WMO WORLD RECORD LIGHTNING EXTREMES

Longest Reported Flash Distance and Longest Reported Flash Duration

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A WMO committee has judged that the world's longest reported distance (321 km) for a single lightning flash occurred over Oklahoma in 2007, while the world's longest reported duration (7.74 s) for a single lightning flash occurred over southern France in 2012.

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: 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 very high-frequency (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 s on 30 August 2012 over parts of southern France. It should be noted that, as with all WMO evaluations of extremes (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 4 October 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. Uman (2001, p. 8) defined a lightning flash as "a transient, high-current electric discharge whose path length is measured in kilometers." The American

Meteorological Society (AMS) Glossary of Meteorology defines lightning flash as "the total observed lightning discharge, generally having a duration of less than 1 s" (American Meteorological Society 2015b), while it (American Meteorological Society 2015a) defines a lightning discharge 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 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 bidirectional 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 in steps of around 50 m 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% 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 and artificial structures, or from flat ground and water surfaces. Typically, an LMA misses these upward streamers near the surface of 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.

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When the stepped leader is within 30–50 m 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 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 abovementioned discussion should not be construed as suggesting that a ground stroke (CG) alone is what produces light output from flashes and that it is the dart leader–return stroke process associated with CGs that drives channel extension. Many of the same basic extension and illumination processes take place with intracloud (IC) and cloud to cloud (CC) 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 ms) pause before another negatively charged leader (the dart leader) begins moving toward 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 1 s (e.g., Lang et al. 2010; Bruning and Thomas 2015; Montanyà et al. 2014). Consequently, the committee concluded that the phrase "within 1 s" 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 1-s duration is now possible. Therefore, the committee for the WMO Archive of Weather and Climate Extremes evaluation has unanimously suggested amendment of the definition of lightning discharge by removing the phrase "within 1 s" and replacing it 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, leaders, etc.), while the weather forecasting community commonly uses the more specific AMS Glossary of Meteorology definition of a "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 s" 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 in 2007 and France in 2012—have been put forth as extremes in lightning flash distance and duration, respectively. Both of these events were detected with an 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 that are not mentioned or advertised.

LIGHTNING MAPPING AND MONITORING TECHNOLOGIES. The LMA is a time-of-arrival (TOA) 3D 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 (Stock et al. 2014). 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 first correlating the arrival times for the same event at multiple stations, then locating each source via a 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 spatiotemporal 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 six 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 NMIMT (Rison et al. 1999). Because the flashes in this study were very large, they spanned a substantial fraction of each LMA domain, and therefore they 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 Montanyà 2013).

Oklahoma Network. The Oklahoman LMA (OKLMA) is operated by the University of Oklahoma, the National Oceanic and Atmospheric Administration (NOAA)/National Severe Storms Laboratory (NSSL), and 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 the 100-km range from the network centroid and about 1.2 km at the 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 became only partially decorrelated from the reflectivity structure beyond the 120-km range (Lang et al. 2011). The flash in this study had sources ranging from 9 to 206 km distance from the 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 kilometer) 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 have only 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.

Southern France Network. The Hydrology Cycle in the Mediterranean Experiment (HyMeX; 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, 2015).

The HyMeX LMA (HyLMA) system consisted of 12 stations, lent to the campaign by Dr. Rich Blakeslee of the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center (MSFC). It was deployed around Alès in the Cévennes Vivarais region in France by personnel from NMIMT and the Laboratoire d'Aérologie in Toulouse, France. 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 × 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. The design of HyLMA 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 the 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 the OKLMA and HyLMA systems, respectively (Thomas et al. 2004). Using Eq. (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 70 ns, is ($\chi_c^2 \times 4$), where χ_c^2 is the calculated value.

VLF/LF LIGHTNING DETECTION NETWORKS. Most lightning monitoring groups around the world utilize very low-frequency (VLF)/low-frequency (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 (Warner et al. 2012), in which a total of 81 upward flashes were observed from 2004 to 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 a network of collaborative efforts 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—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 Improved Accuracy through Combined Technology (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, for example, 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 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.

