

# Prolific Lightning and Thunderstorm Initiation over the Lake Victoria Basin in East Africa

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## ABSTRACT

The Lake Victoria basin of East Africa is home to over 30 million people, over 200 000 of whom are employed in fishing or transportation on the lake. Approximately 3000–5000 individuals are killed by thunderstorms yearly, primarily by outflow winds and resulting large waves. Prolific lightning activity and thunderstorm initiation in the basin are examined using continuous total lightning observations from the Earth Networks Global Lightning Network (ENGLN) for September 2014–August 2018. Seasonal shifts in the intertropical convergence zone produce semiannual lightning maxima over the lake. Diurnally, solar heating and lake and valley breezes produce daytime lightning maxima north and east of the lake, while at night the peak lightning density propagates southwestward across the lake. Cluster analysis reveals terrain-related thunderstorm initiation hot spots northeast of the lake; clusters also initiate over the lake and northern lowlands. The most prolific clusters initiate between 1100 and 1400 LT, about 1–2 h earlier than the average cluster. Most daytime thunderstorms dissipate without reaching Lake Victoria, and annually 85% of clusters producing over 1000 flashes over Lake Victoria initiate in situ. Initiation times of prolific Lake Victoria clusters exhibit a bimodal seasonal cycle: equinox-season thunderstorms initiate most frequently between 2200 and 0400 LT, while solstice-season thunderstorms initiate most frequently from 0500 to 0800 LT, more than 12 h after the afternoon convective peak over land. More extreme clusters are more likely to have formed over land and propagated over the lake, including 36 of the 100 most extreme Lake Victoria thunderstorms. These mesoscale clusters are most common during February–April and October–November.

## 1. Introduction

With a surface area of approximately 68 800 km<sup>2</sup>, Lake Victoria is the world's largest tropical lake. The lake is located in a broad basin between the western branch of the East African Rift (or Albertine Rift) and

the eastern branch of the East African Rift (or Gregory Rift). This basin is home to over 30 million people, over 200 000 of whom are employed in the fishing or transportation industries that operate on the lake. It is estimated that 3000–5000 of these individuals are killed by thunderstorms each year, primarily by outflow winds and resulting large waves (Semazzi 2011; Cannon et al. 2014). This human cost has motivated recent efforts to improve the understanding and prediction of thunderstorms that impact the lake. Recent high-resolution modeling of the Lake Victoria basin has improved skill over the global models in identifying the 24-h periods in which thunderstorms will occur; however, these models need improvement in the diurnal timing of storms and precipitation, and produce too many false alarms (Chamberlain et al. 2014; Woodhams et al. 2018), suggesting that greater understanding of convective initiation and development in this region is needed.

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As is frequently the case in convectively active regions of the tropics, climatological thunderstorm occurrence over Lake Victoria and adjacent lands is dominated by diurnally varying wind regimes driven by the diurnal cycle in low-level heating (Kikuchi and Wang 2008; Venugopal et al. 2016; for a full description of these wind regimes see chapter 14 of Stull 1988). Land surfaces have a smaller heat capacity than water and thus warm more rapidly on sunny days and cool more rapidly at night compared to the lake (see the online supplemental material). These temperature contrasts lead to pressure gradients along the coastline and the development of lake breezes, ascent over adjacent land areas, and the associated subsiding branch of the circulation over the lake during the afternoon. Elevated heating of the terrain to the east of the lake, including the Kenyan Highlands and Cherang'any Hills, leads to upslope valley breezes that serve to draw the lake-breeze front farther inland (Anyah et al. 2006; Thiery et al. 2015; Woodhams et al. 2019). At night, analogous land-breeze circulations develop, enhanced by mountain breezes (katabatic winds) from the terrain to the east.

The impact of the diurnally varying circulations on weather in this region has been documented using observations of cloud occurrence (Ba and Nicholson 1998; Laing et al. 2011; Chamberlain et al. 2014), including overshooting tops (Thiery et al. 2016), as well as lightning (Virts et al. 2013; Cecil et al. 2015; Albrecht et al. 2016a; Holle and Murphy 2017), precipitation (Kikuchi and Wang 2008), and regional models (Anyah et al. 2006; Thiery et al. 2015; Williams et al. 2015; Woodhams et al. 2019). Solar heating and the associated lake and valley breezes lead to an afternoon maximum in deep moist convection over land, with lightning peaking around 1300–1600 LT lagged by precipitation around 1500–1800 LT. At night, a deep convective maximum shifts from northeast to southwest over the lake, frequently including upscale growth into mesoscale convective systems (MCSs; Jackson et al. 2009), and lightning density over the lake peaks shortly after sunrise (0700–0800 LT). These nocturnal thunderstorms are of particular interest because they endanger individuals in the fishing industry, who operate on the lake primarily at night (Semazzi 2011; Cannon et al. 2014).

The observational studies of diurnal convective variability over Lake Victoria cited in the previous paragraph have generally focused not on the full thunderstorm life cycle but, rather, on the peak timing (i.e., when the coldest cloud tops, most frequent lightning, or highest rain rates are observed), or the spatial patterns of these quantities throughout the diurnal cycle. Little is known about the initiation of intense thunderstorms over Lake Victoria and the surrounding region, including such basic

information as the preferred locations and times for initiation. The convergence of land and mountain breezes combined with the conditionally unstable atmosphere over the warm lake surface has often been suggested as a mechanism for initiating and/or sustaining nocturnal thunderstorms. As noted by Anyah et al. (2006) and Holle and Murphy (2017), land breezes are generally weaker than their sea- or lake-breeze counterparts, although modeling work by Thiery et al. (2016) found that cold pools produced by intense daytime storms over land increased the nighttime land–lake temperature gradient, thus strengthening land breezes and moisture convergence over Lake Victoria. Other suggested initiation mechanisms include outflow boundaries and gravity waves from the daytime deep moist convection over land, or persistence and upscale growth of land-initiated convection that then propagates directly from the Kenyan Highlands southwest over the lake (Thiery et al. 2016; Holle and Murphy 2017).

This knowledge gap regarding the initiation of prolific Lake Victoria thunderstorms reflects an observational gap: long, continuous observational records of atmospheric conditions and storm structure are lacking in this region. Dual-polarimetric Doppler radars, a key observation component for thunderstorm nowcasting, are located along the northern (Entebbe, Uganda) and southern coasts of Lake Victoria (Mwanza, Tanzania) and to the southwest near Kigali, Rwanda. Archives of the radar volume scans are not available for the period analyzed in this paper, although a recent case study by Waniha et al. (2019) using the Mwanza radar emphasized the role of gust fronts and other preexisting boundaries in initiating new convective storms over the lake. Precipitation radars aboard the Tropical Rainfall Measuring Mission (TRMM; Kawanishi et al. 2000) and Global Precipitation Measurement (GPM; Skofronick-Jackson et al. 2017) satellites and Lightning Imaging Sensors on board TRMM (TRMM-LIS; Christian et al. 1999) and the International Space Station (ISS-LIS; Blakeslee et al. 2014) have proved useful for process studies and in characterizing deep moist convection; however, these sensors only observe the region for 90 s or less during sporadic overpasses and thus do not observe the full convective life cycle. Continuous observations of primarily cloud-to-ground (CG) lightning from the ground-based World Wide Lightning Location Network (WWLLN; Rodger et al. 2006) and Global Lightning Dataset (GLD360; Mallick et al. 2014) are available and have been used by Virts et al. (2013) and Holle and Murphy (2017), respectively, to examine the climatological-mean diurnal cycle of lightning occurrence over the Lake Victoria basin. However, neither study examined the total lightning activity

[CG + intracloud (IC)] or tracked the initiation and subsequent evolution of individual convective storms.

