// Lightning flashes can be as big as the thunderstorm complex that made them, and modern lightning mapping can connect strike points on the ground to the whole channel in the cloud."

—Eric Bruning

MEGAFLASHES

Just How Long Can a Lightning Discharge Get?

Adapted from "Megaflashes: Just How Long Can a Lightning Discharge Get?" by Walter A Lyons (FMA Research), Eric C. Bruning, A. Warner, Donald R. MacGorman, Samantha Edgington, Clemens Tillier, and Janusz Mlynarczyk. Published in BAMS online January 2020. For the full citable article see DOI:10.1175/BAMS-D-19-0033.1.

Lightning is sometimes described as "a really big spark." So how "big" can a lightning flash get? The vertical extent is generally limited by the altitude of the main charge centers in the cloud (typically 6–10 km) and certainly by the cloud top, rarely more than ~20 km high. The flash within large storm systems can be much longer horizontally, reaching "mesoscale" dimensions, defined here as 100 km or greater.

The first hint of mesoscale lightning was gleaned from fast-scanning radar studies of the mid-1950s. Some lightning channels, in what today would be termed a leading-line trailing-stratiform mesoscale convective system (MCS), originated from the upper level of the storm's leading edge and propagated rearward down into the light precipitation zone by as much as 160 km. These reports remained mostly a curiosity for several decades until the realization that lightning routinely occurred in the stratiform region of convective storm systems from atmospheric chemistry and aviation safety studies.

On 22 October 2017, the trailing stratiform region of a quasilinear convective system passes over a TV antenna farm northeast of Oklahoma City. Special cameras capture a massive dendritic lightning discharge and a powerful +CG (extreme right). Milliseconds later, the enhanced electric field prompts a lightning-triggered upward lightning flash from a tall tower. The +CG, if it lowered sufficient charge to ground, might also have induced a red sprite some 75 km above. These phenomena are typically associated with megaflashes. (Photo Credit: Tom A. Warner/WeatherVideoJD.TV)

Total lightning refers to the sum of flashes that strike ground [cloud-to-ground flashes (CGs)] and flashes that do not [intracloud flashes (ICs)]. CGs can have one or more discrete, large current surges to ground (each called a return stroke), traveling through the same or sometimes separate channels. A CG can lower either negative charge to ground (−CG; roughly 90% of CGs on average, though this value is highly variable) or positive charge (+CG). Modern, ground-based lightning detection networks, such as the U.S. National Lightning Detection Network (NLDN), locate 80–95% of CG ground strikes with an average accuracy better than 500 m. ICs constitute perhaps three-quarters of all lightning discharges. A satellite-borne sensor detects total lightning by responding to the optical energy emerging from cloud tops.

Exceptionally long lightning discharges propagating through the stratiform precipitation region of an MCS sometimes produce unusually powerful +CGs, as propagating lightning channels tap into huge reservoirs of positive charge present therein. Frequently, a lightning discharge originates near the top of the convective cells in the leading line (~8–10-km altitude) and then travels rearward and downward, following the trajectory of descending positively charged ice crystals, often to near the melting layer. The discharge leaders then can continue at that approximate altitude while generating multiple CGs often separated by tens of kilometers. Some of the +CGs can result in lightning-triggered upward lightning (LTUL) from tall towers and wind turbines, or even sprites, the vast but brief (<~100 ms), faintly glowing discharges originating around 70–75-km altitude that extend through the middle atmosphere.

The advent of 3D Lightning Mapping Array (LMA) systems confirmed that lightning discharges exceeding 100 km in length and spawning multiple CGs of both polarities, often separated by considerable distances, were not uncommon.

A 2007 research campaign utilizing a low-light camera network, the NLDN, satellite, radar, and the Oklahoma LMA (OKLMA) investigated a large nocturnal MCS on 20 June 2007 that produced almost 250 observed sprites. Numerous horizontally extensive lightning flashes occurred, including one selected for

▲ * Time-integrated GLM radiances from 0513:27.433 to 0513:33.613 UTC 22 Oct 2017. Two distinct electrical regimes are evident. The first is a cluster of smaller flashes in the leading line of convective cells stretching from eastern Oklahoma and then southwest into north Texas. The second regime is an extensive horizontal flash, lasting 4.76 s, propagating from near the Red River in Texas across central Oklahoma into southeastern Kansas. An animated version of the larger Q LCS and of this figure are included as electronic supplements in AMS journals online (see DOI:10.1175/BAMS-D-19-0033.1).

detailed analysis that produced 13 CGs, including two sprite-producing +CGs, while maneuvering from the leading line convection back through the trailing stratiform for “approximately 300 km.” A decade later, the flash initiation to termination points were confirmed to span a 321-km straight-line distance (over a period of 5.70 s.) This is the official WMO record for the longest distance for a continuous lightning discharge, even though it may not even have been the longest discharge in that

particular MCS. (A flash lasting 7.74 s within a French MCS was the longest duration event officially verified in the WMO study.)