LONGEST DISTANCE: 20 JUNE 2007, OKLAHOMA. This extreme lightning event started around 0607:22 UTC 20 June 2007 and lasted 5.70 s over central Oklahoma (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 0603 UTC 20 June 2007, shows 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 s. 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 0607:26 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 nine positive CG strokes, four negative CG strokes, and four IC events, as reported by 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 Montanyà 2013). Essentially, in this type of plot significant leaders show up as coherent lines of sources (e.g., between 0 and 1 s, and near 3 s; good examples of this are shown in Fig. 4a), 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 s, 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 4–5), especially beyond the 250-km distance from the 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,

Fig. 1. Linear representation of the Oklahoma flash event for 0607:22 UTC 20 Jun 2007 using the maximum great circle distance method described in the text; the WMO-evaluated "longest distance lightning flash" event.

animations (available in the online supplemental material) indicated spatiotemporal continuity in flash behavior throughout its duration.

Two sprites were observed from this flash. The first occurred at 0607:26.364–0607:26.397 UTC and the second occurred at 0607:26.643–0607:26.660 (Lang et al. 2010, 2011). These were associated with two distinct parent positive CGs (+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. 5, top) with a short wave evident at 700 hPa using the Twentieth Century Reanalysis, version 2 (v2; 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 both the embedded secondary convection and the horizontal area of weak reflectivity in the stratiform region were increasing (Lang et al. 2010).

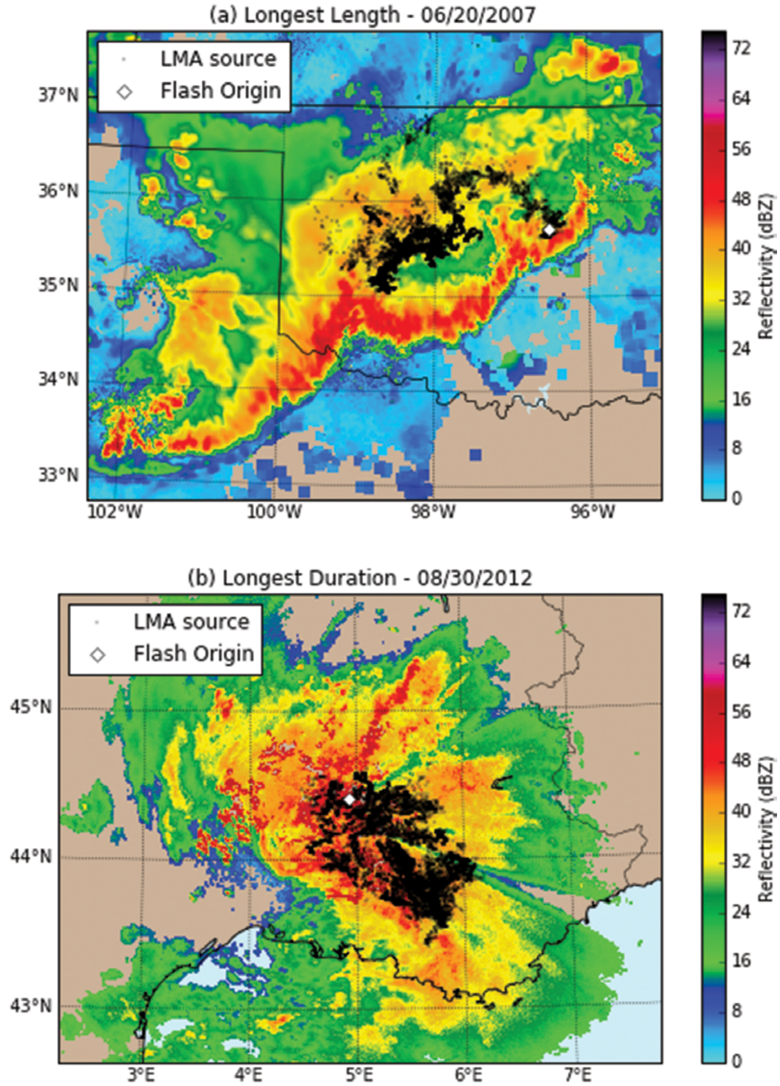

Fig. 2. (a) Mosaic radar reflectivity at 1 km MSL, valid at 0603 UTC 20 Jun 2007. Also shown is a plan projection of the VHF sources encompassing the longest-length flash, which occurred around 0607:22 UTC on this day. See Lang et al. (2010) for more details about this multiradar mosaic product. Flash origin is set as the median of the first 10 sources. (b) Reflectivity from the Aramis (Bollène) radar at 0.8° elevation angle, valid at 0415 UTC 30 Aug 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 0418:50 UTC on this day. Flash origin is set as the median of the first 10 sources.

