Lake Victoria Thunderstorms: Radar-Observed Initiation and Storm Evolution Modes

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ABSTRACT: The enhanced observation period during the HIGHWAY field campaign in East Africa provided the opportunity to obtain continuous ground-based radar observations over the Lake Victoria basin. This provided insight into thunderstorm initiation processes and thunderstorm evolution. This insight is significant for it can lead to nowcasting thunderstorms over Lake Victoria, which is particularly important because of the >200,000 fishers using the lake daily and the extremely high number of drownings resulting from capsized boats caused by large waves and high winds from thunderstorms. Radar data from the south shoreline of Lake Victoria made it possible to observe thunderstorm activity over the entire lake. Unexpectedly the radar returns from high concentration of insects over the lake made it possible for the radar to observe boundary layer convergence lines. With this information a radar-trained forecaster could provide nowcasts of severe storm locations and by using extrapolation techniques provide nowcasts of their future location. In addition, rules for forecasting the timing and extent of nighttime thunderstorm activity over the lake based on radar monitoring of earlier activity along the northeast land/lake region are provided. While there are many obstacles to overcome, it is hoped that in the near future this possible life-saving information can be provided to Lake Victoria boaters.

SIGNIFICANCE STATEMENT: Radar data from the south shore of Lake Victoria has enabled new understanding of thunderstorm initiation and evolution over the lake. This understanding provides the potential to nowcast thunderstorms over Lake Victoria. This is particularly important because of the extremely high number of drownings that occur over the lake that result from capsized boats caused by large waves and high winds from thunderstorms. Radar-based rules are provided for forecasting and nowcasting the timing and severity of Lake Victoria thunderstorms.

KEYWORDS: Radars/Radar observations; Nowcasting; Africa; Thunderstorms

1. Introduction

Lake Victoria is Africa's largest and the world's second largest freshwater lake, with an area of 69,000 km² bordering Tanzania, