

Thunder Hours

How Old Methods Offer New Insights into Thunderstorm Climatology

Elizabeth A. DiGangi, Michael Stock, and Jeff Lapierre

ABSTRACT: Lightning data are often used to measure the location and intensity of thunderstorms. This study presents 5 years of data from the Earth Networks Global Lightning Detection Network (ENGLN) in the form of thunder hours. A thunder hour is defined as an hour during which thunder can be heard from a given location, and thunder hours can be calculated for the entire globe. Thunder hours are an intuitive measure of thunderstorm frequency where the 1-h interval corresponds to the life-span of most thunderstorms, and the hourly temporal resolution of the data also represents long-lived systems well. Flash-density-observing systems are incredibly useful, but they have some drawbacks that limit how they can be used to quantify global thunderstorm activity on a climatological scale: flash density distributions derived from satellite observations must sacrifice a great deal of their spatial resolution in order to capture the diurnal convective cycle, and the detection efficiencies of ground-based lightning detection systems are not uniform in space or constant in time. Examining convective patterns in the context of thunder hours lends insight into thunderstorm activity without being heavily influenced by network performance, making thunder hours particularly useful for studying thunderstorm climatology. The ENGLN thunder hour dataset offers powerful utility to climatological studies involving lightning and thunderstorms. This study first shows that the ENGLN thunder hours dataset is very consistent with past measurements of global thunderstorm activity and the global electric circuit using only 5 years of data. Then, this study showcases thunder anomaly fields, designed to be analogous to temperature anomalies, which can be used to diagnose changes in thunderstorm frequency relative to the long-term mean in both time and space.

KEYWORDS: Atmosphere; Convection; Diurnal effects; Lightning; Atmospheric electricity; Climatology

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Corresponding author: Elizabeth A. DiGangi, edigangi@earthnetworks.com

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Lightning data interests those studying climate science because changes in lightning over time, tracked by metrics such as flash density and flash rate, reflect changes in convection, or “storminess” (e.g., Price 2013; Aich et al. 2018; Lavigne et al. 2019). But how do we characterize a change in lightning on a climatological scale?

Before the advent of global lightning detection networks, scientists’ understanding of lightning trends was based on transforming human observations of thunder at the surface into a quantity known as thunder days. A thunder day (TD) is a day out of the year when thunder could be heard within range of a given location by a person (World Meteorological Organization 1953). The longest published lightning climatologies are analyses of thunder days (e.g., Changnon 1985; Changnon and Changnon 2001; Kitagawa 1989), which are useful for determining seasonal and annual trends in lightning and thunderstorm activity.

Once global lightning detection became viable, thunder day studies became less common. Global lightning climatologies developed in the last two decades have generally relied instead upon satellite-based lightning detection instrumentation, such as the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS). OTD was a polar-orbiting satellite that captured data between $+75^{\circ}$ and -75° latitude from 1995 to 2000 (Christian et al. 2003), while LIS captured reliable data between $+38^{\circ}$ and -38° latitude while mounted to the Tropical Rainfall Measuring Mission (TRMM) satellite from 1998 to 2013 (Albrecht et al. 2016; Lavigne et al. 2019). A widely used long-term, near-global lightning dataset is the combined OTD–LIS dataset (Cecil et al. 2014), because TRMM–LIS has excellent coverage over the tropics and OTD provides coverage at higher latitudes. This dataset’s greatest setback is that TRMM–LIS could only sample a given $600\text{ km} \times 600\text{ km}$ region for 90-s intervals and OTD sampled $1,300\text{ km} \times 1,300\text{ km}$ regions for 180-s intervals (Cecil et al. 2014).

The caveat to using OTD–LIS data is that their inherent sparsity requires significant averaging in either time or space in order to capture the diurnal convective cycle (Negri et al. 2002). Integrating OTD–LIS data over long periods forces the user to assume that the interannual variability of the diurnal cycle of storminess is negligible, especially outside of the tropics. The alternative is to evaluate the interannual changes in diurnal flash densities by spatially integrating over a large region. In either case, analysis of convective trends requires sacrificing some resolution of the dataset. The flight spare of LIS is now operating aboard the International Space Station (ISS), but it suffers from similar limitations. While the long-term global flash densities from the past satellite-based datasets can be updated as time goes on, monitoring how lightning is changing with a changing climate at the convective scale is still quite difficult to do.

There are also ground-based global lightning detection networks, such as the Earth Networks Global Lightning Network (ENGLN), which monitor lightning in real time all over the world. These ground-based networks suffer from variable detection efficiency, especially where it is difficult or impossible to deploy sensors, such as over the oceans. However, they also operate continually and are constantly providing new information about global lightning frequency across the world. More recently, the Geostationary Lightning Mappers (GLMs) launched aboard Geostationary Operational Environmental Satellites (GOES) have been able to provide a completely different view of lightning from space, including flash extent

densities and the horizontal extents of individual flashes. However, GOES-GLM data are only available for the Americas at this time, and GLM has several limitations, including ocean glint artifacts, limited coverage at high latitudes, and limitations on its detection efficiency for small and short-duration flashes (Zhang and Cummins 2020). Flash rate density data are highly useful for diagnosing thunderstorm intensity, but all the different limitations of the lightning detection systems mentioned above present problems when applying those data to long-term climatology studies.

The problems with the various lightning detection technologies have led some researchers to circle back to the thunder day. Most studies featuring thunder day observations predate large-scale total lightning detection networks. However, modern studies have continued to make use of the thunder day observations still being recorded at weather stations around the world (Pinto et al. 2013; Pinto 2015; Bourscheidt et al. 2012; Fujibe 2017; Lavigne et al. 2019). Thunder observations also correlate well with flash rate densities (FRDs) in most cases. Lavigne et al. (2019) analyzed 42 years of thunder day reports from ground stations all over the globe and compared their interannual trends with 16 years of TRMM-LIS flash data. They found that in most parts of the world, trends in thunder day frequency were positively correlated with those in the flash data from TRMM-LIS. Regions with no correlation or a negative correlation between TDs and flash densities were often still positively correlated with thunderstorm frequency, and those regions were sometimes characterized by storms producing less lightning than they did in previous years, such as monsoonal convection in India. Lavigne et al. (2019) concluded that lightning and thunderstorm frequency are both increasing with time in most parts of the world, and that the overall statistically significant correlation between TRMM-LIS flash observations and ground-based TD observations meant that satellite observations would be useful for diagnosing how global lightning and thunderstorm activity change over time.

However, there is another implication to this conclusion: if changes in thunder observations are well correlated to changes in flash density observations overall, and particularly well correlated to thunderstorm frequency, then thunder observations are an effective measure of global storminess and how storminess is changing with the climate.

Thunder days will certainly be used by the community to study thunderstorm climatology going forward, but it is important to remember that they lack the temporal resolution to capture the diurnal cycle that drives most convection in the world. Less frequently used than the TD, the thunder hour (TH; Jayaratne and Ramachandran 1998; Bourscheidt et al. 2012; Huffines and Orville 1999) is an hour during which thunder could be heard. The logic behind counting thunder hours is the same as that of thunder days, but thunder hours facilitate analysis of diurnal trends as well as seasonal and annual ones. Thunder hour datasets differ from flash densities because they show trends in thunderstorm frequency, whereas flash densities give insight into thunderstorm intensity. In flash density datasets of short temporal durations, the stronger storms produce far more lightning, and so skew trends in favor of strong storm characteristics. Long-term datasets such as the OTD–LIS flash density data are averaged over long-enough periods that this effect is smoothed out, but storm intensity bias is very relevant when considering shorter-term FRD datasets. In TH datasets, strong storms carry similar weight as weak storms when their durations are similar. However, longer-lived storms like mesoscale convective systems (MCSs) are easier to distinguish in thunder hour datasets than in thunder day datasets because, in a thunder day dataset, a 12-h MCS and single-cell storm lasting 30 min carry equal weight. Additionally, Bourscheidt et al. (2012) demonstrated that thunder hours have the potential for great utility in climatological analyses of lightning data due to their ability to ignore variations in lightning location system detection efficiency. This is because the probability of detecting one or more lightning flashes in an hour of a thunderstorm's lifetime is much greater than the probability of detecting all lightning flashes in the hour. Thunder hours are an extension of thunder days, and the difference between them

is essentially a difference in the granularity of thunderstorm duty, the percent of time in a year experiencing thunder. The annual thunderstorm duty cycle of a region is generally a small fraction of its number of annual thunder days (Peterson 2019; Peterson et al. 2021), so quantifying it in units of hours rather than days is reasonable. In theory, thunderstorm duty could be calculated from lightning observations at an even finer temporal scale than hours, such as thunder minutes. However, as the temporal scale of the observations becomes smaller, the uniformity of the measurement is reduced, which reintroduces the problem of variable detection efficiency.

In this study, we convert 5 years of ENGLN data into thunder hours and thus produce a recent dataset of thunder hour data with global coverage. Diurnal patterns in the 5-yr TH dataset will be described in detail for the globe and for select regions to demonstrate the overall consistency of the dataset with past literature. The 5-yr ENGLN TH trends will then be shown to be consistent with established global electric circuit characteristics, including the Carnegie curve. Finally, we will demonstrate how to use thunder hour data to generate monthly and seasonal thunder anomaly maps, and discuss how this methodology and view of thunder data could be applied to global climate change research.

Data and methods

A thunder hour is defined as an hour during which thunder can be heard (e.g., Jayaratne and Ramachandran 1998; Bourscheidt et al. 2012). Traditionally, thunder hours would be recorded by trained human observers. Unfortunately, human observation of thunder hours is spatially sporadic and inconsistent, and impossible in high density on a global scale. Further, the distance at which thunder can be heard by a human observer is dependent on environmental conditions, as well as the training of the human. In this study, we will instead be simulating thunder hour observations using total lightning data from the ENGLN. The ENGLN dataset consists of lightning location observations from over 1,800 Earth Networks Total Lightning Network (ENTLN) lightning sensors combined with observations from over 70 World Wide Lightning Location Network (WWLLN) sensors. ENTLN utilizes ground-based broadband (1 Hz to 12 MHz) electric field change sensors to detect and locate both intra-cloud (IC) and cloud-to-ground (CG) lightning up to 1,500 km from the sensors. WWLLN is comprised of ground-based very low-frequency (VLF) electric field sensors to locate primarily CG lightning on a global scale (Rodger et al. 2006; Hutchins et al. 2012). Lapierre et al. (2021) demonstrated that ENGLN detects thunderstorms with high efficiency compared with ISS LIS. The detection efficiency of ENTLN (Bitzer and Burchfield 2016) is generally much higher than that of WWLLN in the vicinity the ENTLN sensors, while in more remote locations (e.g., over the oceans) WWLLN provides superior coverage. In addition, a subset of the ENTLN sensors have been modified to provide raw waveform data to the WWLLN system to improve WWLLN's detection efficiency (Rodger et al. 2017).

To convert from lightning flash locations to thunder hours, we have slightly modified the definition of thunder hour to an hour during which lightning was located within a 15-km radius of a given point. Fifteen kilometers is related to the range at which thunder can be heard from a lightning flash: Brooks (1925) noted that thunder could typically be heard up to 16–19 km away from a flash, while Bourscheidt et al. (2012) used 5–10-km distance criteria when they tested the sensitivity of simulated thunder observations from lightning location systems to system performance. Fifteen kilometers is a good compromise between these two ranges. The 15-km criterion is also related to the industry standard lightning alert radius (about 10 miles, or 16 km). This criterion is admittedly imperfect, as a 15-km range is used for all flashes with no corrections for flash amplitude or IC/CG classification made. Sensitivity testing revealed that the average number of TH in a grid cell is proportional to the thunder radius, but changing the radius does not significantly impact the distribution of

TH. A description of the relationship between the thunder radius criterion and the average number of thunder hours in a given grid cell can be found in the appendix.