This MCS produced 282 observed transient luminous events (TLEs) over a 4-h 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 in variation in flash length estimates.

In evaluating the Oklahoma lightning extreme, four different methods were discussed and evaluated. Two of these methods, however, are mathematically equivalent. Specifically, the methods used were the calculation of flash distance through 1) the major axis of the ellipse fitted to the convex hull (Fitzgibbon et al. 1996; Bruning and Thomas 2015), 2) 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 3) 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 (MacGorman et al. 2008), 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

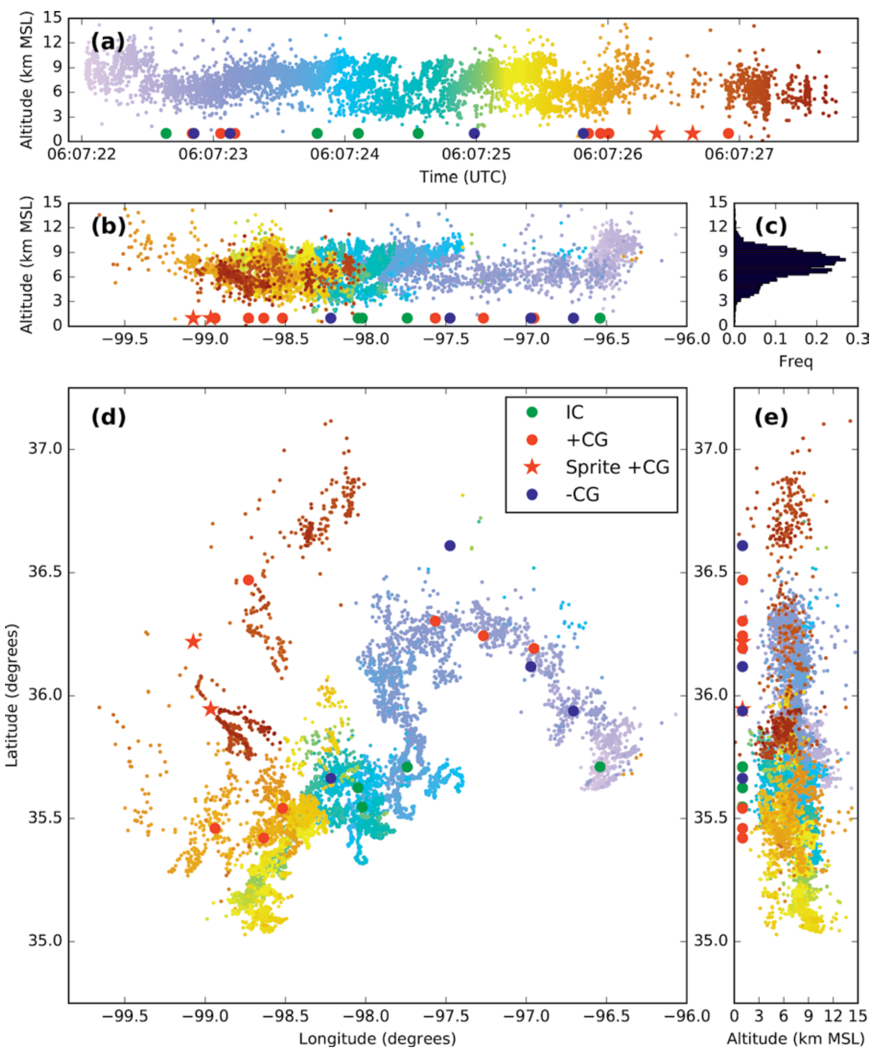

Fig. 3. Characteristics of the Oklahoma flash event for 0607:22 UTC 20 Jun 2007. (a) Time–height (km MSL) evolution with color variations indicating time intervals, (b) longitude (°)–altitude (km MSL) plot, (c) altitude (km MSL)–frequency diagram, (d) latitude–longitude plot time-sequenced flash event, and (e) altitude (km, MSL)–latitude (°) plot. Also shown on most panels are locations and times of NLDN-detected ICs, positive CGs, and negative CGs.

