more likely to occur based on what is available in the literature. For instance, the extremes of this current study are related to MCSs and one should expect similar and maybe new extremes from regions prompt to the occurrence of MCSs, like Argentina and probably Congo Basin. These regions of extremes are very well documented in Zipser et al. (2006) ("Where are the most intense storms on Earths?") and Albrecht et al. (2016) ("Where are the lightning hotspots on Earth?"). Moreover, I also think it is appropriate to mention that lightning over oceans is known to have large and long durations seen from satellites (Peterson and Liu, 2013). This type of discussion could be included in the conclusions, maybe after L 541 for example.	That is a good point and we have made those additions **It should be noted that, as with all WMO evaluations of extremes (e.g., temperature, pressure, wind, etc.), the proposed extremes are identified based on only those events with available quality data and brought to the WMO's attention by the meteorological community. When higher extreme events are effectively recorded and brought to the attention of the WMO, subsequent evaluations of those extremes can occur. With regard to the lightning extremes discussed below, it is possible that the occurrence of Mesoscale Convective Systems (MCSs) in locations such as Argentina and Congo Basin (e.g., Zipser et al. 2006 and Albrecht et al. 1016) may produce more extreme lightning. Additionally, extreme duration/distance lightning over oceans has been observed from satellites (Peterson and Liu, 2013).**
Minor remarks:	
L 231-236: I think there are switched references. In L 231-233 the reference should be (Drobinski et al. 2014; Ducrocq et al. 2014), and in L 233-236 the reference should be (Defer et al. 2015).	Correct. We have made that change

L 308-309: Where are these strokes relative to the storm and the LMA flash? It would be nice to see them in Figures 2 and 3. (Same comment for L489-490)	Figure 2 is too zoomed out for add this information to be scientifically useful. We have added the NLDN and EUCLID strokes to Figs. 3 and 8.
L 375: maybe remove "however" from the end of this sentence?	We have made that change
Figure 6, L 762: "xamimum" = maximum	
L 391: "… derived from (1) detections by at least seven (7) stations and (2) must have an adjusted…". This is kind of confusing a first glance, so please substituted (1) and (2) by (i) and (ii) (or (a) and (b))	We have made that change (using "a)" and "b)")
L 410-411: … between two sources is 323 km, minus 2km (two standard errors), resulting in 321 km.	We have made that change
L 431, Figure 1: I think you should explain that this is the linear representation of the maximum great circle distance of the longest distance lightning. The way it is shown it can mislead the reader that this is the actual traveled distance once it is the first figure in the manuscript. This is why I have previously asked to also include the LMA sources in this figure. The same comment is valid for Figure 7, L488,, where the reader can get the false impression that it took 7.74 s to travel from the start point to the end of the red line, while in fact is it traveled longer distance if we count all the lightning channels.	We have made that change in the caption of the figure
L432, and Figure 7: is the "horizontal length" the maximum the representation of the maximum great circle distance? If not, what is the maximum great circle distance and why have you reported a different method of length calculation if it was agreed that the maximum great circle is the right way to compute lightning distance? Please clarify.	We have added great circle distance to clarify this measurement.
L 438: Maybe Peterson and Liu (2013) have more references or could also be a reference here.	We have added that reference
L 456: Figure 6d	We have made that correction
Nice paper!!! I very much enjoyed reviewing it. :)	We appreciate the detailed comments and, with your permission, will acknowledge your contributions to this valuable paper.

Rachel Albrecht	
Reviewer #2: Summary comments:	
I thank the authors for their detailed and substantive revisions and replies. Unless noted below, the authors have addressed my concerns. My recommendation is still for major revisions, though they primarily concern the background material and overall context of this study. The authors' revisions concerning the flashes were very helpful in clarifying how the analysis was conducted.	We thank the reviewer for the detailed recommendations below.
I'd also like to add a note here (putting on my hat as the AMS Atmospheric Electricity STAC chair) that, once the review process has concluded, I would welcome the opportunity to put the authors' proposed, revised definition before the full STAC. It is my understanding (according to AMS documents) that a revision should be initiated with the AMS glossary editor and should eventually trickle its way down to the STAC.	Yes, we will definitely pursue the opportunity to work with you and others in created a revised AMS definition. Our appreciation and, with your permission, will acknowledge your contributions to this valuable paper.
-Eric Bruning	
New major comment 1:	
In response to reviewer 1 the authors have added a description of a typical CG lightning flash, which also addresses my request for further detail which could educate the non-lightning specialist. On line 143 the authors draw out the need to emphasize cloud process. I think it might be beneficial, in discussing the typical CG flash, to place less emphasis on the attachment and return stroke processes and more emphasis on those processes happening in the cloud. The focus on the steps leading to a ground strike could lead non-specialists to misconstrue the text as stating that a ground stroke alone is what (uniquely) produces light output from all flashes, and that it is the dart leader / return stroke process associated with CGs which drives channel extension. Of course, many of the same basic extension and illumination processes	Because the CG flash is what many non-lightning specialists associated with lightning, we believe that the general discussion is still useful BUT we totally agree that non-lightning specialists MUST understand that these processes occur in IC and CC as well. Consequently, following your excellent wording, we have added an extra "disclaimer" paragraph onto our general discussion: **However, the above discussion should not be construed as suggesting that a ground stroke (CG) alone is what produces light output from flashes and that and that it is the dart leader / return stroke process associated with CGs which drives channel extension. Many of the same basic extension and illumination processes take place with ICs and CCs (IntraCloud and Cloud-to-Cloud) as well. For example, recent interferometer work (Stock et al. 2014) have begun to show that at least in some cases recoil processes are the in-cloud predecessors of dart leaders. This is one example of how the ground strike description above is a special case that fits in the general framework of universal channel extension and charge transfer processes. This understanding is critical with regard to the future Geostationary Lightning Mapping (GLM) technology when lightning detection will add to the current**