The thunder-hour calculation was made using a $0.05^\circ \times 0.05^\circ$ latitude–longitude grid. For each grid point and for each hour, if at least two lightning pulses were located within 15 km of that point, the grid value was set to true (or 1), otherwise the grid value was false (or 0). The two-pulse criteria helps prevent spurious detections from having a significant impact on the results, although the results were not strongly dependent on this criteria. This computation was made for all grid points and all UTC and local solar time (LST) hours from 1 January 2015 to 31 December 2019. The gridded data were then aggregated by calendar month. For each hour in a calendar month for all 5 years analyzed, the probability of thunder being observed at each grid cell was calculated. This is simply $N_{\text{thunder}}/N_{\text{total}}$, where N_{thunder} is the number of observations of thunder in a given hour of a given calendar month, and N_{total} is the total number of observations of the same hour of that calendar month. For example, for the 1200 UTC hour of March, $N_{\text{total}} = 31 \text{ days} \times 5 \text{ years} = 155$ observations. That value of N_{total} is the same for each other hour of the day for the month of March at all locations on the globe. The overall result of the analysis is the average day of thunderstorm activity for each calendar month. Achieving the same computation for shorter durations (i.e., calendar weeks instead of calendar months) is possible, but will result in larger variability in the probability of thunder calculation. For the purposes of this study, which examines thunderstorm behavior and frequency on a synoptic-to-global scale, the one month aggregation periods offer a good compromise between sampling and seasonal resolution.

Global lightning observations

The average number of thunder hours in one year from the full dataset is depicted in Fig. 1a, and mean annual FRD from the LIS–OTD 0.5 Degree High Resolution Full Climatology (Cecil 2001; Cecil et al. 2014) is depicted on a similar color scale in Fig. 1b. There is broad agreement between the annual global TH frequency and annual global FRD from LIS–OTD. Significant FRD maxima in Colombia, the Congo Basin, and the Straits of Malacca in the Maritime Continent region, which have been identified in LIS–OTD lightning climatology studies (e.g., Cecil et al. 2015; Albrecht et al. 2016; Peterson et al. 2021), also appear as maxima in the global TH distribution. An animation of monthly TH probabilities for the entire globe is included in the supplementary material (Fig. S1), which shows the diurnal frequency of global thunderstorms and how thunder activity changes throughout the year.

Figure 2 depicts the hour of peak annual TH probability in LST. On a global scale, most storms are classified as airmass convection, which is driven by daytime heating, and generally persist for around 1 h (Changnon 1988), making them well represented by thunder hours. Diurnal-heating-driven airmass thunderstorms tend to occur over land during local afternoon and early evening hours, as demonstrated by the shades of orange dominating land surfaces in Fig. 2. This trend is also visible in Fig. S1, where TH probabilities are generally high in the vicinity of the day–night line.

Land–sea breeze interactions are a common control on spatial and temporal distributions of storms in Africa, the Maritime Continent, and the northern extent of the Andes (Albrecht et al. 2016), as well as most other coastal regions in the tropics and subtropics. Sea breezes develop due to differential heating of the ocean and adjacent land areas, creating a strong temperature gradient along the coast. Sea-breeze thunderstorms are evident as TH probability maxima over coastal areas during the daytime hours, which then shift offshore during the night when sea breezes reverse and become land breezes (Fig. 3 and Fig. S1); particularly clear examples of this reversal are seen in Central America/the Caribbean and the Maritime Continent. The same principle holds for very large lakes, such as the North American Great

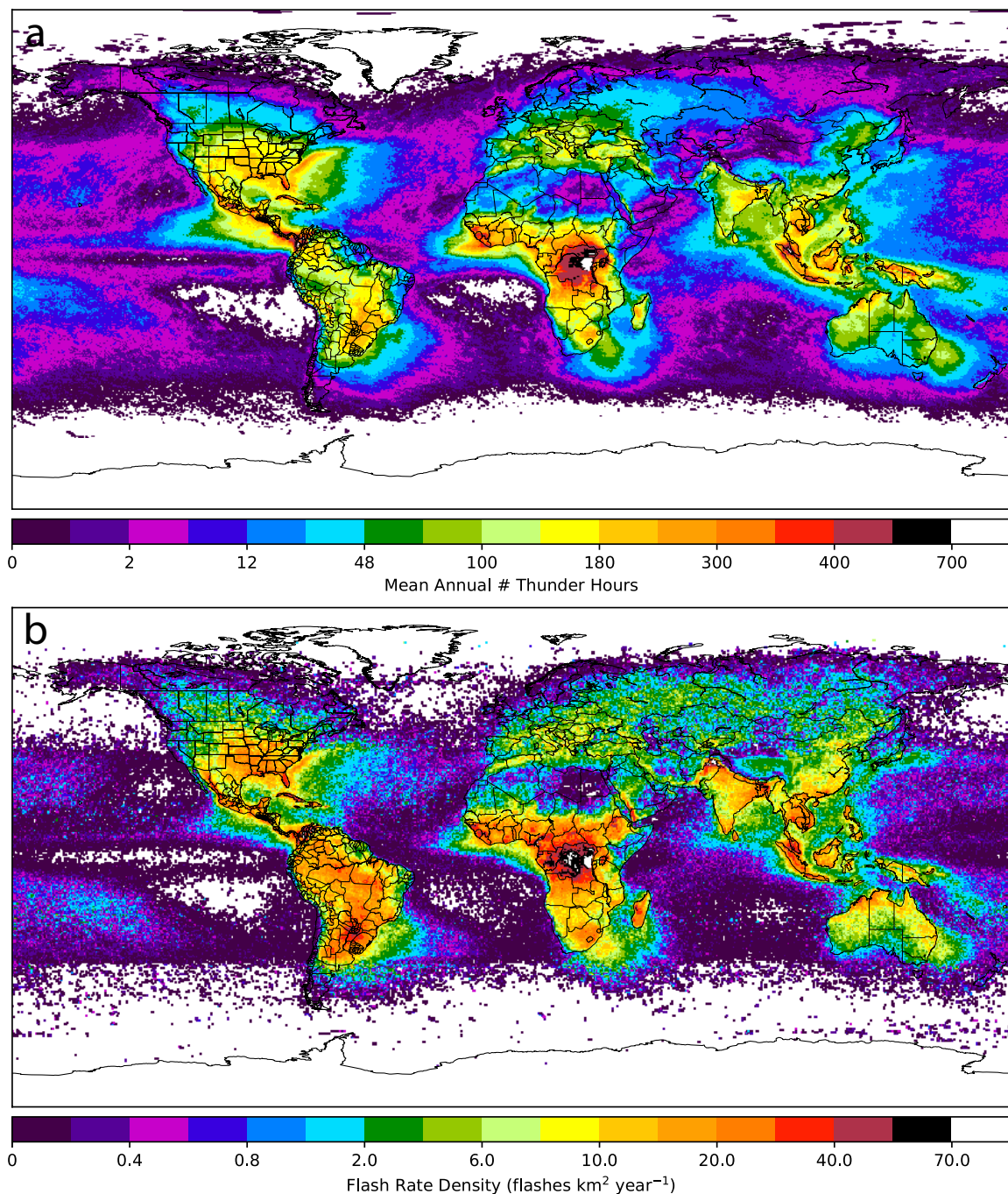


Fig. 1. (a) Mean annual ENGLN thunder hour counts for the entire globe from 2015 to 2019. (b) Mean annual LIS-OTD flash density from 1995 to 2014.

Lakes and Lake Victoria, which experience a land–lake breeze cycle analogous to the sea–land breeze cycle of coastal regions.

In addition to insolation and sea-breeze dynamics, topography plays a significant role in convection initiation and enhancement around the globe: Albrecht et al. (2016) found that most of Earth’s lightning hot spots are located in regions of complex terrain. Peaks in TH frequency in the mountains of Central America, in and along the Andes and their foothills in South America, along the southern edge of the Himalayas, the Kenyan Highlands and Cherang’any Hills east of Lake Victoria, the Mitumba Mountains in the Democratic Republic of the Congo, and in Indonesia and Papua New Guinea (Fig. 1a and Fig. S1) mirror the hot spots identified by Albrecht et al. (2016). Local summer maxima in TH probabilities in Europe are found over mountain ranges such as the Alps, the Pyrenees, and the Carpathian Mountains

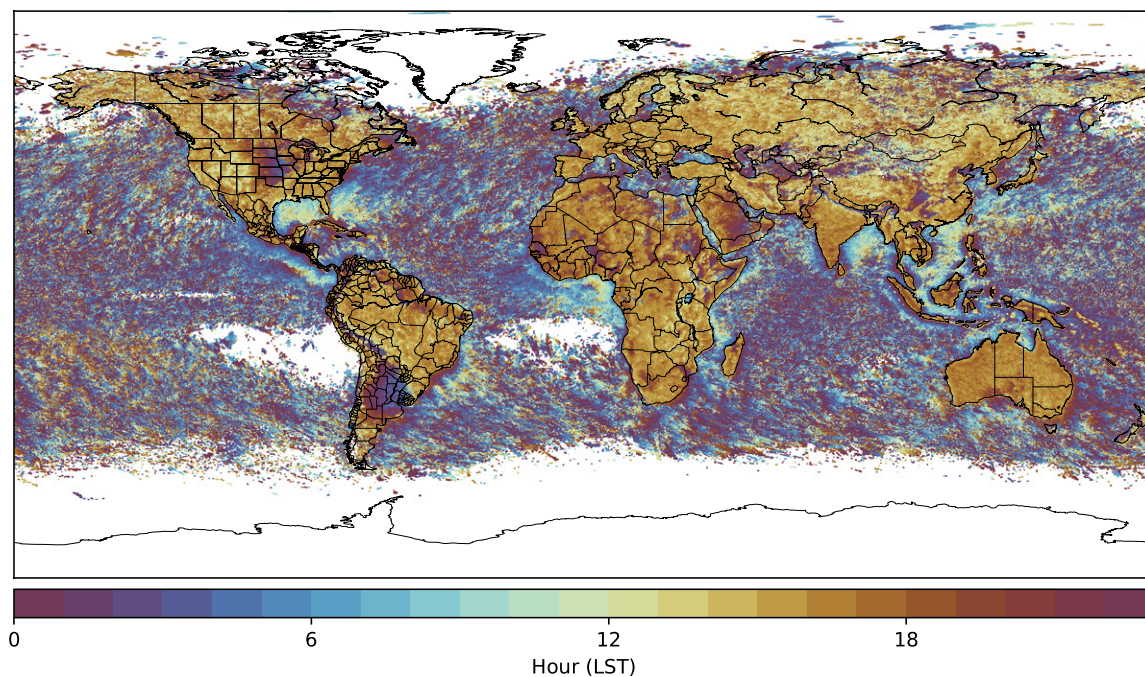


Fig. 2. Time of mean annual peak TH probability in LST for the entire world.

(Fig. S1), which are consistent with OTD–LIS mean annual flash density local maxima in the same areas (Fig. 1b; Cecil et al. 2014). Regions of broad highlands, such as in eastern Brazil and across Australia, are also characterized by enhanced TH probabilities, especially during local spring and summer months.

A clear global feature captured by the TH analysis is the intertropical convergence zone (ITCZ). The ITCZ is a region of broad convergence and rising motion typically associated with the equator, but which actually migrates northward and southward with the seasons, bringing widespread storminess to different tropical regions throughout the year (Waliser and Gautier 1993; Waliser and Jiang 2015; Schneider et al. 2014). The ITCZ is visible as latitudinally oriented bands of consistent daily TH probabilities over equatorial landmasses and extending to the adjacent oceans in Fig. S1 and mean annual thunder hours in Fig. 1a.