Beginning in 2014, Earth Networks (EN) has established a network of lightning sensors around Lake Victoria, providing the first opportunity to examine continuous observations of total lightning in this region. This paper examines the lightning climatology of the Lake Victoria basin, comparing the patterns of lightning variability observed by the EN's Global Lightning Network (ENGLN; [Earth Networks 2014](#)) with previous observations from other networks and sensors. We then leverage the continuous observations of total lightning available from ENGLN to analyze individual lightning clusters, with a focus on the seasonal and diurnal variations in the initiation of prolific, high-impact thunderstorms over Lake Victoria and the surrounding region. Lightning in these storms represents both a direct danger to the local population as well as an indicator of storm depth and updraft intensity ([Cecil 2005](#); [Deierling and Petersen 2008](#)) that relate to the other threats such as storm outflow gusts, wind-driven waves, and hail ([Williams et al. 1989, 1999](#)). Improved understanding of the initiation of these storms will help improve nowcasting efforts that will benefit the millions of stakeholders in the basin given the storms and storm-driven waves on the lake that cause significant loss of life in the fishing and transportation industries.

## 2. Data and methodology

EN employs a network of sensors that detect low-frequency–high-frequency radiation produced by lightning (1 Hz to 12 MHz; [Liu and Heckman 2012](#)). The time of arrival (TOA) technique is applied to the detected waveforms from multiple sensors in order to locate individual lightning strokes in time and space. The broad frequency range enables detection of total lightning, both strong CG strokes as well as weaker IC pulses. Globally, dense networks of EN sensors are located in regions such as the United States and Brazil. Beginning in 2014, a network of over 15 EN sensors was placed around Lake Victoria, with the greatest concentration in Uganda and western Kenya. For the ENGLN dataset, stroke and pulse data from all EN sensors are combined with WWLLN stroke data to increase the global coverage; the strokes and pulses are then grouped into flashes using spatial and temporal clustering criteria of 10 km and 0.7 s (M. Stock 2019, personal communication). In this study, ENGLN data in the Lake Victoria region are analyzed for the period September 2014–August 2018, for a total of approximately 125 million flashes. In addition to the flash location and time of the largest stroke or pulse, ENGLN also reports the flash type (CG or IC) and the peak current in kA. ENGLN performance is assessed in [Thompson](#)

[et al. \(2014\)](#) and [Rudlosky \(2015\)](#), and a direct comparison of ENGLN with ISS-LIS reported lightning in the Lake Victoria region is in the supplemental material.

For this study, ENGLN flash data are used to generate annual-mean, monthly, and hourly lightning density climatologies at  $0.04^\circ \times 0.04^\circ$  resolution, or roughly the same as the 4-km resolution that has been used in daily model forecasts over the Lake Victoria basin ([Chamberlain et al. 2014](#)). No interpolation is applied to these climatologies. In addition, in order to examine the initiation and attributes of individual thunderstorms, ENGLN flashes are clustered into thunderstorms using a weighted Euclidean distance method patterned after [Mach et al. \(2007\)](#):

$$\text{WED}^2 = \left(\frac{D}{10}\right)^2 + \left(\frac{T}{600}\right)^2, \quad (1)$$

where  $D$  is the distance between two flashes in km and  $T$  is the time between them in seconds. Two flashes are assigned to the same thunderstorm cluster if  $\text{WED} < 1$ . The choice of 10 km and 600 s (i.e., 10 min) for clustering criteria is somewhat arbitrary, although they are close to the 16.5 km spatial window used to cluster LIS and OTD flashes into storm-sized “areas” ([Mach et al. 2007](#)) and the  $0.12^\circ$  and 18-min parameters employed in the clustering of WWLLN strokes into thunderstorms ([Hutchins et al. 2014](#)). As a sensitivity test, ENGLN flashes were also clustered into thunderstorms using values of 30 km and 1800 s (i.e., 30 min) in the denominators of Eq. (1). The results shown in this paper were qualitatively similar for both sets of clustering criteria. For each cluster, variables were recorded including the location and time of the first flash, the total number of flashes in the cluster, and the number of flashes over Lake Victoria (i.e., within the polygon shown in [Fig. 1](#)).

TRMM-LIS operated in low-Earth orbit over the tropics from 1998 to 2015. [Albrecht et al. \(2016a\)](#) describe a  $0.1^\circ$  resolution global climatology based on LIS observations of total lightning ([Albrecht et al. 2016b](#)), which we use for comparison with the ENGLN climatology.

The Integrated Surface Database (ISD; [National Centers for Environmental Information 2003](#); [Lott et al. 2008](#)) includes records from over 35 000 surface observation stations worldwide. The quality controls applied to the station data are described in [Lott \(2004\)](#). From this database, four stations with frequent and regular observations were identified near Lake Victoria ([Table 1](#)). At least 16 000 observations were available from each station during the September 2014–August 2018 analysis period, and these observations were evenly distributed throughout the day and night. The reported data include wind speed and direction; wind gust velocities are not reported.

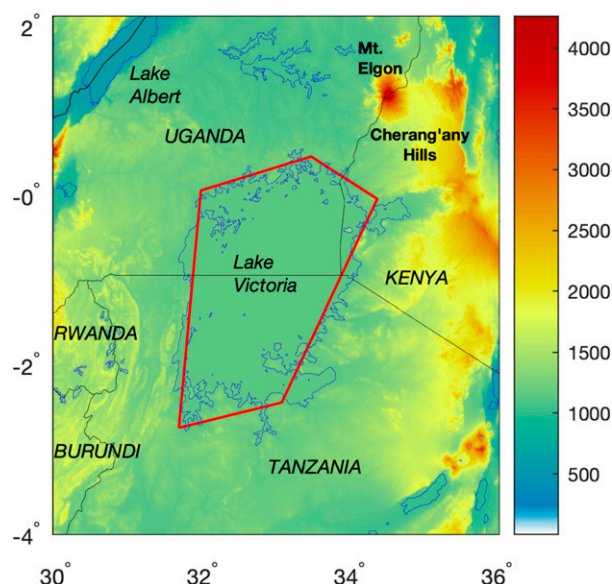


FIG. 1. Elevation (m) of the Lake Victoria domain. Thick red lines outline the “lake” polygon.

The large-scale weather patterns associated with prolific lightning occurrence in this region are represented by data from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5; [ECMWF 2017](#)), which is available hourly at  $0.25^\circ$  (or about 28 km) resolution in latitude and longitude.

### 3. Climatological lightning density

In the annual mean ([Fig. 2a](#)), lightning in this region is most frequent over Lake Victoria, over a broad plain to the north of the lake, and to the east between the lake and the highlands of the Eastern Rift. Thunderstorms are an almost daily occurrence over the lake: at least one flash was reported in the Lake Victoria polygon ([Fig. 1](#)) on 95% of the days in the study period, with at least one CG flash on 93% of the days. At least 100 flashes were observed over the lake on 89% of the days. Compared to Lake Victoria, lightning densities are one to two orders of magnitude lower to the west of the lake and over the lower-elevation areas at the eastern edge of the domain. Local minima are also observed over Mount Elgon near the Uganda–Kenya border, and along the eastern shore of Lake Victoria. Each of these features is also evident in the TRMM-LIS climatology ([Fig. 2b](#)), including the absolute maximum in lightning density near the center of Lake Victoria. The mean ENGLN flash density over the Lake Victoria polygon is  $183 \text{ flashes km}^{-2} \text{ yr}^{-1}$ , almost seven times higher than TRMM-LIS and an order of magnitude higher than the GLD360 stroke density for the lake reported by [Holle and Murphy \(2017\)](#), illustrating

TABLE 1. Name and location of surface observing stations around Lake Victoria, with the total number of observations during the September 2014–August 2018 analysis period.

| Name                                  | Latitude | Longitude | No. of observations |
|---------------------------------------|----------|-----------|---------------------|
| Bukoba, Tanzania                      | 1.333°S  | 31.817°E  | 17 657              |
| Entebbe International Airport, Uganda | 0.042°N  | 33.444°E  | 25 331              |
| Mwanza, Tanzania                      | 2.444°S  | 32.933°E  | 17 160              |
| Musoma, Tanzania                      | 1.500°S  | 33.800°E  | 16 195              |

the sensitivity of the high-density sensor network around the lake. The most notable spatial difference between the ENGLN and TRMM-LIS climatologies occurs near Lake Albert in the northwestern corner of the domain and over the lowlands south of the lake, where fewer ENGLN sensors are located and TRMM-LIS observes proportionally more lightning than does ENGLN. Note that the domain does not include the eastern Congo, where [Albrecht et al. \(2016a\)](#) identified the world’s second-leading lightning hot spot.

For the Lake Victoria domain as a whole, 93.4% of the ENGLN-reported lightning flashes are IC. Of the remaining 6.6% that are CG flashes, 94.9% lowered negative charge to ground. The Z ratio (IC:CG) of 14.1 reported by ENGLN for this region is higher than the 3.53 estimated globally by [Mackerras et al. \(1998\)](#), although high Z ratios have also been reported in severe thunderstorms over the U.S. Great Plains (e.g., [McCaul et al. 2002](#); [Lang and Rutledge 2002](#)). The distributions of flash type and polarity are shown in [Figs. 2c–f](#). Each resembles the total lightning climatology, although the proportion of CG flashes increases toward the southwest corner of the domain (not shown), where the network of sensors is less dense. The proportion of CG flashes is also enhanced by a factor of approximately 2–3 over Mount Elgon compared to the surrounding lowlands.

Seasonal variations in the lightning density ([Fig. 3](#); see also a monthly animation in the supplemental material) reflect the latitudinal shift of peak solar heating and the associated equatorial trough and intertropical convergence zone (ITCZ). While, as noted above, thunderstorms are an almost daily occurrence over Lake Victoria, the lightning density over the lake is largest during the equinox seasons of March–May (MAM; the “long rains”) and September–November (SON; the “short rains”). During these seasons the mean lightning density over the lake (represented by the polygon in [Fig. 1](#)) is 212 and 215  $\text{flashes km}^{-2} \text{ yr}^{-1}$ , respectively, compared to 164 and 126  $\text{flashes km}^{-2} \text{ yr}^{-1}$  during the solstice seasons of December–February (DJF) and June–August (JJA). The greatest contrast between lake and land occurs during DJF, when the

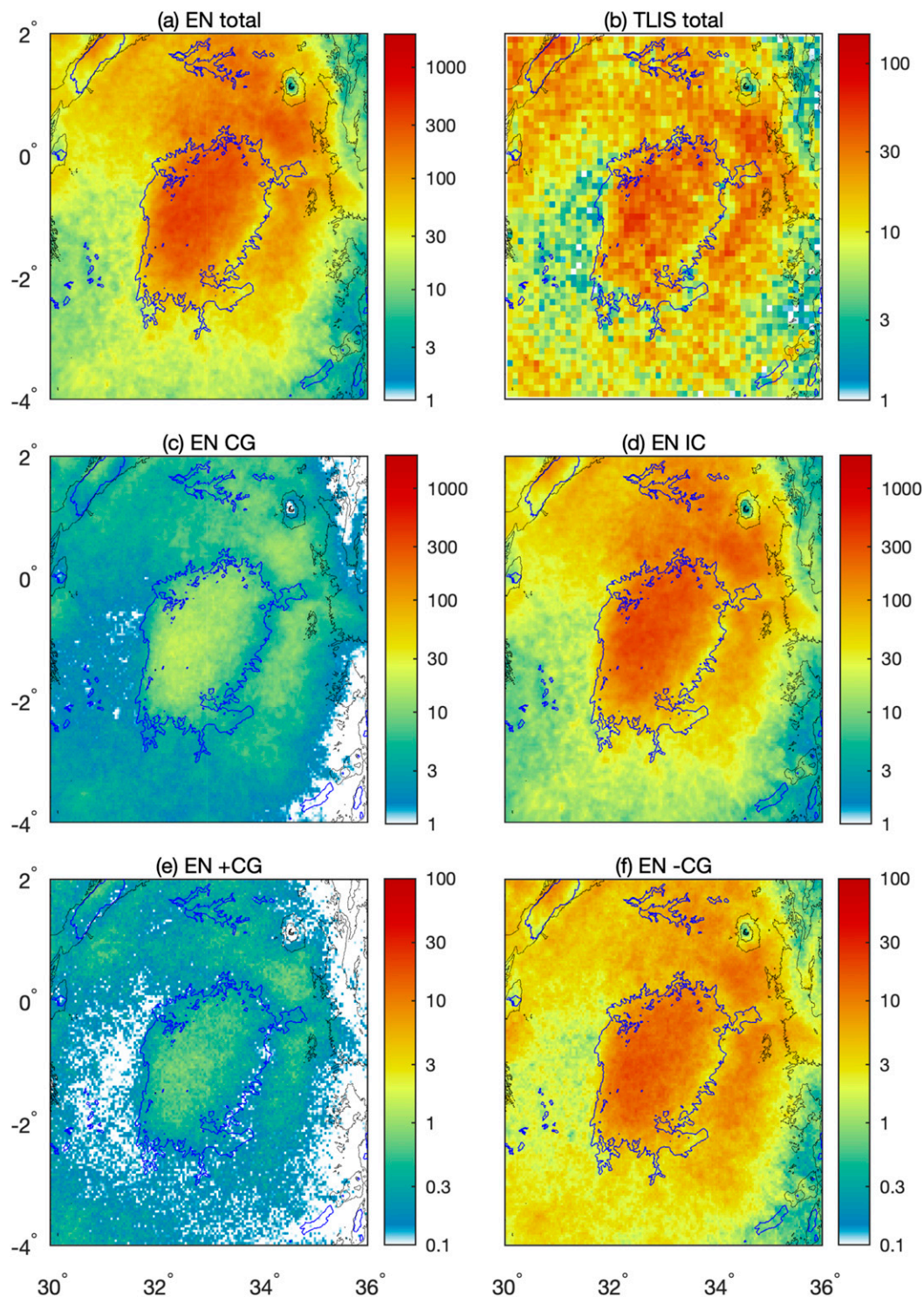


FIG. 2. Annual-mean density ( $\text{flashes km}^{-2} \text{yr}^{-1}$ ) of (a) ENGLN total lightning, (b) TRMM-LIS total lightning, (c) ENGLN CG lightning, (d) ENGLN IC lightning, (e) ENGLN +CG lightning, and (f) ENGLN -CG lightning. Elevation contours at 1000-m intervals are in black. ENGLN lightning data are for the period September 2014–August 2018.

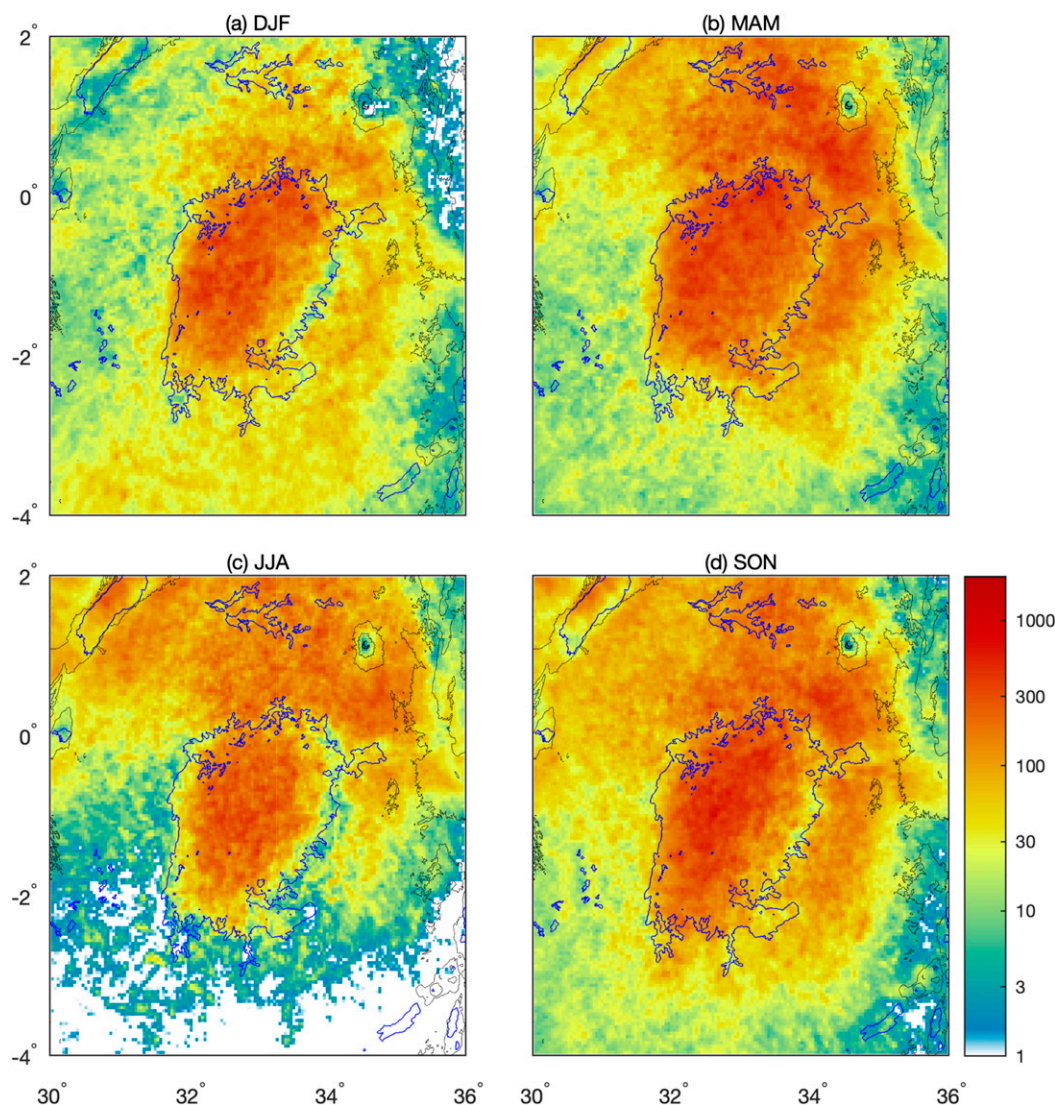


FIG. 3. ENGLN seasonal-mean lightning density (flashes  $\text{km}^{-2} \text{yr}^{-1}$ ) during (a) December–February (DJF), (b) March–May (MAM), (c) June–August (JJA), and (d) September–November (SON). Elevation contours at 1000-m intervals are in black. A monthly animation is available in the supplemental material. Lightning data are for the period September 2014–August 2018.

mean lightning density over the lake is more than 5 times larger than over land (i.e., the area external to the polygon in Fig. 1).

The diurnal cycle of lightning in this region is shown in an hourly animation in the supplemental material and is summarized in Fig. 4, while Fig. 5 uses wind roses, or the observed frequency of wind speed as a function of wind direction, to summarize diurnal surface wind variability at four sites around the lake. Lake breezes dominate the daytime wind roses (note that while Mwanza is on the south side of Lake Victoria, the local coastline is to the northwest of the station location, such that the northwesterly winds reported during the day are approximately

perpendicular to the local coastline). The strongest daytime winds on average are on the eastern side of the lake where lake breezes combine with valley breezes directed toward the slopes of the Eastern Rift. The combination of increased instability due to solar heating along with convergence due to these daytime circulations promotes thunderstorm formation over the land surrounding Lake Victoria (Fig. 4a), particularly to the north and east of the lake, where lightning densities peak at an equivalent of more than 1000 flashes  $\text{km}^{-2} \text{yr}^{-1}$  between the lake and Mount Elgon. An afternoon maximum is observed over all land areas except the strip of land immediately west of the lake (Fig. 6). During this period, Lakes Victoria and Albert

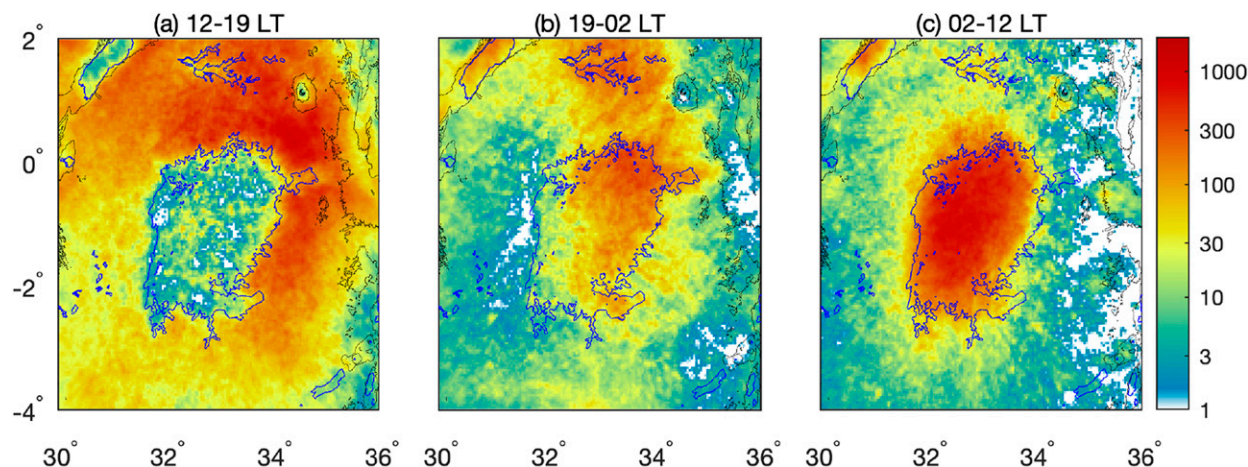


FIG. 4. Diurnal summary of ENGLN lightning density (flashes  $\text{km}^{-2} \text{yr}^{-1}$ ) during (a) daytime (1200–1900 LT), (b) evening and early night (1900–0200 LT), and (c) night and morning (0200–1200 LT). Elevation contours at 1000-m intervals are in black. An hourly animation is available in the supplemental material. Lightning data are for the period September 2014–August 2018.

to the northwest experience the subsiding branch of the lake-breeze circulations and daily minimum lightning.

By evening and early night, the lightning maximum has shifted to northeastern Lake Victoria (Fig. 4b), although storms also linger over the plain to the north of the lake. At night, the development of land-breeze and mountain-breeze circulations produces lakeward winds at each surface station around Lake Victoria (Fig. 5). However, as previously noted by Mapes et al. (2003) and Anyah et al. (2006), land breezes typically have weaker velocities than sea or lake breezes. For Bukoba and Entebbe to the west and north of the lake, nighttime wind speeds are 30%–50% weaker than during the day, and an even greater diurnal contrast is observed between the combined lake/valley and land/mountain breezes at Musoma on the eastern shore of the lake. Hourly analysis (see the supplemental material) indicates that wind speeds tend to increase slowly through the night and early morning prior to the shift back to landward breezes. The lightning maximum over Lake Victoria shifts from northeast to southwest during the night (Figs. 4c, 6; see also the supplemental material), with peak lightning densities equating to about  $1000 \text{ flashes km}^{-2} \text{yr}^{-1}$  over the west-central lake. A secondary lightning maximum is observed over Lake Albert during the evening and night. The spatial pattern and timing of the diurnal cycle of lightning as observed by ENGLN closely agrees with previous analysis based on GLD360 data (Holle and Murphy 2017), while the maximum precipitation and coldest cloud tops lag the lightning maximum by several hours (Chamberlain et al. 2014; Williams et al. 2015). The observed diurnal coupling of surface winds and lightning occurrence near Lake Victoria suggests that the wind speed and direction may be useful in predicting

afternoon lightning onset and high-risk situations, in a manner similar to lightning prediction schemes used in other locations where sea breezes force strong diurnal variability, such as Florida (Watson et al. 1987; Lericos et al. 2002; Shafer and Fuelberg 2006).