take place with ICs as well. So, while the current text is accurate, it could further educate by focusing on what causes channels to extend in the general case, thereby suiting the purpose of this paper in discussing long-lived and extensive flashes. The ground strike is then a special case that fits in the general framework. This would help the meteorological reader whose prior knowledge would not lead them to suspect the richness of cloud processes that are observed and are absolutely essential to understand in the upcoming GLM era. In constructing the above remarks, I was thinking of the recent interferometer work at NMT and Osaka Univ. (Stock, Krehbiel, Kawasaki, et al.) as well as high speed video imagery. These studies have begun to show that at least in some cases recoil processes are the in-cloud predecessors of dart leaders. This is one example of how I might connect universal channel extension and charge transfer processes back to the CG model with which readers are familiar. Of course, there are many others, and I recognize I'm asking for a challenging balance of simplicity, brevity, and universality.	**LMA and other ground-based networks (such as described in this study) that do not use any optical light.**
New major comment 2:	
line 150: I thank the authors for addressing the comment of Reviewer 1 in adding this paragraph. Here I provide some additional remarks to be taken in a friendly light to assist the authors in clarifying these issues for the diverse BAMS audience as much as possible. The authors' choices of flash definition are reasonable and they note the possibility of debate, which is all that I can fairly expect from a single manuscript. With that said, I'm not sure the contrast the authors are making in this paragraph is entirely clear. What is the distinction between the list of processes in the "entire lightning discharge" and a "series of electrical processes"? From context, I think this might refer to connected plasma channels (within or protruding from the	We agree … but because of the growing length of the paper and the possibility of becoming too technical in this BAMS paper, we would suggest that we leave the paper with our minor corrections (change 1 second to continuously) and address the more complete issues with Dr. Eric Bruning as a follow-up to this paper. Specifically, one of our co-authors Bill Rison, notes, " The AMS Glossary says "charge transferred along a discharge channel", while a lightning flash has many discharge channels (again, as the paper already states, channel needs to be updated to channels). Even with modern technology it is not possible to "see" some channels (positive leaders radiate weakly and are often not detectable), so if a system detects a breakdown channel, then after a delay of a few milliseconds, detects another breakdown channel

thundercloud) vs. disconnected channels which are nonetheless coupled through the electric field? Later, on lines 468-9 and 482-3, the authors adopt the field-coupled viewpoint, and it might be beneficial to note near line 150 which definition the authors have adopted in this study, or that further discussion of these choices if forthcoming. Field-coupling certainly is expedient in eliminating the need to infer connected plasma channels through a careful reading of the LMA data. (The counterpoint is that "field-coupled channels = one flash" opens up a great deal of uncertainty as to how to count flashes in high flash rate storms, since so much is taking place simultaneously, though the authors contribute a useful insight about this on line 482-3.) For the purposes of the AMS glossary definition, the meaning of "connected" takes on two different meanings - connected through the field coupling vs. connected as a plasma along which charge can flow. So, I think it would be a helpful foundation for follow-on work to make this distinction in flash definitions as clear as possible.	a few hundred meters away, are these two channels connected by an undetected channel, or by field coupling? When developing flash grouping algorithms (how to group LMA sources into different flashes), parameters which are used are how long of a delay is acceptable and how large of a distance is acceptable in calling LMA sources a single flash, or two (or more) different flashes. From a practical point of view it doesn't matter whether there was an undetectable channel or field coupling connecting the two. If the connection is by a currently undetectable channel, advances in technology may allow us to detect such channels in the future; it it is field coupling, then the community has to decide how large of a distance and how long of a time is acceptable in order to call two channels part of a single flash. Since we don't know whether the channels in the "world's longest duration lightning flash" are connected by another undetectable channel or field coupling, and there is no guidance on what to do in this case, the best we can do is to tell the readers what we did (which we do in 468-469 and 482-483), and say that the definition of a flash needs to be updated because of the recent advances in technology (which we also do). The only other thing we might do is to add a couple of sentences like I have in the first paragraph about undetectable channels vs field coupling, but I think that stirs up too many details which will make the paper less readable and less enjoyable.”
Minor comments	
line 104: "rapid series of electrical processes" — this wording does not distinguish whether the processes themselves are rapid or the gaps between the processes are relatively short and happen in quick succession. Presumably rapid is in comparison to something like the thunderstorm's characteristic time scale or that of human visual acuity?	We have removed the reference to "rapid series of electrical processes."
line 122: "normally 60 microseconds" - is this the time to cloud base, to the initiation	We have removed the mention of 60 microseconds.