Regional monsoons captured by the TH analysis include the Asian monsoon, the Australian monsoon, the African monsoon, the Amazon monsoon, and the North American monsoon (Fig. S1). Although many of these may be influenced by the ITCZ migration in some way due to their proximity to the tropics, monsoon flow is typically driven by regional flow patterns dependent on synoptic-scale mid- and upper-level features that transport moisture into the areas that experience monsoons (e.g., Adams and Comrie 1997; Schott and McCreary 2001; Hall and Peyrillé 2006).

Regions that experience frequent mesoscale convective systems (MCSs) are identifiable in the TH dataset based on their widespread nocturnal time of peak TH over land (Fig. 2). The U.S. Great Plains, northern Argentina, northern India and Bangladesh, and West Africa are all regions prone to frequent nocturnal MCS activity. These regions were identified by Albrecht et al. (2016) as the locations of nocturnal flash rate density maxima. MCSs can occur multiple times per week, and can persist for up to 12 h (Geerts et al. 2017), producing lightning over broad regions throughout their long lifetimes.

An interesting set of features identifiable in the TH dataset are areas of enhanced thunderstorm activity over the oceans. The oceans east of the United States, subtropical South America, South Africa, Japan, and Australia, as well as the Mediterranean Sea, all have near-continual TH probability signatures (Fig. S1) and high mean annual TH counts compared with other regions of open ocean outside of the tropics (Fig. 1a). Albrecht et al. (2016) noted a negligible

annual, seasonal, or diurnal cycle to most zones of coastal oceanic lightning detected by TRMM-LIS, which are characterized by frequent synoptic-scale storm systems propagating off the nearest coast. For example, the Mediterranean Sea exhibits a pattern of convective enhancement manifesting without a discernible diurnal signal, which appears similar to that of some of the previously listed coastal regions. The warm sea surface temperatures of the Mediterranean enhance lightning activity associated with synoptic scale weather systems moving over the sea (Kotroni and Lagouvardos 2016). What seasonal variation exists in the Mediterranean manifests as a shift in the location of thunderstorm activity in Fig. S1, which is consistent with the findings of Kotroni and Lagouvardos (2016). Studies focusing on enhanced oceanic lightning over the Gulf Stream noted that, unlike most oceanic lightning, it had a diurnal cycle and, to a lesser degree, a seasonal cycle (Holle 2014; Virts et al. 2015). The Gulf Stream is characterized by warmer sea surface temperatures than the surrounding ocean, which leads to localized convergence over it and thus enhanced convection (Virts et al. 2015). That mechanism is much more active when there are nocturnal land breezes flowing off the east coast of the United States during the warm season.

Regional highlights

The contiguous United States. Thunder hours in the contiguous United States (CONUS) reveal a mix of storm modes in the region, consistent with past studies performed on American lightning climatologies (e.g., Changnon 1988; Changnon and Changnon 2001; Albrecht et al. 2016; Holle 2014). Airmass convection forced by diurnal heating is the most common convective mode seen in the United States, resulting in the peak mean TH probability for most of the CONUS occurring between 1300 and 1600 LST during boreal spring (March–May, or MAM), summer (June–August, or JJA), and autumn (September–November, or SON) (Figs. 3a–c). Regular summer convection in the mountainous southwestern United States is part of the northward extension of the North American Monsoon (NAM; Adams and Comrie 1997), which typically occurs during JJA (Holle and Murphy 2015). In the southeastern United States, the diurnal fluctuation in thunder hours and thus convection during JJA is largely the result of sea-breeze dynamics (Huffines and Orville 1999; Holle 2014). Florida in particular experiences enhanced convection during the summer and autumn months due to sea-breeze convergence over the center of the peninsula (Fig. S2). During boreal winter (December–February, or DJF), there is no consistent diurnal pattern to the infrequent lightning that does occur in the region (Fig. 3d), indicating that DJF lightning in the United States is driven by synoptic systems rather than daytime heating effects.

Severe convection during spring in the Great Plains manifests as a scattered pattern of peak TH times focused between late afternoon and about midnight LST (Fig. 3a). During JJA (and to a lesser extent, SON), this pattern expands and becomes more consistent: the local maximum in TH probability, which develops over the High Plains and western Great Plains regions after nightfall and then propagates eastward in a bowing pattern (Fig. S2 and Fig. 3b), represents the region's frequent nocturnal MCSs. They begin as clusters of storms that develop between the Rockies and the Great Plains, merge, and then propagate east across the plains as MCSs overnight (Knupp and Cotton 1987). The nocturnal signal is so strong that, even though that pattern occurs for only part of the year, it is still clear in the annual composite peak TH probability analysis (Fig. 2). The peak TH probability over the Rocky Mountains, denoted by white elevation contours, occurs earlier in the day than the rest of the country, and it is the most consistent during JJA, when the TH probabilities are highest for this region (Fig. S2). This pattern is associated with the NAM during JJA. During MAM and SON, convection is much less frequent in this area than during JJA, but it still tends to occur earlier in the afternoon.

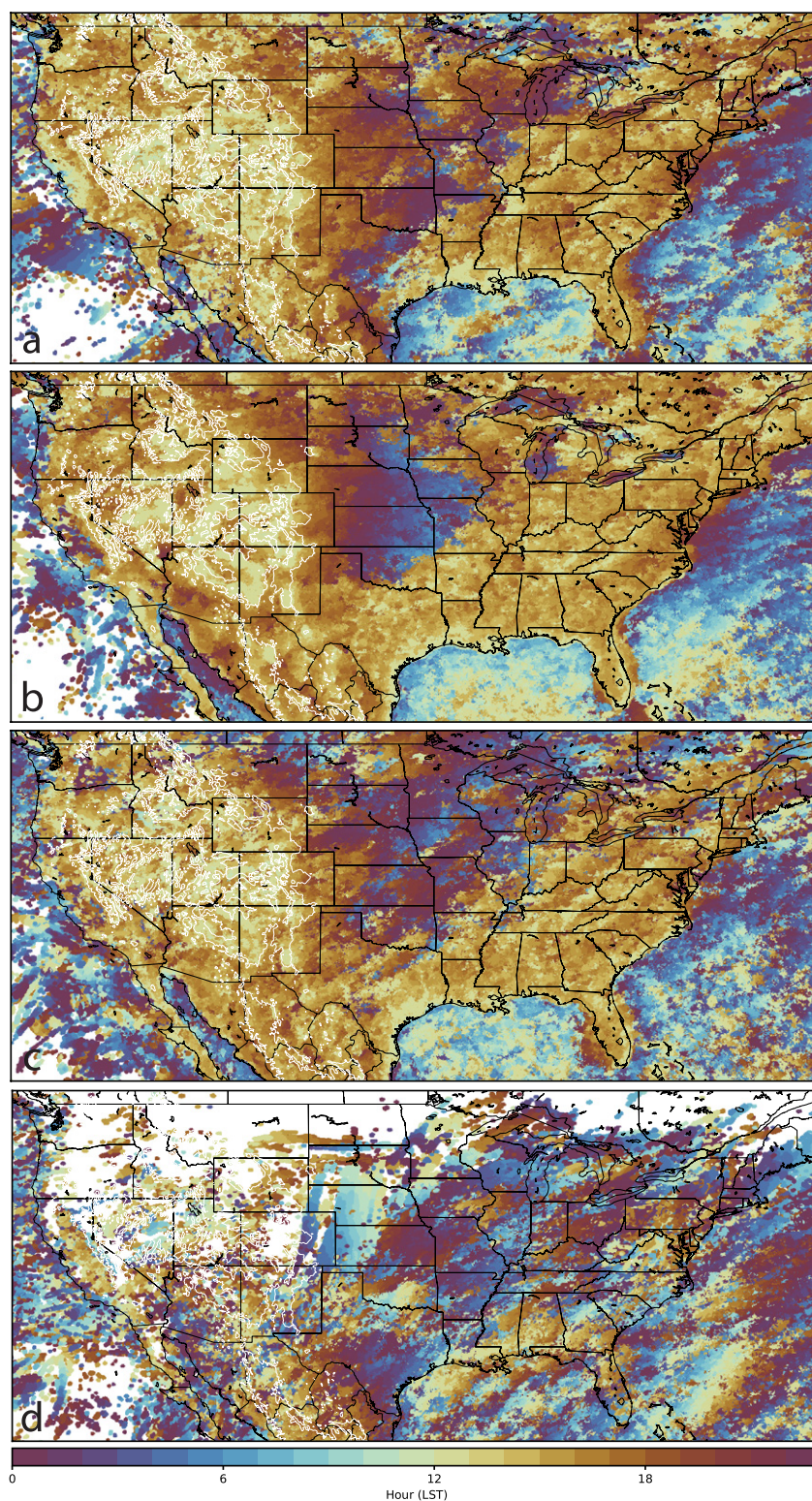


Fig. 3. Time of mean seasonal peak TH probability in LST for CONUS, divided by meteorological season: (a) MAM, (b) JJA, (c) SON, and (d) DJF. White contours depict 1,750-, 2,875-, and 4,500-m elevations above mean sea level.

South America. From October to April, there will likely be thunder in central Brazil on a daily basis, according to the TH dataset (Fig. S3), which corresponds roughly with the Amazon wet season (e.g., Albrecht et al. 2011). The TH signature is broad, and storm motions tend to be from generally the northeast to the southwest (Fig. S3). The storm motions in the Amazon basin have been attributed to easterly surface winds, which increase in strength along the coast and penetrate inland for hundreds of kilometers before abruptly weakening, leading

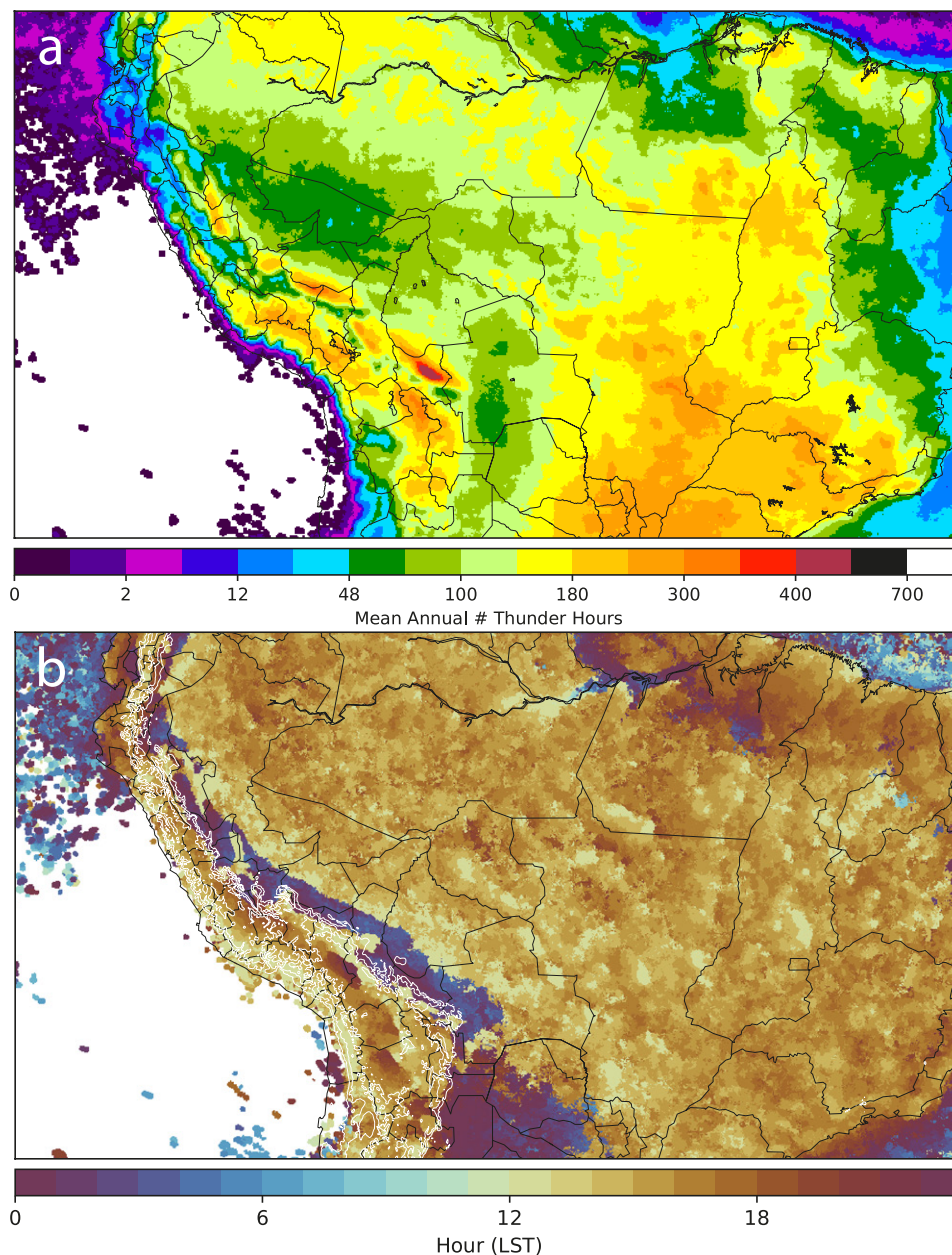


Fig. 4. (a) Mean annual ENGLN thunder hour counts for northern South America from 2015 to 2019. (b) Time of mean annual peak TH probability in LST for northern South America; white contours depict 1,750-, 2,875-, and 4,500 m elevations above mean sea level.

to light surface winds and low-level convergence (e.g., Romatschke and Houze 2010). The broad convergence over the Amazon Basin combined with daytime heating effects is likely the primary source of convection there.