While density maps such as Figs. 2–4 are useful in understanding and summarizing the major patterns of lightning variability in this region, they also necessarily smooth out the finer-scale characteristics of individual storms that are important for nowcasting and short-term forecasting. Hot spots on a density map indicate where storms tend to reach their greatest lightning production and are thus useful for public risk assessment; however, such maps contain limited information about where the storms initially formed. Previous studies of this region (see section 1) have not analyzed whether, for example, the nocturnal thunderstorms over Lake Victoria typically initiate over land and subsequently propagate southwest over the lake, or whether they form in situ over the lake due to one of the mechanisms discussed in section 1. For this reason, it will be instructive to examine individual thunderstorms as represented by the ENGLN lightning clusters described in section 2.

#### 4. Thunderstorm initiation

The initiation locations of clusters that eventually produced  $>10$  or  $>1000$  flashes during their lifetime are shown in Figs. 7a and 7b, respectively. A prominent maximum occurs over the steep western slopes of Mount Elgon, with additional maxima along the slopes of the valley that extends northeast from Winam Gulf at the northeast corner of Lake Victoria, and over other terrain to the east and northeast of the lake (cf. with Fig. 1).

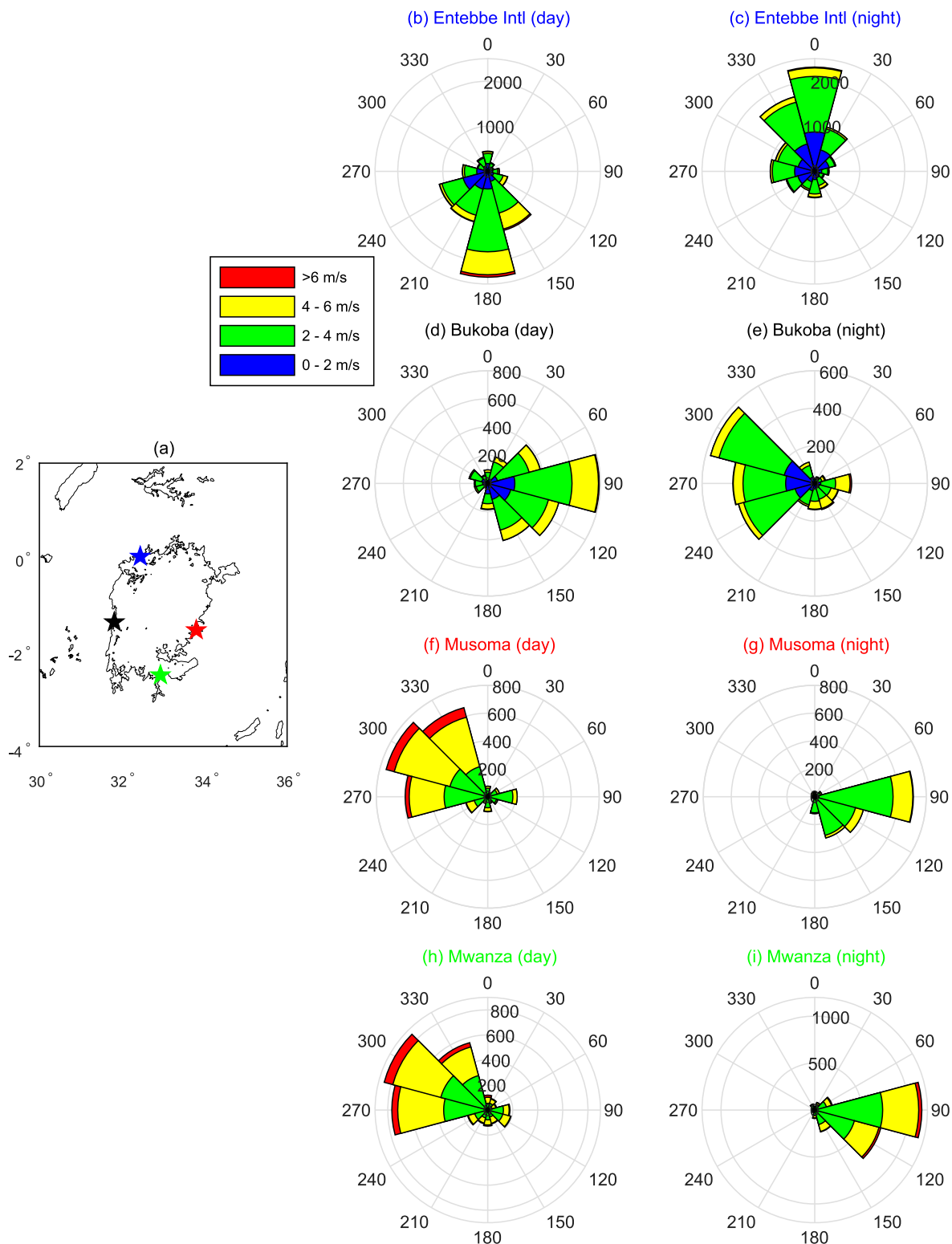


FIG. 5. (a) Location of four surface stations around Lake Victoria. (middle) Daytime and (right) nighttime wind roses from each station: (b),(c) Entebbe International Airport, Uganda, (d),(e) Bukoba, Tanzania, (f),(g) Musoma, Tanzania, and (h),(i) Mwanza, Tanzania (note that the local coastline is to the northwest of this station). Analysis periods are 1000–2000 LT (daytime) and 2200–0800 LT (nighttime). The color of the panel title text matches the color of the observation site in (a).

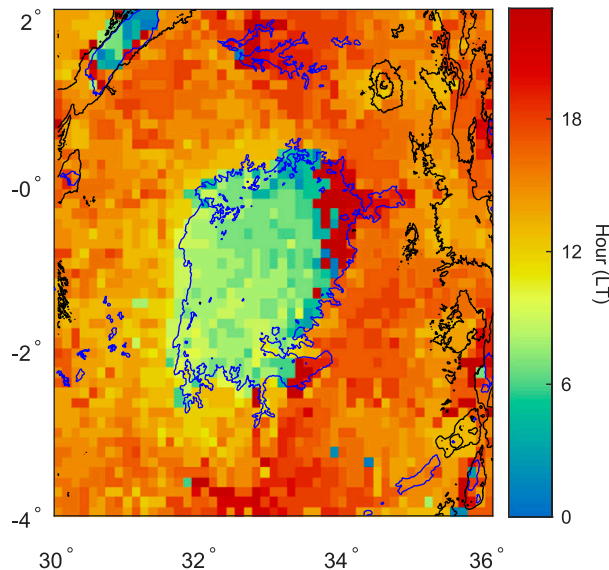


FIG. 6. Time of day (LT) of peak lightning occurrence at each location. Elevation contours at 1000-m intervals are in black. Lightning data are for the period September 2014–August 2018.

These terrain-related maxima reinforce the importance of daytime valley-breeze circulations in aiding in the development of deep moist convection in this region. Cluster initiation also frequently occurs over the broad plain north of the lake and over the lake itself, while minima are observed west and south of the lake.

Figure 7c shows the initiation locations for the subset of clusters that was most prolific over Lake Victoria, eventually producing >1000 flashes over the lake (i.e., within the polygon shown in Fig. 1). The vast majority (84.8%) of such clusters initiated in situ over the lake. Those clusters that did initiate over land formed mainly to the immediate north and northeast of the lake. The terrain-related maxima evident in panels a and b are absent here; while animations of lightning occurrence indicate that terrain-induced clusters often propagate with a southward or westward component toward the lake, they generally dissipate before reaching the lake (see the supplemental material).