point, or to the farthest end of the negative charge?	
line 123: "produces strong electric fields" - since the focus is sferics, I suggest "radiates electromagnetic fields" to distinguish from the DC electric fields (which also change).	That change has been made.
Is the sentence that ends on line 139 missing a concluding phrase?	Yes, the sentence now reads **"Improved detection of long duration and long distance, particularly the horizontal part of lightning flash extremes, indicates that evaluation of lightning flashes of longer than one-second duration is now possible."**
line 149: remove "so that" and start a new sentence?	That change has been made.
lines 199 & 220: as noted by one of the other reviewers, another recent reference discussing LMA source detection efficiency is Chmielewski and Bruning (2016, JGR). This paper addresses the influence of the receiver thresholds, and also partially addresses the shortcoming noted on line 379.	We have added that excellent reference in at (old) line 220 and 379.
As in my previous review, I note that, while the authors provide a good background on EUCLID, they provide no references or background regarding the NLDN in their lightning mapping technology section.	We have added that material now (and moved, per suggestion of Reviewer 1) the material on EUCLID immediately after: **Most lightning monitoring groups around the world utilize a form of the National Lightning Detection Network (NLDN), a system that provides accurate data on the time, location, amplitude, and polarity of the individual return strokes in CG flashes (Cummins et al. 1998b).System accuracy is high, as demonstrated, for example, in a comparative test of the NLDN with tower observations in Rapid City, South Dakota, USA (Warner et al 2012), in which a total of 81 upward flashes were observed from 2004–2010 using GPS time-stamped optical sensors, and in all but one case, visible flash activity preceded the development of the upward leaders. In that study, time-correlated analysis showed that the NLDN recorded an event within 50 km of towers and within 500 ms prior to upward leader development from the tower(s) for 83% (67/81) of the upward flashes.** **In our study, the Southern France event discussed below employed the European Cooperation for Lightning Detection (EUCLID) system. EUCLID is network is a collaborative effort among national lightning detecting networks across Europe with the aim to identify and detect lightning over the entire European area. This cooperation was established in 2001 by six countries (Austria, France, Germany, Italy, Norway, and Slovenia) and subsequently other countries as Spain, Portugal, Finland, and Sweden also joined this cooperation.** **EUCLID is based on NLDN technology, combining both magnetic direction finding and TOA techniques as one, called IMPACT sensors (Cummins et al. 1998a), to locate return strokes or large current intracloud discharges in the VLF/LF range. This system has undergone multiple validation studies. Validation of the EUCLID network was primarily done with**

	independent ground truth data; e.g., tower measurements, video, and field measurement data. Most of the validation in terms of location accuracy (LA) and detection efficiency (DE) was accomplished in Austria (Diendorfer et al. 2009; Diendorfer et al. 2010; Schulz et al. 2014) but an experiment in Belgium also occurred in 2011. The performance of EUCLID was estimated during the HyMeX SOP1 campaign based on high-speed video camera records and electric field measurements. The estimated DE of the network for negative CG flashes was 90%/87% and the DE for positive CG flashes/strokes was 87%/84%. Because the EUCLID performance suffered during the observation period due to the outage of a close sensor, the estimated DEs are lower than the performances measured in Austria and Belgium (Schulz et al. 2014). However, all sensors covering the HyMeX region were up and running when the flash under study occurred. EUCLID was then totally operational at that moment.
line 364: Bruning and Thomas (2015) did not discuss a method for fitting the ellipse to the convex hull, so the authors' method is not strictly reproducible from that reference. Can the authors cite a reference for the precise method they used, or at least a add a few words to help distinguish the various methods that turn up with a quick Google search? (e.g., https://www.cs.cornell.edu/cv/OtherPdf/Ellipse.pdf)	We have explicitly added the Fitzgibbon et al. (1996) reference. Fitzgibbon, A. W., M. Pilu, and R. B. Fischer, 1996: Direct least squares fitting of ellipses, Proc. of the 13th International Conf. on Pattern Recognition, 253–257, International Association for Pattern Recognition, Vienna, Austria.
line 456: Check to be sure that Fig. 5d. is the correct reference.	No, the reviewer is correct: that should be Fig 6d.
Reviewer #3	
This is the second review of this manuscript and the authors have addressed my comments from the first round. Therefore, the reviewer recommends that the Journal accept the manuscript in its current form.	Many thanks!
SPECIFIC COMMENTS	
409 Double comma.	Corrected
- M.J.Peterson	

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Fig 7

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