Annual mean TH counts for northern South America are shown in Fig. 4a. They appear generally consistent with total thunderstorm duration calculated for the region in Peterson (2019). The regions with the highest TH counts are in and adjacent to the Andes mountains and the Brazilian highlands. Figure 4b shows that, in all seasons, thunderstorms in the pictured region are most likely to occur in late afternoon, much like the CONUS region, indicating that the diurnal cycle plays a major role in the production of convection across northern South America. There are also frequent, relatively short-lived MCSs that occur over coastal Brazil and the interior of the Amazon (e.g., Anselmo et al. 2021; Rehbein et al. 2018) and thus contribute to the thunder hour signatures therein. The absence of a widespread nocturnal maximum in the time of peak TH across much of the Amazon basin

(Fig. 4b) indicates that most of these MCSs likely occur during the day, which is consistent with the findings of Rehbein et al. (2018). The exception to this is the band of nocturnal peak TH probabilities, coincident with a local minimum in mean annual TH counts (Fig. 4a), extending southeast from the Amazon River (Fig. 4b). These two signatures combined are likely associated with convection from Amazonian coastal squall lines (Cohen et al. 1995) weakening as the sea breeze slows, followed by the Amazonian low-level jet triggering new nocturnal convection in the same area (Anselmo et al. 2021). Nocturnal river convection documented in past studies (e.g., Negri et al. 2000; Burleyson et al. 2016) is also captured by the analysis, including over eastern parts of the Amazon River and the Negro River (Fig. 4b).

Orographically enhanced convection along the Andes leads to a noteworthy convective pattern in northern South America (Fig. 4a and Fig. S3). There is a prominent daytime maximum in TH probability over the Altiplano region of Peru and Bolivia primarily from September to April, which is not seen anywhere else in that mountain range. The Altiplano TH signature is a narrow band that dissipates after propagating northeast into the eastern arm of the Andes after sunset (Fig. S3). Another TH maximum appears later in the night where the Andes foothills meet the Amazon basin. These signatures are evident in the time of peak TH probabilities (Fig. 4b), but are minimal during May and nearly absent during JJA (Fig. S3), which is the Amazon dry season. The nocturnal storms at the base of the foothills are nearly stationary, unlike the other storm systems in the region (Fig. S3). Romatschke and Houze (2010) noted that large amounts of daytime heating over mountain crests and plateaus lead to extreme convergence of surface winds at those high elevations. Combined with moisture transport by upslope flow originating in the Amazon basin, deep convective cores are observed over the Altiplano during the day. The upslope flow feeding Altiplano convection, in turn, creates a region of strong divergence in the foothills, which suppresses convection there. Romatschke and Houze (2010) further speculated that outflow from the dissipating Altiplano storms flows downslope into the foothills and converges with the weak easterly winds transporting moisture from the Amazon basin, which results in nocturnal convection in that region.

Lake Victoria. A region of particular interest in equatorial Africa is Lake Victoria and the surrounding landmass. Lake Victoria is the largest lake in the world, and its diurnal convection pattern varies little throughout the year (Fig. S4); the JJA months are the driest months for the region, but there are still thunder hours recorded over and in the immediate vicinity of the lake during that season (Fig. S4). The mean annual TH frequency over the lake and the Kenyan highlands immediately northeast of it are some of the largest in the world (cf. Fig. 5a with Fig. 1a) after the Congo Basin and the Strait of Malacca, in part due to the unique topography there. Daytime heating of the land around the lake results in lake breezes, which move over the surrounding land area and, especially in the highlands to the north of the lake, initiate convection during the afternoon and evening hours. At night, these storms sometimes propagate over the lake. Outflow boundaries from those storms and land breezes also initiate new convection over the lake itself. TH probabilities over Lake Victoria itself thus peak in the late night and early morning hours throughout the year (Fig. 5b). The dynamics controlling convection on and around the lake are thus a combination of diurnal heating, lake and land breezes, and orographic effects, as discussed by Virts and Goodman (2020). Albrecht et al. (2016) pointed out that Lake Victoria shares some characteristics with Lake Maracaibo in South America, deemed Earth's foremost lightning hotspot: both have lightning activity that is most frequent at night, in both cases caused by nocturnal convection driven by convergent land breezes, which are enhanced by nearby topographical effects. All of these dynamics result in two consistent trends in TH probability occurring at

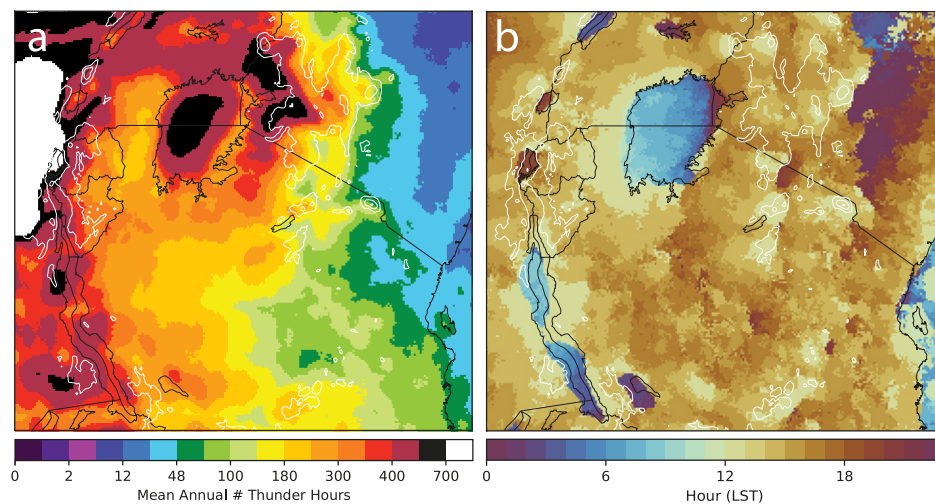


Fig. 5. (a) Mean annual ENGLN thunder hour counts for the Lake Victoria region from 2015 to 2019. (b) Time of mean annual peak TH probability in LST for the Lake Victoria region. White contours depict 1,750-, 2,875-, and 4,500-m elevations above mean sea level.

different times: over Lake Victoria, the peak occurs overnight and into the morning, while for the surrounding land regions, the peak occurs in late afternoon, consistent with the findings of Virts and Goodman (2020). The nearby Lake Tanganyika has a similar diurnal convection pattern as Lake Victoria, but most of the convection over that lake occurs during SON–DJF, rather than year-round (Fig. S4).

The Maritime Continent. The Maritime Continent region, which includes Indonesia, Malaysia, Papua New Guinea, the Philippines, and other island nations, is one of the most active lightning regions in the world. These islands are located in the ITCZ, where a tropical climate and consistent large-scale rising motion enables convection forced primarily by differential diurnal heating throughout the year. The islands all follow the typical sea-breeze convective pattern year round, with TH probabilities peaking over land during the day and then peaking just off the coast at night (Fig. S5). Albrecht et al. (2016) noted several lightning hot spots in the Strait of Malacca, where there is both sea-breeze convection over adjacent land and enhanced nocturnal convection over the strait itself resulting from convergent offshore breezes. The same pattern is seen in the TH dataset, where the maximum mean annual TH count peaks in the Strait of Malacca and coincides with a late-night time of maximum TH probability (Figs. 6a,b and Fig. S5). The signal is present, although not as dramatic, in between other islands located close to one another. Storm motions according to TH probabilities (Fig. S5) suggest that the land–sea breeze oscillation combined with complex terrain features on the islands (note the white contours in Fig. 6b) determines which direction these storms propagate rather than large-scale flow. The migration of the ITCZ across this region twice per year also serves to enhance sea- and land-breeze convection (Albrecht et al. 2016); TH probabilities are lowest in this region between June and September, when the ITCZ has migrated northward. The island of Papua/Papua New Guinea has perhaps the most interesting diurnal cycle of the Maritime Continent, because the greatest daytime TH probabilities actually occur in distinct bands along the coasts and in the interior of the island (Fig. 6a). The Maoke Mountains and Bismarck Range, both east–west-oriented mountain ranges running along the length of the island, are thus contributing to convective forcing there in addition to the sea-breeze circulation. Figure 6b further shows that outside the coastal waters immediately adjacent to the islands, in the deeper ocean, there is no perceptible diurnal signal in the TH, indicating synoptic-scale weather systems likely drive convection there.

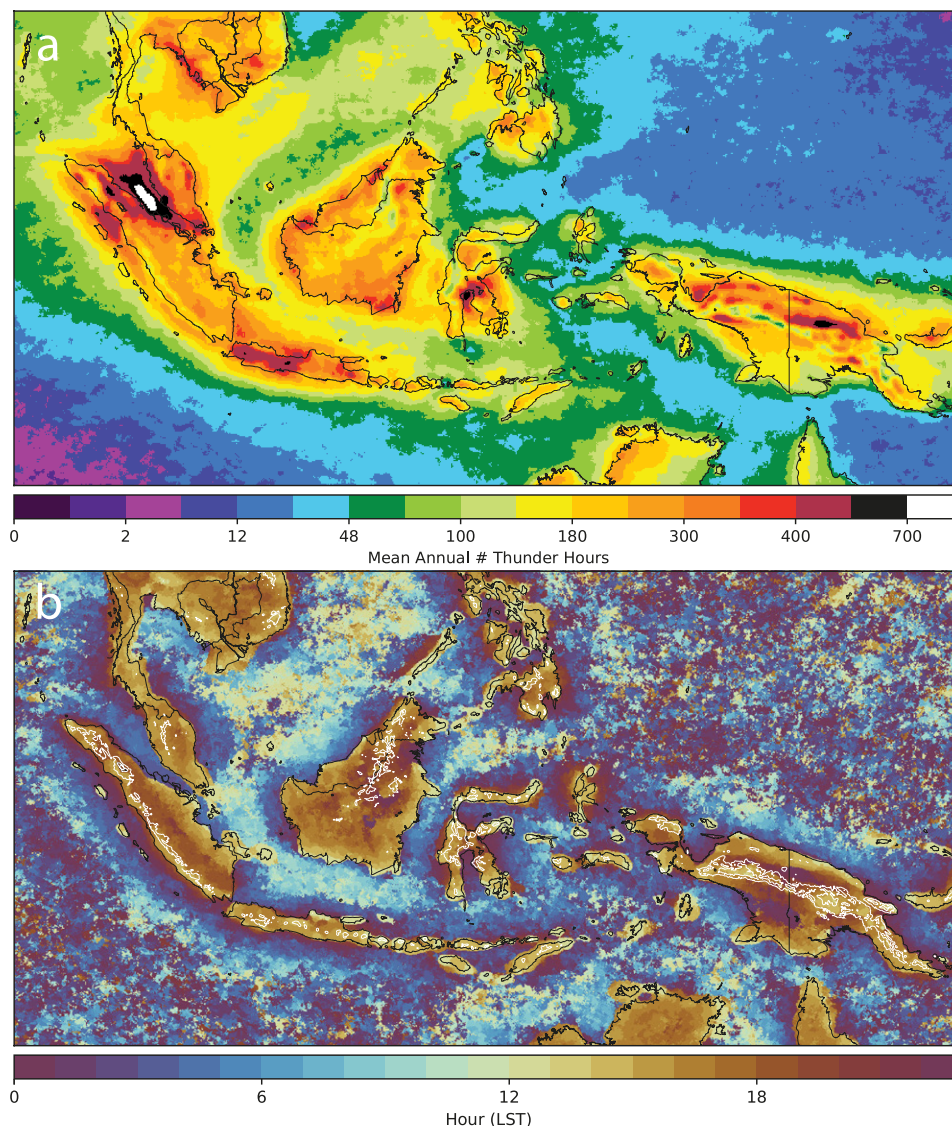


Fig. 6. Mean annual ENGLN thunder hour counts for the Maritime Continent from 2015 to 2019. (b) Time of mean annual peak TH probability in LST for the Maritime Continent; white contours depict 1,000-, 2,000-, and 4,500-m elevations above mean sea level.