Seasonal and diurnal variability in cluster initiation are shown in Fig. 8. Clusters producing >10 flashes initiate most frequently between 1300 and 1500 LT, around the time the lake and valley breezes reach their maximum amplitude and just prior to the peak lightning occurrence over land from 1400 to 1800 LT (Fig. 6; Holle and Murphy 2017). The October/November peak period exhibits a slight tendency for earlier initiation compared with the rest of the year. Thunderstorm initiation during the evening and early night hours (2000–0300 LT) is most frequent during March–May. For the subset of

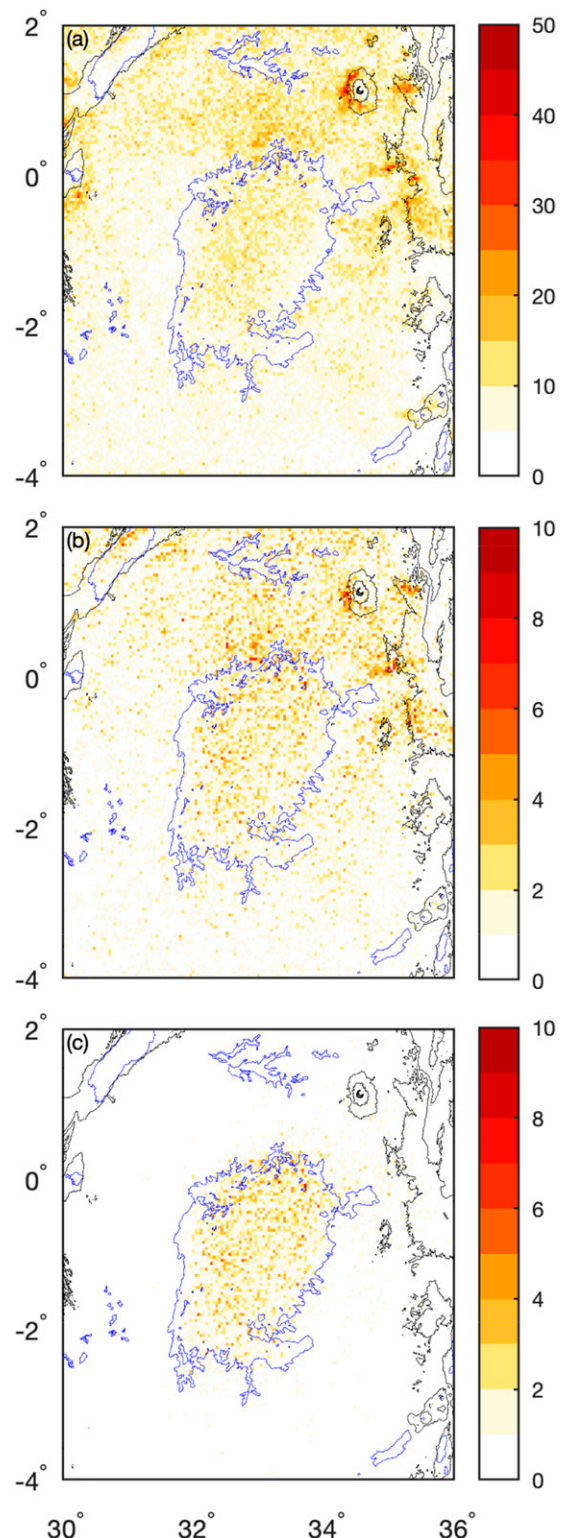


FIG. 7. Location of first flash of lightning clusters producing (a) more than 10 flashes during their lifetime, (b) more than 1000 flashes during their lifetime, and (c) more than 1000 flashes over Lake Victoria. Elevation contours at 1000-m intervals are in black. For the location of Mt. Elgon, see Fig. 1. Lightning data are for the period September 2014–August 2018.

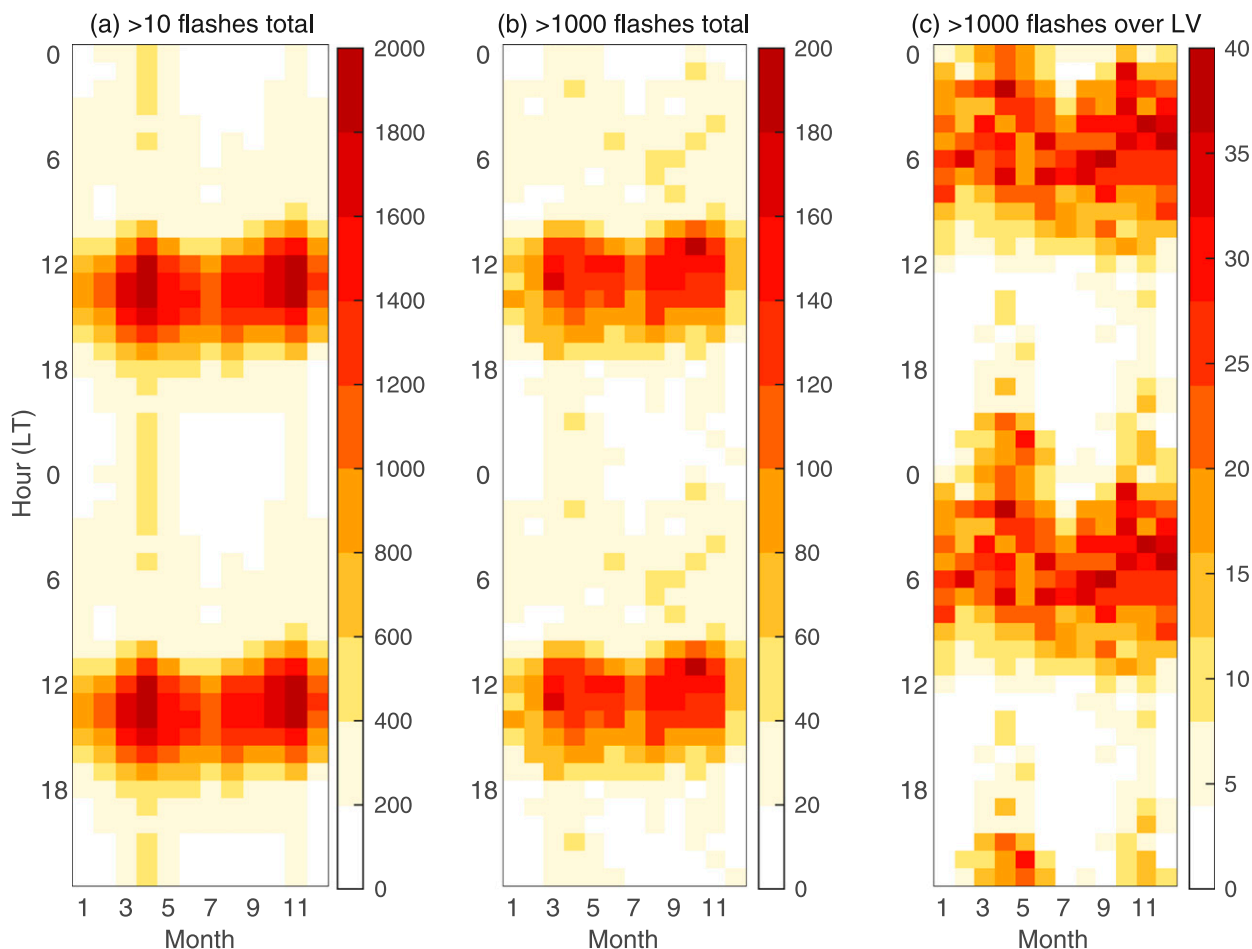


FIG. 8. Histograms of the month (abscissa) and local time (ordinate) of the first flash of lightning clusters producing (a) more than 10 flashes during their lifetime, (b) more than 1000 flashes during their lifetime, and (c) more than 1000 flashes over Lake Victoria. The diurnal cycle is repeated for clarity. Lightning data are for the period September 2014–August 2018.

more prolific clusters producing  $>1000$  flashes (Fig. 8b), initiation tends to occur 1–2 h earlier, peaking around 1100–1400 LT.