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, 1) the method may be needlessly complicated and 2) 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 1) detections by at least seven stations and 2) 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 and 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, then the specific method of distance calculation must be identified in professional discourse of the distance spanned by a flash.

Given a selection of seven stations and a χ_c^2 of 5, the maximum great circle distance (Haversine method) for the 20 June 2007 (0607:22 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 (0607:22 UTC),

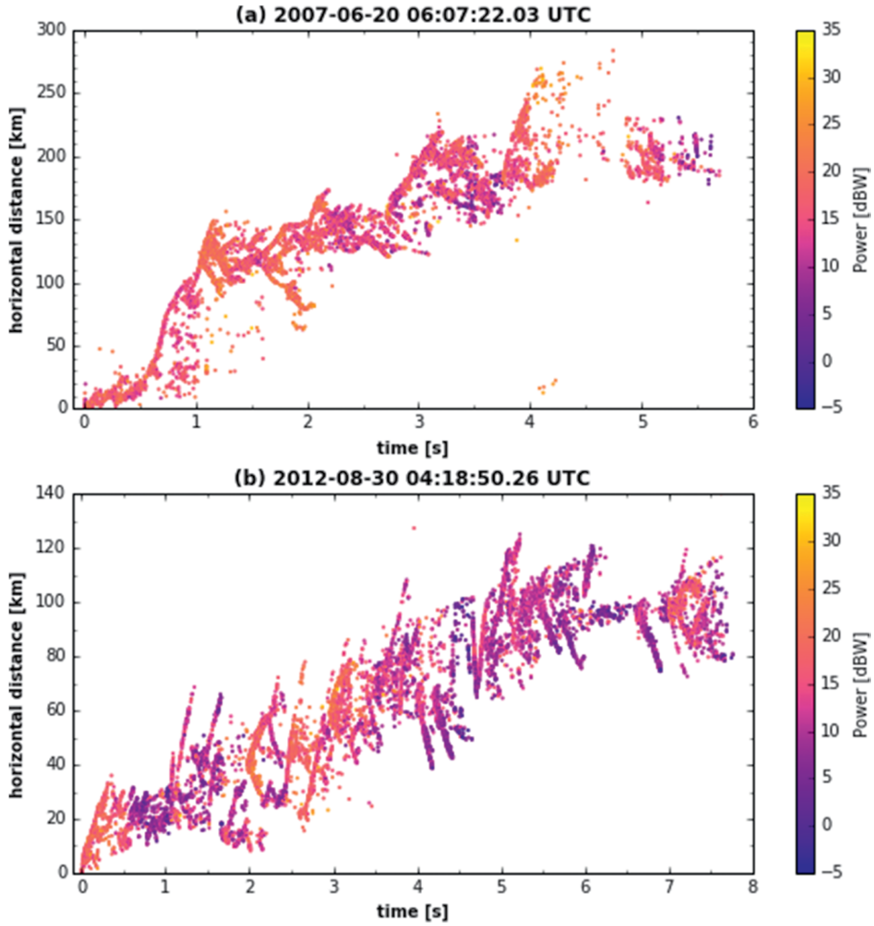

Fig. 4. Time vs horizontal distance as a function of power (dBW) showing the lightning events of (a) 0607:22 UTC 20 Jun 2007 in Oklahoma and (b) 0418:50 UTC 30 Aug 2012 in southern France. For interpretation of the time-vs-distance plot, see van der Velde and Montanyà (2013).

is thereby deemed acceptable as the WMO's official "longest distance" record lightning extreme for the globe (Fig. 1).

LONGEST DURATION: 30 AUGUST 2012, SOUTHERN FRANCE. This particular lightning event was detected around 0418:50 UTC 30 August 2012 over Provence-Alpes-Côte d'Azur, France (Fig. 7), during the 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. 5, bottom). Surface analysis by the Met Office (UKMO) indicated a surface front entering France from the northwest at 0000 UTC, while surface station observations indicated substantial surface moisture in southern France with surface dewpoints ranging from 18° to 22°C. Reflectivity from the Aramis (Bollène), France, radar at 0.8° elevation angle, valid at 0415 UTC 30 August 2012, shows the origin point of the flash (set as the median of the first 10 sources) together with the plan projection of the VHF sources encompassing the longest-duration flash, which occurred around 0418:50 UTC (Fig. 2b).