Thunder hours and the Carnegie curve

Global thunderstorm activity is strongly coupled to the Earth's global electric circuit. In fair weather conditions, at the surface of the Earth there is an electric field of about 140 V m^{-1} , which varies over the course of a day (Harrison 2013). In a very well-known study, Whipple (1929) showed that the variation of this electric field is largely independent of where it is measured. The average variation of the fair weather electric field is now called the Carnegie Curve. Whipple and Scrase (1936) demonstrated that an estimate of global thunder hours corresponds well to the independent electric field measurements made to study the Carnegie Curve (Whipple 1929; Harrison 2013). Whipple and Scrase (1936) further showed that the shape of the Carnegie curve is qualitatively related to thunderstorm activity in the Americas, Africa, and Asia using hourly thunder observations. A similar analysis using the ENGLN thunder hour data are shown in Fig. 7a.

Here the hourly thunderstorm activity is computed by integrating the gridded thunder hour data over grid area and then averaging across all days in a calendar year. The result is the average global thunderstorm activity (measured in area of storms) for the year 2017 (black line), which has a shape very similar to that of the daily variation of the fair weather electric field (e.g., Whipple and Scrase 1936). The same analysis can be regionalized for the Americas

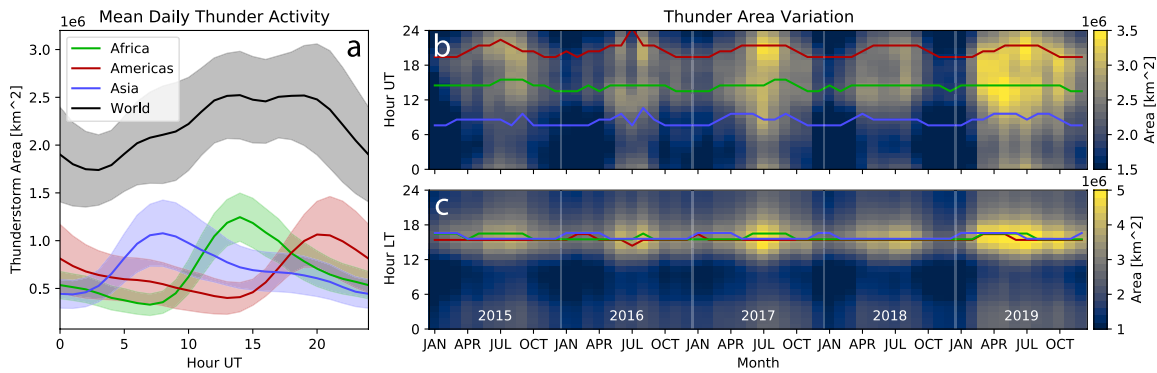


Fig. 7. Representation of the Carnegie curve as calculated from ENGLN thunder hours. (a) Mean daily thunder activity integrated over area for the entire world (black line), Africa–Europe (green line), the Americas (red line), and Asia–Australia (blue line). Shaded regions represent the standard deviation of the curves. (b) Diurnal and annual variation in thunder area with time in UT. Color fill represents thunder area per hour per month of the year. Colored curves represent the variation in the curves of the same colors from (a). (c) As in (b), but for LT.

(red line, longitudes -130° to -30°), Africa (green line, longitudes -20° to $+50^{\circ}$), and Asia (blue line, longitudes $+60^{\circ}$ to $+160^{\circ}$). The standard deviation of the Carnegie curve is represented by the shaded region of each curve. The mean is not very stable, and the observations are not normally distributed. There is significant seasonal and interannual variation in the curve, such that if the analysis were repeated for a different 365-day period, the mean thunderstorm activity would likely fall well outside the standard error calculated by Harrison (2013).

Mean thunderstorm activity was computed for every calendar month in the 5-yr ENGLN dataset, and the resulting variation in the 5-yr Carnegie curve is shown in Figs. 7b and 7c. A strong diurnal signal is evident in Fig. 7c. In most years, global thunderstorm activity peaks during Northern Hemisphere summer (Figs. 7b,c), which is expected since there is more land-mass north of the equator. Overlaid on top of the global thunderstorm activity is the time of the peak activity for the three chimney regions. The time of these peaks shifts in UTC hour as the thunderstorm activity shifts in longitude during the year, causing phase changes in the Carnegie curve. The primary driving force for the thunderstorms for all regions (and the globe) is insolation. If the analysis is repeated in LST instead of UTC, all three chimneys have their thunderstorm activity line up, and the phase variation of the Carnegie curve is eliminated (the seasonal variation remains). This is depicted in Fig. 7c.

The curves shown here are not exactly the same as the curves plotted by Whipple and Scrase (1936) and Harrison (2013) because the ENGLN calculation included oceanic thunder observations while the classic analyses only used terrestrial thunder observations, and because the curves shown here were calculated with a different year of data. The analysis shown in Fig. 1a is based on 365 days of observations from the year 2017, whereas the original Carnegie curve was computed based on 82 undisturbed days over a 2-yr cruise. However, there is significant consistency between the classic Carnegie curve and the curve produced from the ENGLN data, indicating that the ENGLN TH dataset is representative of global storminess trends.

Global thunder anomalies

Thunder hour data can be used to examine monthly, seasonal, and interannual trends in storm frequency across the globe by calculating thunder anomalies. Anomaly fields demonstrate how the atmosphere is changing over time and space compared with its average state, and are often used in research focused on global changes in temperature and precipitation. We propose that an analogous anomaly field, thunder anomalies, can be generated by taking the difference between the number of thunder hours during some short time period (i.e., a month or a season) and the climatological average number of thunder hours for a longer

time period. For demonstrative purposes, we are showing anomalies compared with the average values from our 5-yr dataset, although 5 years is rather short for a climatology dataset. Thunder observations are better-suited for this type of analysis than FRD because thunder data are smoother than FRD data, which mitigates the impacts of strong individual storms on the analysis and thus produces more robust results in less time.

Figure 8 shows a side-by-side comparison of the June 2019 FRD (Fig. 8a) and TH (Fig. 8b) anomalies calculated from ENGLN data over the central United States. These anomaly fields were generated by subtracting the 5-yr mean FRD and TH frequency observations in June from the number of FRD and TH observations in June 2019, respectively. Shades of red indicate positive anomalies and shades of blue indicate negative anomalies. The central United States was chosen for this comparison because ENGLN has exceptionally high detection efficiency there (Bitzer and Burchfield 2016; Marchand et al. 2019), which means that the effects of network performance on FRD are trivial. At a glance, the smoother nature of the TH data are apparent when compared with FRD data. The FRD anomalies are heavily influenced by individual storms and storm tracks, evident in the finely detailed structure of the anomaly field. For example, in southwestern Minnesota, there is a single region of strong positive FRD anomaly that is the direct result of a single severe thunderstorm event that occurred on 4 June 2019 (NOAA/NWS Weather Forecast Office 2019a). The same location in the TH anomaly field is primarily neutral. Over the Rocky Mountains (i.e., the western third of the domain in Fig. 8), there are neutral to very weak positive FRD anomalies, while in the same area there are widespread positive TH anomalies. Given this discrepancy, it is likely that the storms in this region are characterized by low total flash rates. Thunder hours resolve low-flash-rate storms with similar weight as high-flash-rate storms.

The results of this comparison indicate that the frequency of low-flash-rate thunderstorms in the region was above average during June 2019, which means it was stormier than average in the Rocky Mountains prior to monsoon season. This is consistent with areas of average- to above-average precipitation in the region during that time, attributed to scattered above-average thunderstorm activity by National Centers for Environmental Information (2019a). While higher resolution data are often desirable, climate studies about thunderstorms are typically more interested in broader trends than they are in individual storms. TH are thus more useful for examining how thunderstorm activity over a short period compares with the climatological average of thunderstorm activity for a region.

The seasonal thunder anomalies for the entire globe are shown for all four meteorological seasons for one year (December 2018–November 2019) in Fig. 9. During DJF (Fig. 9a), there were strong positive thunder anomalies in southern Brazil, which corresponded with the fifth-warmest January and fourth-warmest February on record for the region (National Centers for Environmental Information 2019b,c). The negative TH anomalies dominating the rest of Brazil are representative of the below-average rainfall experienced by most of the country in 2019 (Ramos et al. 2020). The tropics became much more active during MAM (Fig. 9b) as the ITCZ began to migrate north. The significant positive anomalies in Southeast Asia and the Maritime Continent, as well as the modest positive anomalies in the central United States, are likely related to a strong Madden–Julian oscillation (MJO) that was active during this season (Becker 2019). During JJA (Fig. 9c), negative anomalies dominated the southwestern United States and northern Mexico, consistent with regional drought conditions and the overall failure of the NAM in 2019 (NOAA/NWS Weather Forecast Office 2019b). There were also widespread positive anomalies across much of Europe, which correspond to above-average temperatures for the summer season there (National Centers for Environmental Information 2019d). Southeast Asia continued to be anomalously convectively active, although much of the Maritime Continent saw negative thunder anomalies during this period, possibly related to the typically drier-than-average conditions associated with El Niño (Lindsey 2016) that persisted until