A New View from the Geostationary Lightning Mapper

While this record approaches the limit of what can be observed by any existing LMA, the new Geostationary Lightning Mapper (GLM) on satellites can detect much larger flashes. The first GLM, launched in 2016 on the (now) *GOES-16* satellite, covers the Americas between 54°N/S, sampling changes in cloud-top optical radiances every 2 ms into pixels of ~8 km near the nadir to ~14 km at the highest latitudes. Such high-resolution total lightning monitoring on a nearly hemispheric scale is yielding a plethora of new insights about mesoscale lightning discharges. During the GLM system check-out phase, at 1800 UTC on 21 October 2017, a squall line (a quasilinear convective system; QLCS) formed ahead of a sharp cold front, extending from Minnesota into northern Texas. It produced several tornadoes and large hail in western Oklahoma. As it was approaching Oklahoma City (OKC) that evening, the line developed a rapidly expanding trailing stratiform region with an embedded secondary precipitation maximum. Tellingly, special cameras operating near OKC that evening noted 39 LTULs from tall TV towers as the stratiform region passed overhead. NLDN reports totaled 1,190,822 IC flashes and 124,431 CGs, of which 15.4% were +CGs, from the QLCS portion south of the Iowa–Missouri border.

GLM animations revealed that after the trailing stratiform developed after about 0000 UTC 22 October, there were really two spatially distinct lightning regimes. Large numbers of relatively small flashes repeatedly peppered the leading-line cellular convection, while mesoscale dendritic lightning flashes periodically originated near the convective cores and propagated back into the expansive trailing stratiform region. As the night progressed, these massive discharges gradually became less frequent, but also larger.

Time integrating one of the larger horizontally extensive flash sequences shows it began close to the leading-line convection in northern Texas and then traversed the extensive secondary precipitation maximum of the trailing stratiform north-northeastward into Kansas. An initial estimate using

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GLM imagery indicates this “megaflash,” as we call it, extended >~500 km end to end—greatly exceeding the official WMO record.

Documenting A Megaflash

Was the GLM mapping a single flash, or an amalgam of smaller flashes? The NLDN and LMA independently demonstrate that the megaflash was a single lightning entity. We will employ, in part, the WMO methodology using LMA data that evaluated the 2007 official record event and also consider NLDN reports to define the terminus of the flash.

The LMA shows that the flash began in extreme northern Texas and propagated along a somewhat meandering and dendritic pathway to the north-northeast. It began around 8–9 km MSL, and over the next 500 ms descended into the trailing stratiform region to around 2–6 km MSL as it moved northward. It was likely occasionally visible as classic “spider lightning” in the trailing stratiform region. With NLDN reports continuing along the GLM-illuminated path well into southeastern Kansas, the megaflash outran the nominal ~200-km OKLMA range for mapping the discharge plan location.

The megaflash begins in the NLDN data some 3 ms after the first LMA sources, just south of the Red River in Texas, as a reported 10.3 kA +CG followed 2 ms later by a reported IC slightly farther south. Thereafter the activity marches northward, finally ending in southeast Kansas. If traveling a straight line (i.e., ignoring any meandering) from the first NLDN report to the northernmost event, the negative leader speed was $\sim 1.5 \times 10^5 \text{ m s}^{-1}$, typical for negative leaders propagating through positive charge layers. After reaching its northern terminus, sporadic pulses of lightning were detected by the NLDN, LMA, and GLM at points along the initial channel. Such rebrightening of segments within horizontally extensive channels is common.

Along the path of the megaflash, the NLDN reported 37 ICs, 23 –CGs (including 10 LTULs), and 17 +CGs. There were 10 +CGs >75 kA (versus none in the leading line cells). At ~2.4 s into the event, two +CGs of 303 kA and 317 kA occurred 42 ms apart, as the megaflash propagated northeast of OKC, each almost certainly resulting in sprites. After the onset of the trailing stratiform region, there was a distinct spatial sorting of large peak current CGs by polarity.

Most of the large peak current –CGs occurred within the leading-line cells, with the large majority of the large peak current +CGs being in the stratiform region.

A 79-kA +CG striking close to a broadcast tower in Tulsa, Oklahoma, induced at least ten LTULs. Also notable, in the seconds before and after and sporadically during, the megaflash, the LMA detected periodic bursts of low-altitude and low-power VHF sources from rotating wind turbines southwest of Oklahoma City near the center of the LMA domain, suggesting widespread elevated electric field values near the surface within the trailing stratiform region.

How big was this megaflash? The maximum great circle distance between any two illuminated GLM pixels was 547 km. By combining the WMO methodology—which uses only LMA data—with the NLDN reports, the great circle distances between candidate most-distant discharge elements are computed as 524.2 km. By either method, this flash is very long.

Summary and Discussion

Analysis shows this GLM report was not merely an artifact resulting from a sequence of much smaller, but adjacent, flashes. It easily exceeds the current official longest-distance flash record, although it has not been evaluated by the WMO. That exercise would be moot, as there may well have been even longer megaflashes in this particular QLCS, and likely in many other storms since.

Our example was not an outlier. A new paper in the *Journal of Geophysical Research-Atmospheres* by Michael Peterson reports a survey of 2018 GLM flashes found discharges of 582, 623, 659, 666, and 673-km length, all within MCS stratiform regions. Additionally, Peterson uncovered a 13.496-s duration flash in another MCS.