The flash started in the main convective part of the storm, located around Pierrelatte (Drôme), France, and propagated into the trailing stratiform region to the southeast of the storm, similar to the Oklahoma flash, toward Brignoles (Bouches-du-Rhône), France. 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 0100 to 0230 UTC. By the time of the longest-duration flash at 0418:50 UTC, 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 2 s, and there was a 5-s flash that occurred at about 0435:00 UTC. The HyLMA sources for this flash are shown in Fig. 8. However, at times within the stratiform region, the France

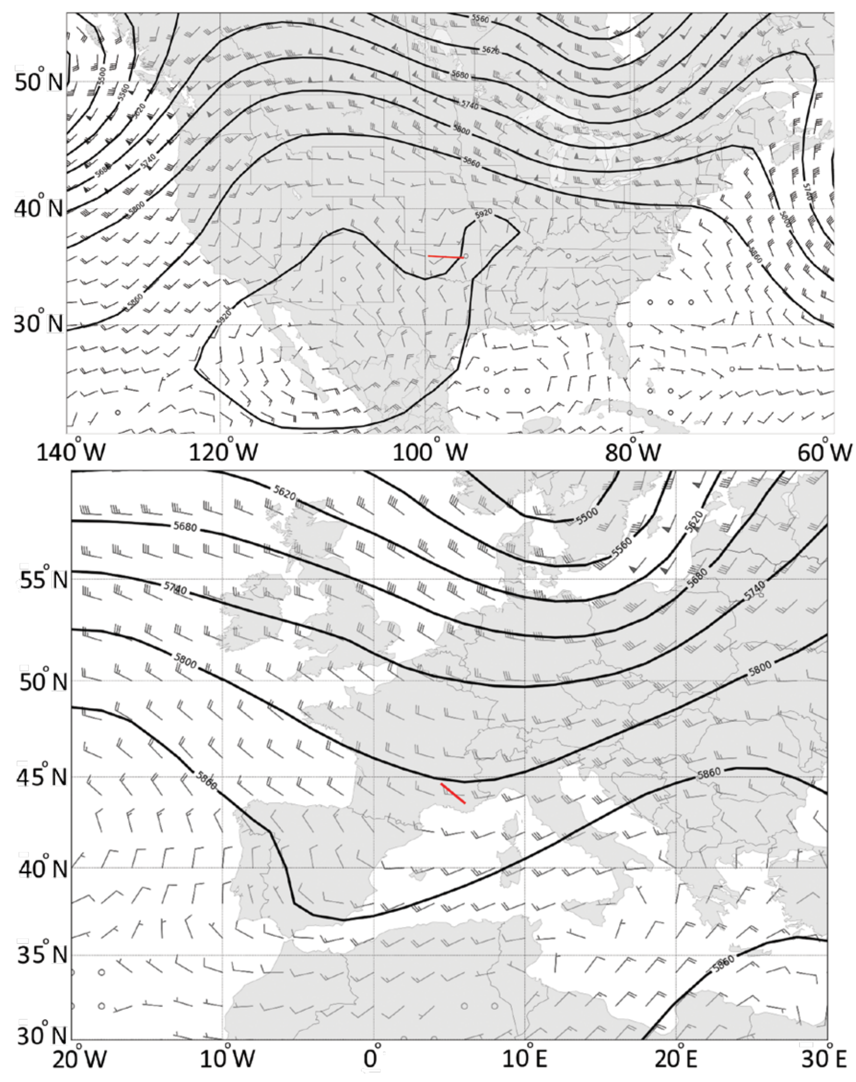

Fig. 5. Twentieth Century Reanalysis (v2) of the 500-hPa height (m) over (top) North America at 0600 UTC 20 Jun 2007 and (bottom) Europe at 0600 UTC 30 Aug 2012.

flash accessed multiple vertically stacked charge layers (e.g., Stolzenburg et al. 1998). The most dramatic example of this was around 0418:57.5 UTC, when a new breakdown along a flash channel, which started just before 0418:57 UTC (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.