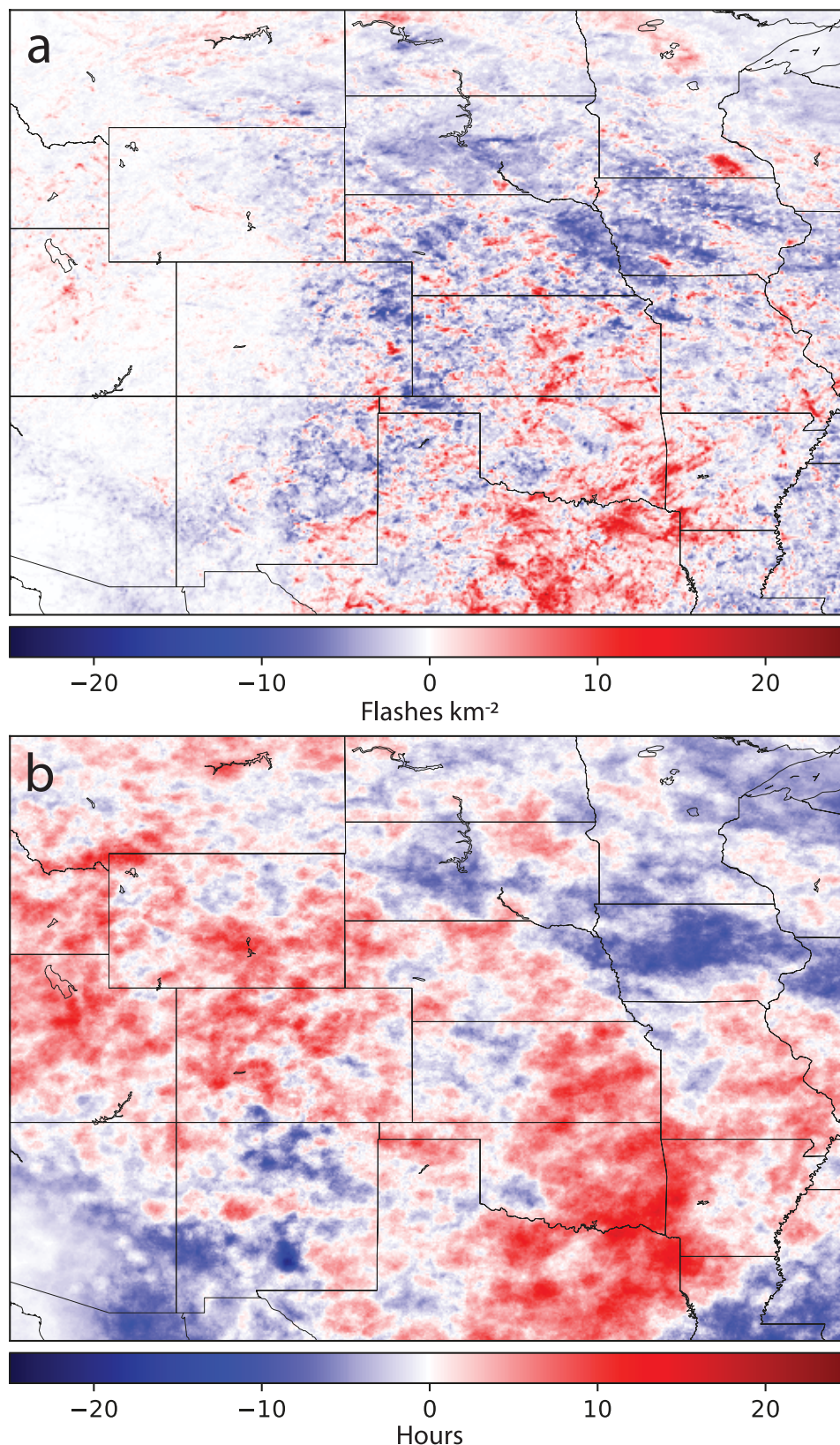


Fig. 8. (a) ENGLN flash rate density anomalies for June 2019 over central CONUS. (b) ENGLN thunder hour anomalies for June 2019 over the central CONUS.

July (Johnson 2019). There were strong positive thunder anomalies in the southernmost tip of Brazil and into Uruguay during this time, indicating a convectively active winter period in the coastal subtropics of South America, which may also be related to El Niño. However, that trend continued into SON (Fig. 9d), after a return to neutral El Niño conditions.

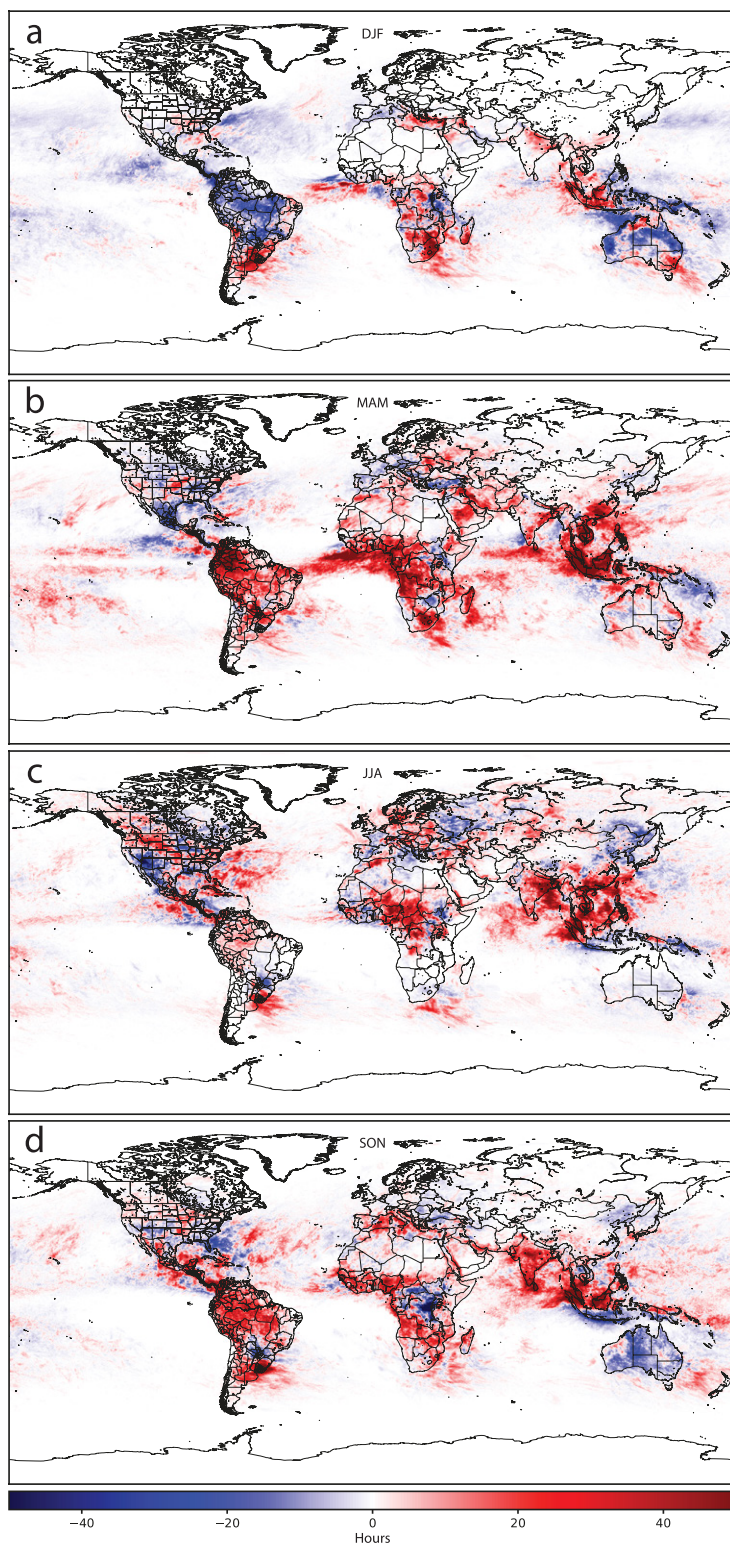


Fig. 9. Global ENGLN thunder hour anomalies for each meteorological season of 2019: (a) DJF, (b) MAM, (c) JJA, and (d) SON.

consistent with the findings of past research, which is remarkable considering its relatively short duration. With only 5 years of data, ENGLN thunder hours yield patterns in the diurnal and spatial distributions of thunderstorms, which have historically required over a decade of satellite data to observe. The ENGLN TH data also accurately represent global thunder features, such as the well-known Carnegie curve, despite deriving those features from synthetic thunder observations. The ENGLN TH dataset will thus be highly useful for research focusing on the global electric circuit.

Summary and conclusions

In this paper, we have presented a 5-yr thunder hours dataset derived from the Earth Networks Global Lightning Detection Network and demonstrated ways to analyze it relative to meteorological phenomena on a variety of scales. The analysis presented is preliminary, a test of the efficacy of the thunder hour methodology in capturing climatological and meteorological patterns around the globe. Thus far, the method appears sound, and has promising implications for the future of climate research related to global thunderstorm frequency.

Global, regional, and local convective features and patterns are well represented. Indeed, widespread monsoonal convection characterized by low-flash-rate storms is given more emphasis than in a typical flash density analysis. Widespread topographically forced convection, MCS-prone regions, local lightning hot spots, and sea-breeze convection have all been examined and compared with previous literature, which focused on a variety of lightning and precipitation analyses, many of them long-term climatologies developed with satellite-based instruments or global reanalysis data. The thunder hours dataset is, overall, con-

One interesting application for thunder hour data are to use it to calculate thunder anomalies, analogous to temperature anomalies. Thunder anomaly maps were generated using the ENGLN thunder hours data, and compared with flash rate density anomalies. FRD, while a proven useful metric for measuring convective intensity, does not lend itself well to anomaly analysis because short-term FRD datasets are heavily biased toward the behavior of individual storms. Generating synthetic thunder observations from lightning substantially mitigates those biases, which means that thunder hours are a natural fit for studying thunderstorm trends on monthly and seasonal scales. Thunder anomalies are just one way thunder hours can be used to analyze changes in convection relative to teleconnection patterns and climate change, which will be essential to the application of lightning data to future climate research on a global scale.

Global lightning climatologies suffer from the limitations of the varying lightning detection techniques with which their data were collected. Every lightning detection technology has its strengths and weaknesses, but data from both ground-based networks and satellite-based optical instruments are invaluable to determining trends in lightning and thunderstorm frequency across the globe. If researchers sought to combine datasets for the most global coverage of convection in space and time, but limited themselves to monitoring the location and frequency of individual flashes, trying to match the datasets from different lightning location systems to one another would be a difficult problem. We propose that by converting flash density observations into thunder observations, we can potentially combine various lightning datasets for use in truly global climatological studies of thunderstorm frequency. Furthermore, by converting flash density observations to thunder observations, these datasets could also be much more easily extended to observing climatological time scales by combining them with historical observations of thunder days recorded during the past century. Creating a combined dataset in this manner would facilitate much more robust analyses of how global storminess changes over time, including through metrics such as thunder anomalies.

Thunder hours represent an incredibly useful middle ground between flash density and thunder days for lightning climatologies. This analysis method has the potential to change how researchers approach climatological studies of lightning by standardizing and even unifying datasets from instruments with varying detection methods, system performance standards, and characteristics. In publishing this dataset and some initial overview analysis of it, we encourage researchers from around the world to make use of the ENGLN thunder hours data, hopefully in conjunction with other datasets, to gain a clearer understanding of diurnal and seasonal convective trends relative to meteorology and climatology.

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Data availability statement. The ENGLN data used in this study were provided by Earth Networks and WWLLN. The data are available at <http://thunderhours.earthnetworks.com/>. The LIS–OTD data used to compare with the thunder hour data are available at https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_otd-climatology.html.