What constitutes a megaflash? The flashes are clearly “mesoscale,” but megaflashes may be qualitatively different as well. It has long been noted that once an MCS develops a stratiform region of at least 10,000 km², the character of its lightning often changes. Flashes longer than ~100 km appear to more readily tap into the vast positive charge reservoir(s) found in these stratiform regions. This allows the +CG continuing currents to lower massive amounts of positive charge to ground, sometimes inducing sprites. We therefore propose

⚡ Lightning observations over 6.52 s starting 0513:27.48 UTC 22 Oct 2017 in central and eastern Oklahoma (state borders, blue). For scale, each GLM pixel is separated by 9 km, GLM events (large rectangles) are colored by total energy during the observation interval at the GLM entrance aperture on a logarithmic scale between 10⁻¹⁵ (dark pink) and 10⁻¹¹ J (yellow). NLDN observations: IC = white circles; –CG = green circles; –CG >75 kA use larger green circle; +CG = magenta pluses; +CG >75 kA use larger and >300 kA largest pluses LMA events (small points) are colored by time (progressing from purple to dark cyan to light green to yellow). New GLM and NLDN detections occurred throughout the time interval, while the northernmost LMA source associated with the megaflash occurred at 0513:30.783 UTC in extreme southern Kansas. LMA observations continued after the megaflash within the cells in the leading convective line. An animated version is included as an electronic supplement (see DOI:10.1175/BAMS-D-19-0033.1).

a megaflash be defined as a continuous lightning flash with a horizontal path length of >100 km (not necessarily in a straight line) that may also produce one or more CGs of either polarity along its path, with some +CGs potentially resulting in sprites and/or LTULs from tall structures. Such discharges are somewhat akin to a “bolt-from-the-blue” CG, in that they may unexpectedly occur far from the storm

BAMS: How did you get interested in this topic?

Walt Lyons: *Already retired by the time of the 99th AMS Annual Meeting, I was in the audience when my coauthors from Lockheed Martin presented the first results from the GLM. I spent the past three decades investigating the unusual lightning discharges that induce mesospheric sprites. That research revealed that extraordinarily long horizontal flashes were often the parent of those rare +CGs triggering sprites. When the animation of this event flashed up on the screen, I almost bolted out of my seat. It stretched from North Texas into Kansas, longer than anything we had previously imagined. Just had to look into this!*

BAMS: So megaflashes are an extension of your work on another extraordinary electrical phenomenon?

WL: *The discovery of sprites by Jack Winckler in 1989 began the quest to unearth what was special about the*

bolts that caused the mesosphere to erupt in fireworks of red light. We knew the lightning was not “garden variety.” We learned that the best place to find these exceptional sprite parent bolts was in the large mesoscale stratiform regions where the giant megaflashes dwell.

BAMS: What surprises you about megaflashes, Eric?

Eric Gruning: *It’s still remarkable to me how well the lightning follows the organization of hydrometeors in storms, and that the extent of lightning matches the scale and stratification of the mesoscale dynamics throughout the MCS/storm complex.*

BAMS: What was the biggest challenge you encountered while doing this work?

EG: *We had to develop new GLM data processing methods customized to this paper, since we’re using the data for an application that wasn’t even envisioned when the*

sensor and data products were designed a decade ago.

BAMS: What’s next? How will you follow up?

EG: *I think there is promise in using lightning flash size information, in combination with flash rate, to detect the minute-by-minute fluctuations of thunderstorm updrafts in the upper part of the cloud. Applying these ideas to GLM data and continuing to use LMA data to understand how the 3D structure of lightning relates to turbulent eddies inside thunderstorms is the focus of several current and future field projects.*

BAMS: Walt, what does lightning research have to do to get you to jump out of your seat again?

WL: *We still have a lot to learn, even about a phenomenon that has been researched since the times of Benjamin Franklin and his contemporaries. If one day GLM sees a 1000-km-long flash, though, I will not be that surprised.*

core long after the apparent lightning threat appears to have passed.

A WMO committee is now reviewing the GLM-based determinations of extreme lightning. Designed to operationally process lightning events on a hemispheric scale in real time, the algorithms can become bogged down. “To overcome this,” Peterson writes, “the algorithms quit when flashes become too complex, and this results in single natural lightning flashes being artificially split into multiple ‘degraded’ flashes.” Therefore, hunting for megaflashes requires significant postprocessing of the raw GLM data. Regardless of the technical challenges, atmospheric electricity researchers have obtained a powerful new tool to better understand the

exceptional discharges that induce many sprites and LTULs and also to develop a climatology of such megaflashes.

The 673-km event already documented by Peterson occurred over southeastern Brazil, a region known for some of the most powerful and expansive thunderstorms on Earth. Ongoing GLM investigations suggest that still larger megaflashes have already occurred.

A megaflash, once initiated, appears able to propagate almost indefinitely as long as adequate contiguous charge reservoirs exist in the secondary precipitation maxima of MCS stratiform regions. Is it possible that a future megaflash can attain a length of 1,000 km? We would not bet against that.

Let the search begin. ♣♣