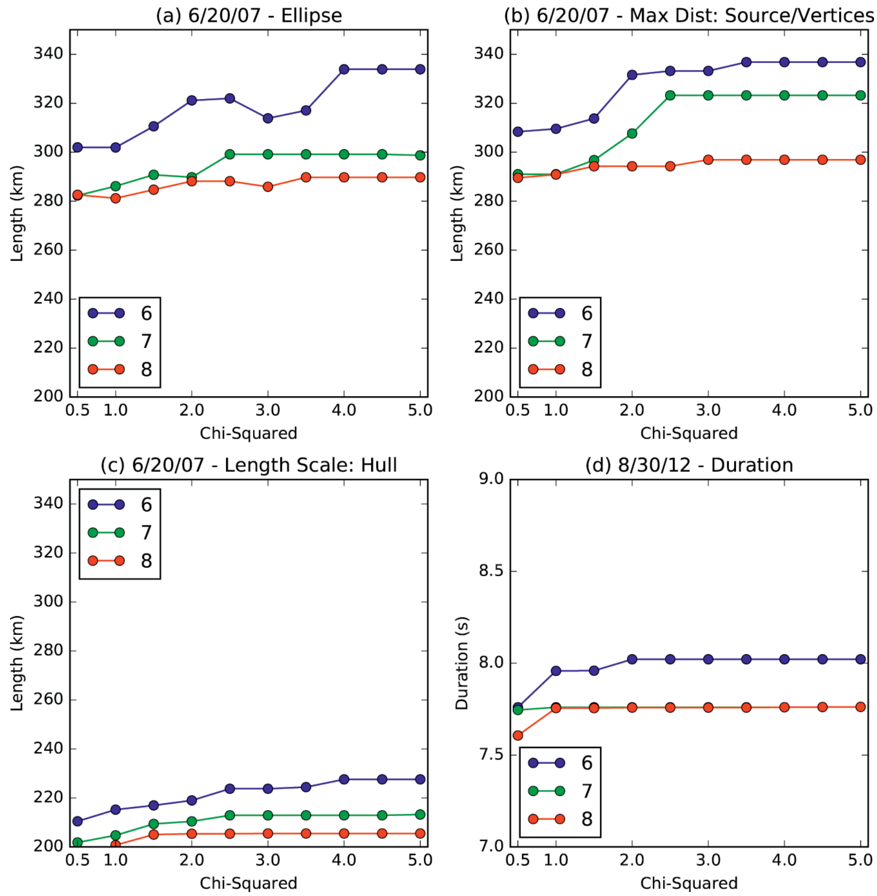

Fig. 6. Computation of the flash length using the four different methods discussed in the text for a variety of stations and χ^2 values for the Oklahoma flash event at 0607:22 UTC 20 Jun 2007. Colors are used for the minimum number of stations (blue, 6; green, 7; red, 8). (a) Ellipse method. (b) Maximum distance between two individual sources or maximum 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 at 0418:50 UTC 30 Aug 2012, for a variety of station numbers and χ^2 thresholds. The seven- and eight-station curves largely overlap.

An analysis of HyLMA data for this flash indicated that application of a variety of χ^2, station numbers, and altitude criteria did not drive the duration below 7.74 s. 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 seven or eight 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 six actually lengthened the flash to 8 s, 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 it 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 that may start at a location a few kilometers from the start of the original leader, and it may propagate back toward the starting point of the original leader, or it may propagate in another direction—perhaps upward 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 s (see the online supplemental 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 that 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 kilometer 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 for 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 that were separated by a 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 kilometers with a duration of several seconds through a large stratiform region. If early activity induces a subsequent breakdown in the same charge region, then 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 s. That lightning flash that was recorded on 30 August 2012 (beginning approximately at 0418:50 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 eight CG return strokes and four 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 0418:50.260 and 0418:50.263 UTC 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 0418:50.480 UTC 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 0418:52 UTC, 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 0418:53.294 UTC, EUCLID recorded a negative CG (−CG) of about −15 kA, 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.

Fig. 7. Linear representation of the southern France flash event for 0418:50 UTC 30 Aug 2012 using the maximum great circle distance method described in the text. This is the WMO-evaluated "longest duration lightning flash" event.