Appendix: The relationship between thunder radius and thunder hours

Thunder observations are a historically relevant measurement, which this study seeks to build upon by connecting lightning observations to thunder. However, the physically audible range of thunder is not constant, and as such there are several radii that could have been used in this study. Changing the thunder radius naturally results in some changes to the number of

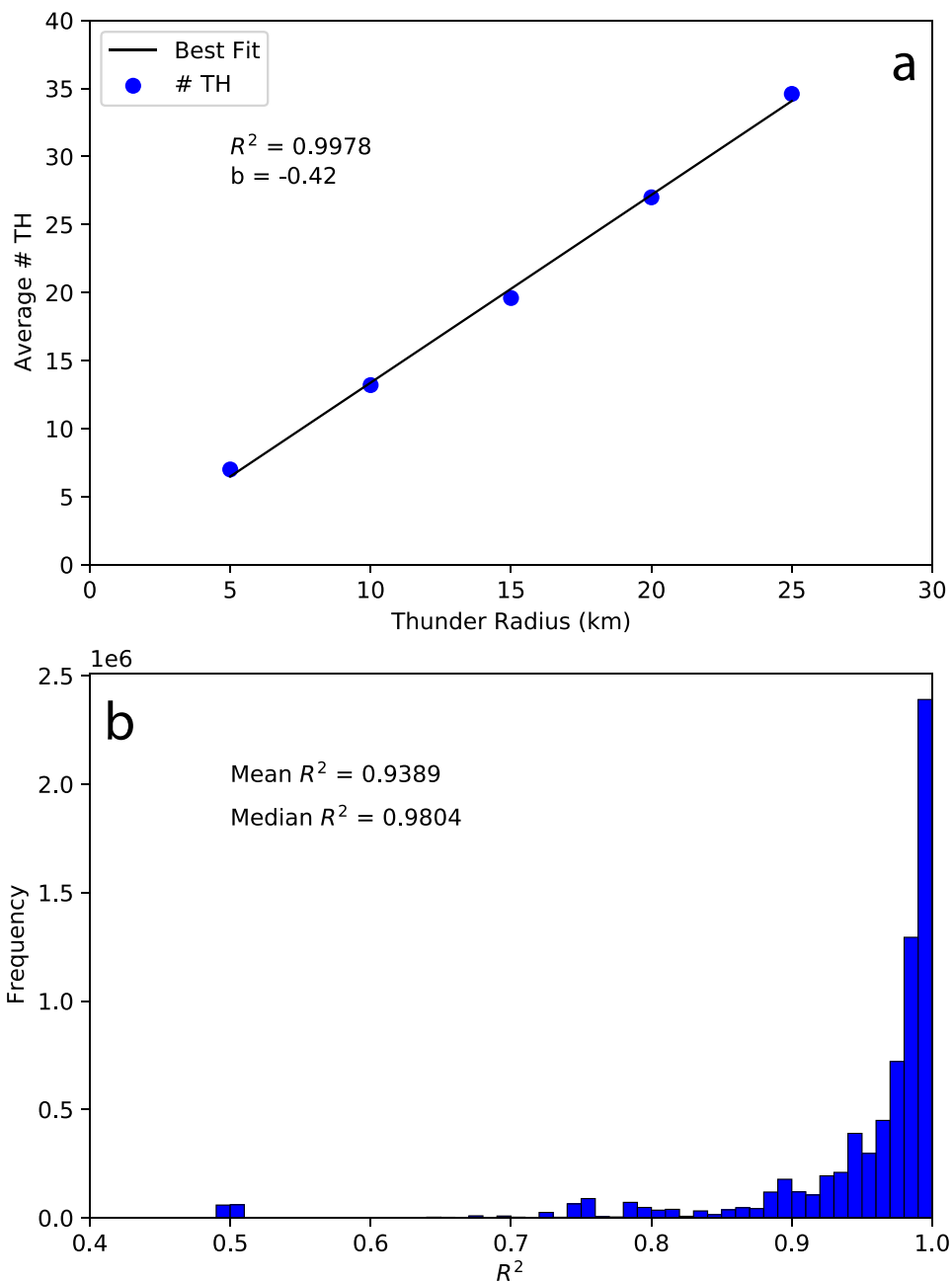


Fig. A1. (a) Linear regression for a randomly selected grid point containing average TH > 5 in the 5-km thunder radius dataset. (b) R^2 values for linear regression analyses of all grid points that were nonzero in the 5-km thunder radius dataset.

thunder hours calculated for a given grid cell. We chose to use 15 km as our thunder radius for this study, as discussed in the “Data and methods” section, but past literature cited several other radii that could have been used instead.

To quantify the relationship between TH and thunder radius, different thunder radii were tested on the 5-yr ENGLN dataset during the month of May. May in particular was chosen because it is one of the most convectively active months of the year globally, and because limiting the analysis to 1 month mitigated its computational cost. First, we calculated the average number of thunder hours (UTC) for May for the entire world between 2015 and 2019 using thunder radii of 5, 10, 15, 20, and 25 km. The 5-km results may be somewhat underestimated because the size of the 0.05° grid cells at some latitudes is larger than 5 km; we include them in this auxiliary analysis for the sake of thoroughness. Next, we randomly selected a grid cell that contained an average TH count of at least 5 h in the 5-km-radius dataset, and

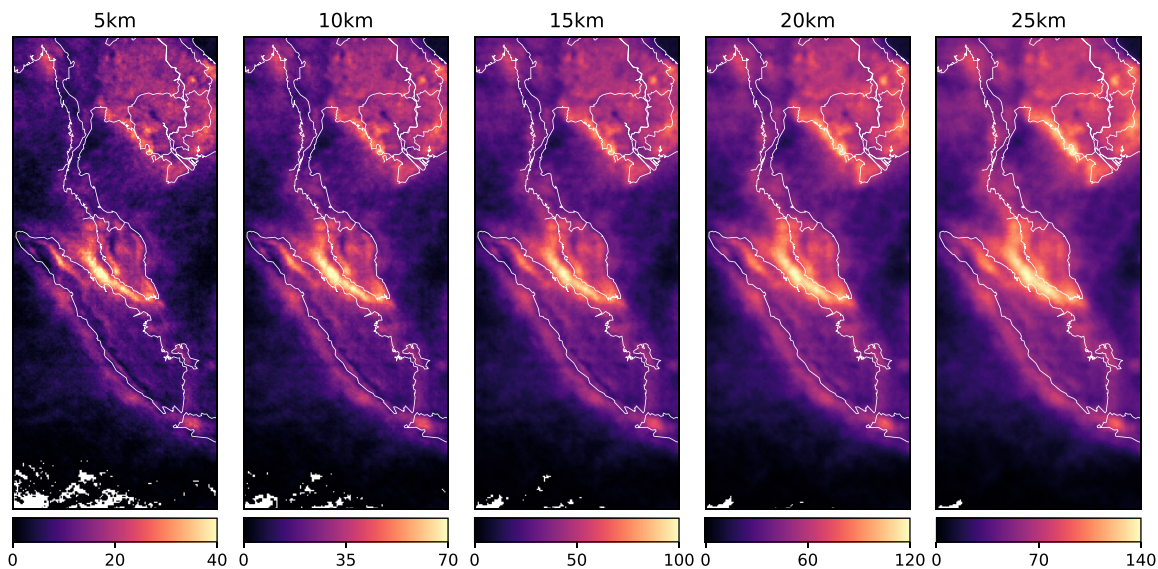


Fig. A2. Average TH counts for the month of May over a portion of the Maritime Continent for each tested thunder radius. Note that the scaling of the color bar increases with increasing thunder radius.

performed a regression analysis between TH and radius. Results are shown in Fig. A1a, with R^2 and intercept indicated. The same regression analysis was then repeated for all grid cells with an average TH count greater than zero, a total of more than 7.2 million regressions. The distribution of R^2 values is shown in Fig. A1b, with mean and median R^2 values indicated. The mean and median intercepts of the regression distribution are 0.034 and -0.1 , respectively. The relationship between thunder radius and TH is thus linear with a near-zero intercept. In other words, TH is directly proportional to the thunder radius used.

Figure A2 demonstrates of how the spatial distribution of average TH counts changes with the thunder radius for a portion of the Maritime Continent region. The overall pattern and relative TH intensity do not change, which is consistent with the linear relationship between TH and radius. However, larger thunder radii result in larger TH counts (note the labels of the color bars in Fig. A2) and smoother TH distributions, while smaller radii result in lower TH counts and more detailed but noisier TH distributions. Since the same patterns can be observed in the spatial distributions of all results, we are confident that the observations made and conclusions drawn in this study would still be valid if applying a different thunder radius.