A quite different pattern emerges when considering only clusters that produced  $>1000$  flashes over Lake Victoria (Fig. 8c). While peak initiation times for clusters over land vary by only 2–4 h throughout the year, a strong, bimodal seasonal cycle is observed for prolific Lake Victoria clusters. During the solstice seasons, these clusters initiate almost exclusively between midnight and noon, with peak initiation times of 0500–0800 LT (i.e., about 12 h after the afternoon peak in deep moist convection). A lightning animation for the sample month of January 2018 (see the supplemental material) reveals multiple instances of nocturnal deep moist convection developing in situ, without any obvious connection to previous land-based convection, while other instances suggest a possible connection with predecessor storms over land. In contrast, during the equinox seasons when

lightning is more frequent over the lake, a greater range of initiation times is observed, from early evening continuing through the night and morning. The hour of peak initiation during these months ranges from 2200 to 0400 LT. The increase in cluster initiations during the evening and early night hours suggests that some may be triggered by outflow boundaries or gravity waves propagating away from decaying convection over land, or that land-originating deep moist convection undergoing a lull in lightning production may be reinvigorated by the warm lake waters and land breezes (see March 2018 animation in the supplemental material). Further investigation of the roles of convective outflow and land and valley breezes requires radar, satellite, or environmental wind and temperature observations that are unavailable for this period.

To further examine seasonal variations in the character of Lake Victoria thunderstorms, Fig. 9a shows the percentage of flashes over the lake during each month that were produced by clusters initiating over the lake.

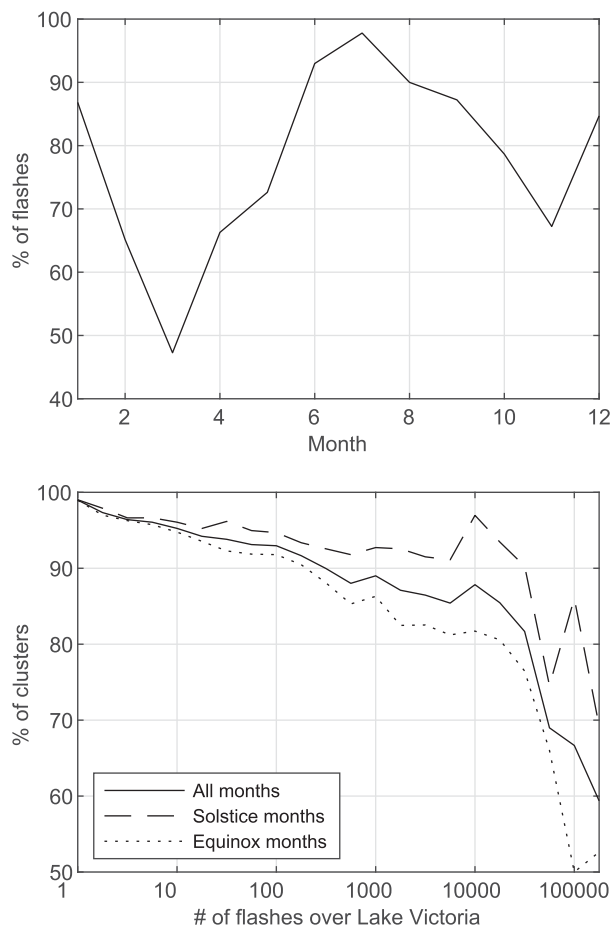


FIG. 9. (a) Monthly percentage of flashes over Lake Victoria that were produced by clusters initiating over Lake Victoria. (b) For bins based on the number of flashes that clusters produced over Lake Victoria (abscissa), the percentage of clusters in each bin that initiated over Lake Victoria (ordinate). Statistic is shown for all months, solstice months (DJF and JJA), and equinox months (MAM and SON). Lightning data are for the period September 2014–August 2018.

These values range as high as 80%–95% during the solstice seasons. In contrast, during February–April fewer than 70% of flashes over the lake were produced by clusters initiating there, including the month of March during which over half of Lake Victoria lightning was produced by clusters initiating over land. A secondary minimum occurred during October–November.

These observations suggest further examination of the statistic, presented earlier in this section, that about 85% of prolific Lake Victoria lightning clusters initiate in situ over the lake. The percentage of clusters initiating over Lake Victoria is shown in Fig. 9b as a function of the number of flashes the clusters produced over the lake. Clusters producing 10 or fewer flashes over the lake initiated almost exclusively over the lake (>98%). This

percentage decreases as the flash count increases, to 88% for the 10 000-flash bin. For even more prolific storms, the decrease becomes even steeper, and of the 100 most extreme lightning-producing clusters (i.e., those producing >85 000 flashes over the lake), 64 initiated over the lake and 36 over land, primarily to the north and east of the lake. This trend occurs during all seasons but is even more marked during the equinox months, when approximately 50% of the most extreme Lake Victoria clusters initiated over land.

The broad environmental conditions associated with the 100 most extreme clusters over Lake Victoria are represented in Fig. 10 by ERA5 composites three hours prior to cluster initiation. Maximum CAPE and low-level moisture are centered over the lake, supporting vigorous deep moist convection, and similar to the environment modeled by Woodhams et al. (2019) for an intense equinox-season storm. A broad trough extends from the lake northward, with low-level winds converging over the lake. Compared with the climatology for that month and hour, CAPE and low-level moisture are enhanced over the basin, with a CAPE maximum directly over the lake. An anomalous pressure gradient is observed approximately from west to east, and 850-hPa winds throughout the region have an anomalously westerly component, indicating enhanced convergence over and east of the lake. The midlevel (500-hPa) winds are easterly over the basin but do not statistically differ from the climatological-mean, and deep-layer shear anomalies over the lake are small. Thus, extreme Lake Victoria lightning clusters form in an unstable environment with enhanced low-level moisture and large-scale low-level convergence. Local processes not resolved in a reanalysis dataset, such as outflow boundaries (Waniha et al. 2019) or converging nocturnal land and mountain breezes, likely also aid in initiating these extreme clusters.

## 5. Conclusions

Previous studies of lightning occurrence for the Lake Victoria region in East Africa, discussed in section 1, have been limited to observations of mainly CG flashes (if using the ground-based networks GLD360 or WWLLN) or to snapshots of total lightning from thunderstorms observed by satellites in low-Earth orbit (e.g., TRMM-LIS). New, continuous total lightning observations by ENGLN permit our analysis of climatological lightning occurrence and the initiation of high-profile, prolific thunderstorms in this region.

Annually, the highest total lightning density in this region (about 450 flashes  $\text{km}^{-2}\text{yr}^{-1}$ ) is over Lake Victoria, where thunderstorms are an almost daily occurrence (Fig. 2). Lightning also frequently occurs over