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 30 and 31 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.

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 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 s" and "along discharge channels" rather than "along a discharge channel").

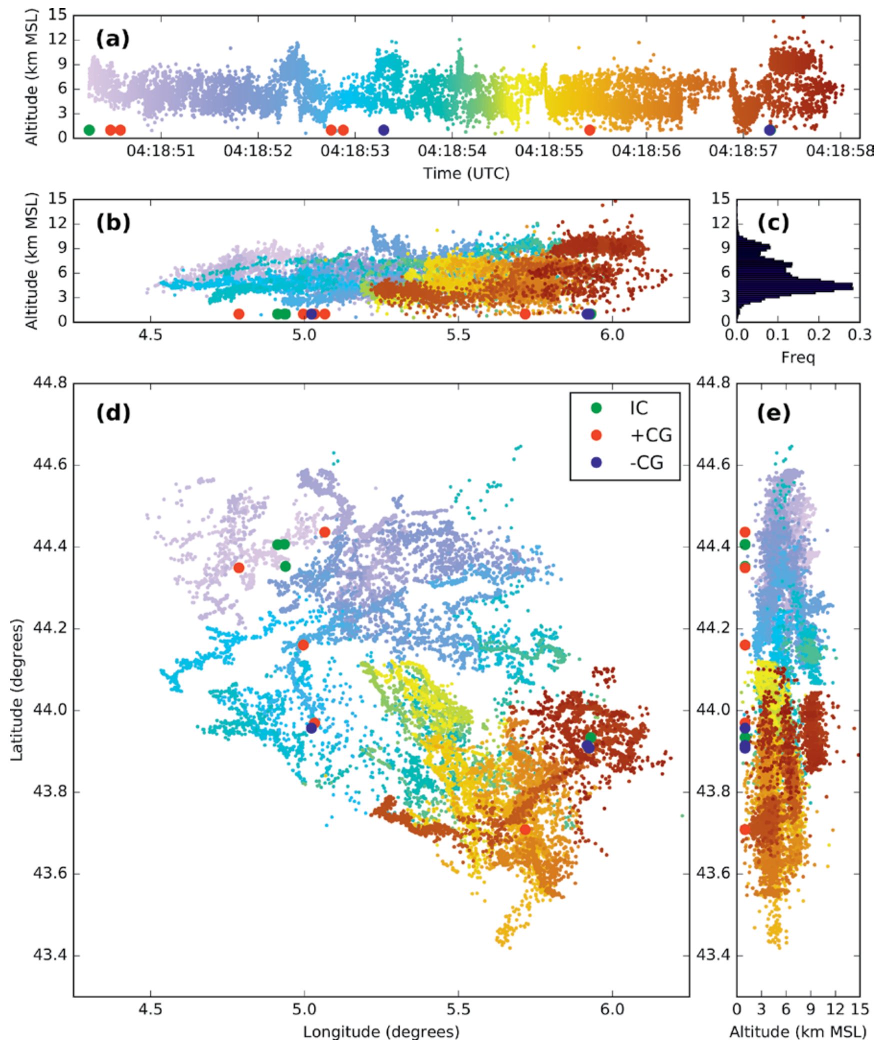

Fig. 8. Characteristics of the southern French flash event at 0418:50 UTC 30 Aug 2012. (a) Time–height (km MSL) evolution with color variations indicating time intervals, (b) longitude (°)–altitude (km MSL) plot, (c) altitude (km MSL)–frequency diagram, (d) latitude–longitude plot time-sequenced flash event, and (e) altitude (km, MSL)–latitude (°) plot. Also shown on most panels are locations and times of EUCLID-detected ICs, positive CGs, and negative CGs.

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 the 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 s 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 (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 MCSs in locations such as Argentina and the Congo basin (e.g., Zipser et al. 2006; Albrecht et al. 2016) may produce more extreme lightning. Additionally, extreme duration/distance lightning over oceans has been observed by satellites (Peterson and Liu 2013).

Validation of these new world lightning extremes 1) demonstrates the recent and ongoing dramatic augmentations and improvements to regional lightning detection and measurement networks, 2) 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 3) provides important fundamental data for lightning engineering concerns.

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