References

- Adams, D. K., and A. C. Comrie, 1997: The North American monsoon. *Bull. Amer. Meteor. Soc.*, **78**, 2197–2214, [https://doi.org/10.1175/1520-0477\(1997\)078<2197:TNAM>2.0.CO;2](https://doi.org/10.1175/1520-0477(1997)078<2197:TNAM>2.0.CO;2).
- Aich, V., R. H. Holzworth, S. J. Goodman, Y. Kuleshov, C. G. Price, and E. R. Williams, 2018: Lightning: A new essential climate variable. *Eos*, **99**, <https://doi.org/10.1029/2018EO104583>.
- Albrecht, R. I., S. J. Goodman, W. A. Petersen, D. E. Buechler, E. C. Bruning, and R. J. Blakeslee, 2011: The 13 years of TRMM Lightning Imaging Sensor: From individual flash characteristics to decadal tendencies. *14th Int. Conf. on Atmospheric Electricity*, Rio de Janeiro, Brazil, ICAE, 1–4, <https://ntrs.nasa.gov/citations/20110015779>.
- , D. E. Buechler, R. J. Blakeslee, and H. J. Christian, 2016: Where are the lightning hotspots on Earth? *Bull. Amer. Meteor. Soc.*, **97**, 2051–2068, <https://doi.org/10.1175/BAMS-D-14-00193.1>.
- Anselmo, E. M., L. A. T. Machado, C. Schumacher, and G. N. Kiladis, 2021: Amazonian mesoscale convective systems: Life cycle and propagation characteristics. *Int. J. Climatol.*, **41**, 3968–3981, <https://doi.org/10.1002/joc.7053>.
- Becker, E., 2019: May 2019 El Niño Update: Feliz Cumpleaños. Climate.gov, www.climate.gov/news-features/blogs/enso/may-2019-el-ni%C3%B1o-update-feliz-cumplea%C3%B1os.
- Bitzer, P. M., and J. C. Burchfield, 2016: Bayesian techniques to analyze and merge lightning locating system data. *Geophys. Res. Lett.*, **43**, 605–612, <https://doi.org/10.1002/2016GL071951>.
- Bourscheidt, V., K. L. Cummins, O. Pinto, and K. P. Naccarato, 2012: Methods to overcome lightning location system performance limitations on spatial and temporal analysis: Brazilian case. *J. Atmos. Oceanic Technol.*, **29**, 1304–1311, <https://doi.org/10.1175/JTECH-D-11-00213.1>.
- Brooks, C. E. P., 1925: *The Distribution of Thunderstorms Over the Globe*. H.M. Stationery Office, 164 pp.
- Burleyson, C. D., Z. Feng, S. M. Hagos, J. Fast, L. A. T. Machado, and S. T. Martin, 2016: Spatial variability of the background diurnal cycle of deep convection around the GoAmazon2014/5 field campaign sites. *J. Appl. Meteor. Climatol.*, **55**, 1579–1598, <https://doi.org/10.1175/JAMC-D-15-0229.1>.
- Cecil, D. J., 2001: LIS/OTD 0.5 degree High Resolution Full Climatology (HRFC). NASA Global Hydrology Resource Center DAAC, accessed 4 June 2021, https://ghrc.nsstc.nasa.gov/lightning/data/data_lis_otd-climatology.html.
- , D. E. Buechler, and R. J. Blakeslee, 2014: Gridded lightning climatology from TRMM-LIS and OTD: Dataset description. *Atmos. Res.*, **135–136**, 404–414, <https://doi.org/10.1016/j.atmosres.2012.06.028>.
- , 2015: TRMM LIS climatology of thunderstorm occurrence and conditional lightning flash rates. *J. Climate*, **28**, 6536–6547, <https://doi.org/10.1175/JCLI-D-15-0124.1>.
- Changnon, S. A., Jr., 1985: Secular variations in thunder-day frequencies in the twentieth century. *J. Geophys. Res.*, **90**, 6181–6194, <https://doi.org/10.1029/JD090iD04p06181>.
- , 1988: Climatology of thunder events in the conterminous United States. Part I: Temporal aspects. *J. Climate*, **1**, 389–398, [https://doi.org/10.1175/1520-0442\(1988\)001<0389:COTEIT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1988)001<0389:COTEIT>2.0.CO;2).
- , and D. Changnon, 2001: Long-term fluctuations in thunderstorm activity in the United States. *Climatic Change*, **50**, 489–503, <https://doi.org/10.1023/A:1010651512934>.
- Christian, H. J., and Coauthors, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, **108**, 4005, <https://doi.org/10.1029/2002JD002347>.
- Cohen, J. C. P., M. A. F. Silva Dias, and C. A. Nobre, 1995: Environmental conditions associated with Amazonian squall lines: A case study. *Mon. Wea. Rev.*, **123**, 3163–3174, [https://doi.org/10.1175/1520-0493\(1995\)123<3163:ECAWAS>2.0.CO;2](https://doi.org/10.1175/1520-0493(1995)123<3163:ECAWAS>2.0.CO;2).
- Fujibe, F., 2017: Long-term change in lightning mortality and its relation to annual thunder days in Japan. *J. Nat. Disaster Sci.*, **38**, 17–29, <https://doi.org/10.2328/jnds.38.17>.
- Geerts, B., and Coauthors, 2017: The 2015 plains elevated convection at night field project. *Bull. Amer. Meteor. Soc.*, **98**, 767–786, <https://doi.org/10.1175/BAMS-D-15-00257.1>.
- Hall, N. M. J., and P. Peyrillé, 2006: Dynamics of the West African monsoon. *J. Phys. IV France*, **139**, 81–99, <https://doi.org/10.1051/jp4:2006139007>.
- Harrison, R. G., 2013: The Carnegie curve. *Surv. Geophys.*, **34**, 209–232, <https://doi.org/10.1007/s10712-012-9210-2>.
- Holle, R. L., 2014: Diurnal variations of NLDN-reported cloud-to-ground lightning in the United States. *Mon. Wea. Rev.*, **142**, 1037–1052, <https://doi.org/10.1175/MWR-D-13-00121.1>.
- , and M. J. Murphy, 2015: Lightning in the North American monsoon: An exploratory climatology. *Mon. Wea. Rev.*, **143**, 1970–1977, <https://doi.org/10.1175/MWR-D-14-00363.1>.
- Huffines, G. R., and R. E. Orville, 1999: Lightning ground flash density and thunderstorm duration in the continental United States: 1989–96. *J. Appl. Meteor.*, **38**, 1013–1019, [https://doi.org/10.1175/1520-0450\(1999\)038<1013:LGFDAT>2.0.CO;2](https://doi.org/10.1175/1520-0450(1999)038<1013:LGFDAT>2.0.CO;2).
- Hutchins, M. L., R. H. Holzworth, J. B. Brundell, and C. J. Rodger, 2012: Relative detection efficiency of the World Wide Lightning Location Network. *Radio Sci.*, **47**, RS6005, <https://doi.org/10.1029/2012RS005049>.
- Jayarathne, E. R., and V. Ramachandran, 1998: A five-year study of lightning activity using a CGR3 flash counter in Gaborone, Botswana. *Meteor. Atmos. Phys.*, **66**, 235–241, <https://doi.org/10.1007/BF01026636>.
- Johnson, N., 2019: August 2019 El Niño Update: Stick a fork in it. Climate.gov, www.climate.gov/news-features/blogs/enso/august-2019-el-ni%C3%B1o-update-stick-fork-it.
- Kitagawa, N., 1989: Long-term variations in thunder-day frequencies in Japan. *J. Geophys. Res.*, **94**, 13 183–13 189, <https://doi.org/10.1029/JD094iD11p13183>.
- Knupp, K. R., and W. R. Cotton, 1987: Internal structure of a small mesoscale convective system. *Mon. Wea. Rev.*, **115**, 629–645, [https://doi.org/10.1175/1520-0493\(1987\)115<0629:ISOASM>2.0.CO;2](https://doi.org/10.1175/1520-0493(1987)115<0629:ISOASM>2.0.CO;2).
- Kotroni, V., and K. Lagouvardos, 2016: Lightning in the Mediterranean and its relation with sea-surface temperature. *Environ. Res. Lett.*, **11**, 34006, <https://doi.org/10.1088/1748-9326/11/3/034006>.
- Lapierre, J., M. Stock, and E. A. DiGangi, 2021: Lightning detection network performance for thunderstorms. *10th Conf. on the Meteorological Application of Lightning Data*, Online, Amer. Meteor. Soc., 6.3, <https://ams.confex.com/ams/101ANNUAL/meetingapp.cgi/Paper/383844>.
- Lavigne, T., C. Liu, and N. Liu, 2019: How does the trend in thunder days relate to the variation of lightning flash density? *J. Geophys. Res. Atmos.*, **124**, 4955–4974, <https://doi.org/10.1029/2018JD029920>.
- Lindsey, R., 2016: Global impacts of El Niño and La Niña. Climate.gov, www.climate.gov/news-features/featured-images/global-impacts-el-ni%C3%B1o-and-la-ni%C3%B1a.
- Marchand, M., K. Hilburn, and S. D. Miller, 2019: Geostationary Lightning Mapper and Earth Networks lightning detection over the contiguous United States and dependence on flash characteristics. *J. Geophys. Res. Atmos.*, **124**, 11 552–11 556, <https://doi.org/10.1029/2019JD031039>.
- National Centers for Environmental Information, 2019a: National climate report for June 2019. NCEI, www.ncdc.noaa.gov/sotc/national/201906.
- , 2019b: Global climate report for January 2019. NCEI, www.ncdc.noaa.gov/sotc/global/201901.
- , 2019c: Global climate report for February 2019. NCEI, www.ncdc.noaa.gov/sotc/global/201902.
- , 2019d: Global climate report for August 2019. NCEI, www.ncdc.noaa.gov/sotc/global/201908.

- Negri, A. J., E. N. Anagnostou, and R. F. Adler, 2000: A 10-yr climatology of Amazonian rainfall derived from passive microwave satellite observations. *J. Appl. Meteor.*, **39**, 42–56, [https://doi.org/10.1175/1520-0450\(2000\)039<0042:AYCOAR>2.0.CO;2](https://doi.org/10.1175/1520-0450(2000)039<0042:AYCOAR>2.0.CO;2).
- , T. L. Bell, and L. Xu, 2002: Sampling of the diurnal cycle of precipitation using TRMM. *J. Atmos. Oceanic Technol.*, **19**, 1333–1344, [https://doi.org/10.1175/1520-0426\(2002\)019<1333:SOTDCO>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<1333:SOTDCO>2.0.CO;2).
- NOAA/NWS Weather Forecast Office, 2019a: Severe thunderstorms from June 4, 2019. National Weather Service, www.weather.gov/arx/jun0419.
- , 2019b: Monsoon 2019 review for the Southwest US. National Weather Service, www.weather.gov/psr/SouthwestMonsoon2019Review.
- Peterson, M., 2019: Research applications for the geostationary lightning mapper operational lightning flash data product. *J. Geophys. Res. Atmos.*, **124**, 10 205–10 231, <https://doi.org/10.1029/2019JD031054>.
- , D. Mach, and D. Buechler, 2021: A global LIS/OTD climatology of lightning flash extent density. *J. Geophys. Res. Atmos.*, **126**, e2020JD033885, <https://doi.org/10.1029/2020JD033885>.
- Pinto, O., Jr., 2015: Thunderstorm climatology of Brazil: ENSO and tropical Atlantic connections. *Int. J. Climatol.*, **35**, 871–878, <https://doi.org/10.1002/joc.4022>.
- , I. R. C. A. Pinto, and M. A. S. Ferro, 2013: A study of the long-term variability of thunderstorm days in southeast Brazil. *J. Geophys. Res. Atmos.*, **118**, 5231–5246, <https://doi.org/10.1002/jgrd.50282>.
- Price, C. G., 2013: Lightning applications in weather and climate research. *Surv. Geophys.*, **34**, 755–767, <https://doi.org/10.1007/s10712-012-9218-7>.
- Ramos, A., L. Alves, J. Marengo, R. Luiz, and F. Diniz, 2020: Annual Climate Report of Brazil -2019 Year 02 -Number 02, 2020. Tech. Rep., 10 pp., <https://doi.org/10.13140/RG.2.2.24189.38885>.
- Rehbein, A., T. Ambrizzi, and C. R. Mechoso, 2018: Mesoscale convective systems over the Amazon basin. Part I: Climatological aspects. *Int. J. Climatol.*, **38**, 215–229, <https://doi.org/10.1002/joc.5171>.
- Rodger, C. J., S. Werner, J. Brundell, E. Lay, N. Thomson, R. Holzworth, and R. Dowden, 2006: Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study. *Ann. Geophys.*, **24**, 3197–3214, <https://doi.org/10.5194/angeo-24-3197-2006>.
- , J. B. Brundell, R. H. Holzworth, E. D. Douma, and S. Heckman, 2017: The World Wide Lightning Location Network (WWLLN): Update on new dataset and improved detection efficiencies. *32nd URSI General Assembly and Scientific Symp.*, Montreal, QC, Canada, URSI, EFGH28-1, [www.ursi.org/proceedings/procGA17/papers/Paper_EFGH28-1\(1349\).pdf](http://www.ursi.org/proceedings/procGA17/papers/Paper_EFGH28-1(1349).pdf).
- Romatschke, U., and R. A. Houze, 2010: Extreme summer convection in South America. *J. Climate*, **23**, 3761–3791, <https://doi.org/10.1175/2010JCLI3465.1>.
- Schneider, T., T. Bischoff, and G. H. Haug, 2014: Migrations and dynamics of the intertropical convergence zone. *Nature*, **513**, 45–53, <https://doi.org/10.1038/nature13636>.
- Schott, F. A., and J. P. McCreary Jr., 2001: The monsoon circulation of the Indian Ocean. *Prog. Oceanogr.*, **51**, 1–123, [https://doi.org/10.1016/S0079-6611\(01\)00083-0](https://doi.org/10.1016/S0079-6611(01)00083-0).
- Virts, K. S., and S. J. Goodman, 2020: Prolific lightning and thunderstorm initiation over the Lake Victoria Basin in East Africa. *Mon. Wea. Rev.*, **148**, 1971–1985, <https://doi.org/10.1175/MWR-D-19-0260.1>.
- , J. M. Wallace, M. L. Hutchins, and R. H. Holzworth, 2015: Diurnal and seasonal lightning variability over the Gulf Stream and the Gulf of Mexico. *J. Atmos. Sci.*, **72**, 2657–2665, <https://doi.org/10.1175/JAS-D-14-0233.1>.
- Waliser, D. E., and C. Gautier, 1993: A satellite-derived climatology of the ITCZ. *J. Climate*, **6**, 2162–2174, [https://doi.org/10.1175/1520-0442\(1993\)006<2162:ASDCOT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1993)006<2162:ASDCOT>2.0.CO;2).
- , and X. Jiang, 2015: Tropical meteorology and climate—Intertropical convergence zone. *Encyclopedia of Atmospheric Sciences*, 2nd ed. G. R. North, J. Pyle, and F. Zhang, Eds., Academic Press, 121–131, <https://doi.org/10.1016/B978-0-12-382225-3.00417-5>.
- Whipple, F. J. W., 1929: Potential gradient and atmospheric pollution: The influence of “summer time.” *Quart. J. Roy. Meteor. Soc.*, **55**, 351–362, <https://doi.org/10.1002/qj.49705523206>.
- , and F. J. Scrase, 1936: Point discharge in the electric field of the Earth, an analysis of continuous records obtained at Kew Observatory. H.M. Stationery Office, 20 pp.
- World Meteorological Organization, 1953: World distribution of thunderstorm days. Part 1: Tables. WMO/OMM-21, 204 pp., https://library.wmo.int/doc_num.php?explnum_id=8020.
- Zhang, D., and K. L. Cummins, 2020: Time evolution of satellite-based optical properties in lightning flashes, and its impact on GLM flash detection. *J. Geophys. Res. Atmos.*, **125**, e2019JD032024, <https://doi.org/10.1029/2019JD032024>.