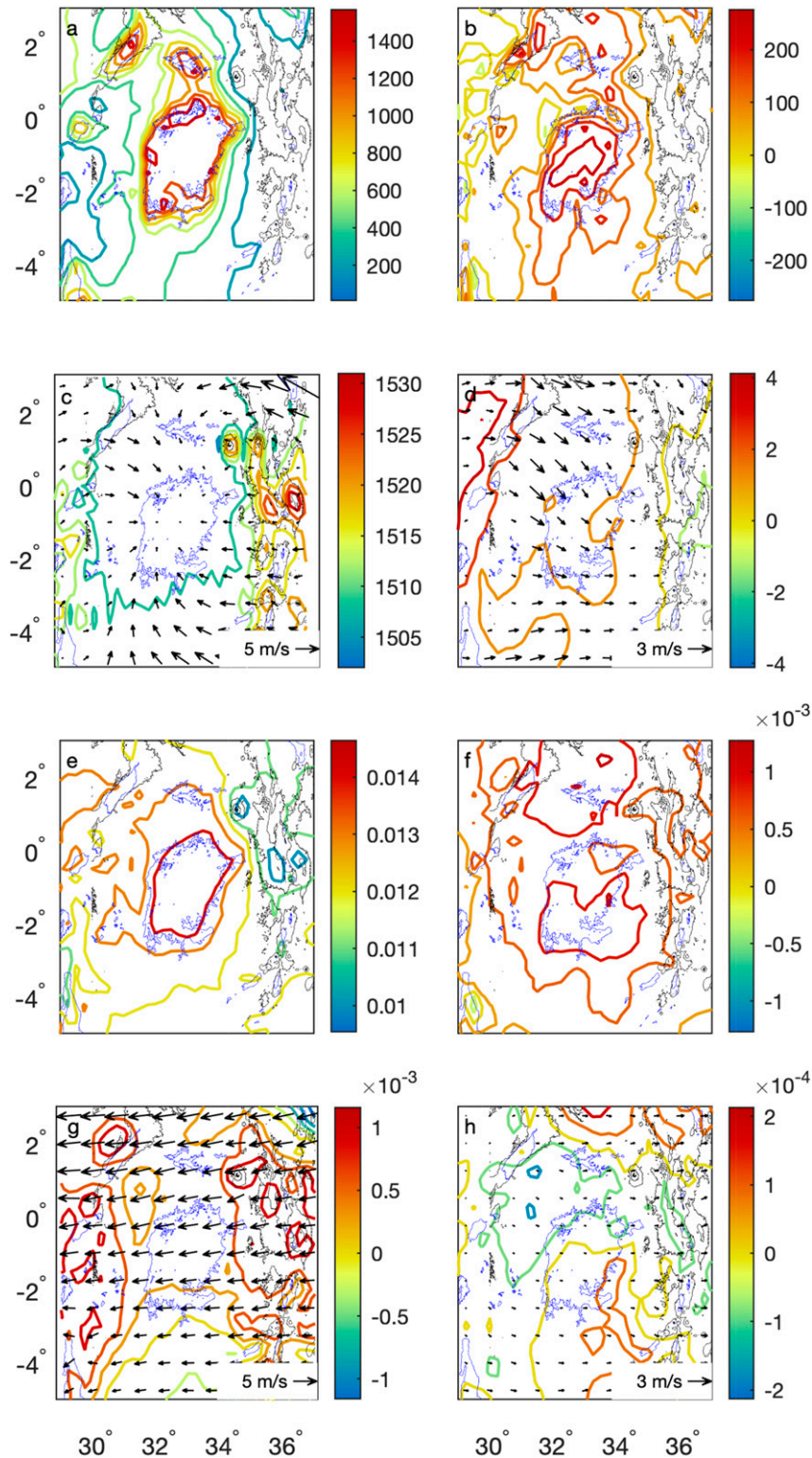


FIG. 10. (a) Composite and (b) anomalous ERA5 CAPE ( $\text{J kg}^{-1}$ ) three hours prior to the initiation of the 100 most extreme Lake Victoria lightning clusters. (c),(d) As in (a),(b), but for 850-hPa geopotential height (m; colored contours) and winds ( $\text{m s}^{-1}$ ; vectors). (e),(f) As in (a),(b), but for 850-hPa specific humidity. (g),(h) As in (a),(b), but for 500-hPa winds ( $\text{m s}^{-1}$ ; vectors) and shear in the 850–500-hPa layer ( $\text{s}^{-1}$ ; colored contours). Anomalies were obtained by subtracting the climatological monthly mean for that hour. Elevation contours at 1000-m intervals are in black.

the plain north of the lake and between the lake and the higher terrain of the Eastern Rift and Mount Elgon near the Uganda–Kenya border. The annual cycle of lightning is dominated by seasonal shifts in the latitude of the equatorial trough and ITCZ, with peak lightning over the lake during the equinox seasons when the sun is most directly overhead (Fig. 3).

As the largest lake in the tropics, Lake Victoria modulates the climate of the surrounding region, in part through the diurnally varying lake- and land-breeze circulations that are evident in Fig. 5 in conjunction with mountain and valley breezes near the elevated terrain. Incoming solar radiation and the associated lake- and valley-breeze circulations lead to afternoon thunderstorm initiation over the slopes of Mount Elgon and the Eastern Rift as well as the lowlands north and east of Lake Victoria (Figs. 4, 6, and 7). Cluster analysis indicates that more prolific clusters tend to initiate from 1100 to 1400 LT, or about 1–2 h earlier than the general thunderstorm population (Fig. 8). After sunset, lightning densities over land decrease, although some thunderstorms persist over the lower-elevation areas east and north of Lake Victoria (Fig. 4). Land-breeze circulations develop slowly through the night and are augmented by cool mountain breezes from the terrain east of the lake, although the nocturnal wind speeds are lower than the daytime landward breezes (Fig. 5; see the supplemental material). A nocturnal lightning maximum moves from northeast to southwest over the warm waters of the lake during the night, producing mean flash rates only slightly lower than those observed over land during the late afternoon (Fig. 4).

We further leverage the continuous observations from ENGLN to track lightning clusters, including the extreme mesoscale clusters that are most dangerous to individuals in fishing or transportation on Lake Victoria. The vast majority (about 85%) of lightning clusters that produce more than 1000 flashes over Lake Victoria initiate in situ over the lake (Fig. 7). However, the more prolific the cluster, the greater the likelihood that it initiated over land before propagating over the lake, and 30%–40% of the most extreme Lake Victoria clusters initiated over land (Fig. 9). These clusters are associated with enhanced instability and low-level moisture along with a broad trough extending from the lake northward and converging winds over Lake Victoria, a pattern associated with anomalously westerly low-level flow in this region (Fig. 10).

Examination of Figs. 8 and 9 and the animations in the supplemental material indicates that the initiation and character of prolific Lake Victoria clusters vary seasonally. During the solstice seasons, the vast majority of lightning over the lake (80%–95%) is produced by

clusters that initiate in situ. Initiation occurs primarily between midnight and noon, peaking around sunrise (0500–0800 LT), approximately 12 h after the afternoon thunderstorm peak over land. In contrast, during the more active equinox seasons the clusters exhibit a broad range of initiation times from early evening through midmorning, peaking from 2200 to 0400 LT. Initiation locations are also more varied during equinox seasons: over 30% of lightning over the lake is produced by thunderstorms that initiated over land and subsequently propagated over the lake, including over half of the lightning flashes during March. Based on these results, both the direct and indirect relationships between thunderstorms over land and lake are stronger during the equinox seasons. More instances are observed of land-originating deep moist convection persisting and propagating over the lake, and the preference for earlier in situ formation suggests a greater role for cool outflow and gravity waves from the land-based storms in touching off thunderstorms over the lake.

Thorough analysis of the initiation and development of Lake Victoria thunderstorms requires observations of environmental conditions and radar data that are unavailable during the analysis period covered in this paper. The High Impact Weather Lake System (HIGHWAY) project is a 3-yr campaign to increase the availability and application of weather data to scientific knowledge and forecasting in the Lake Victoria region. HIGHWAY included a mini field campaign during periods from January to August 2019. The project archive includes any available ground-based radar observations from the Tanzanian Met Authority Mwanza radar as well as ENGLN flash data, surface observations, and 4-km numerical weather prediction model output for the region. The HIGHWAY data archive will enable further analysis of the development and character of prolific thunderstorms in the Lake Victoria basin. In the future, in addition to continuous ground-based observations of total lightning now available in this region, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Meteosat Third Generation (MTG) satellite, currently scheduled to launch in 2021, will carry a Lightning Imager (LI). The advance of continuous total lightning observations from geostationary orbit will further improve the ability to monitor and predict thunderstorm development throughout Africa.

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(DAAC), and the authors thank Earth Networks for providing their data and Mike Stock and Jeff Lapierre for providing information on the ENGLN network. The authors also thank three anonymous reviewers for improving this paper through their detailed comments and suggestions. The HIGHWAY field catalog containing weekly lightning loops, surface, radar, and satellite data as well as forecaster reports can be found at [catalog.eol.ucar.edu/highway](http://catalog.eol.ucar.edu/highway) (UCAR/NCAR–Earth Observing Laboratory 1995). HIGHWAY NWP model output is available at <https://forest.informaticslab.co.uk>.

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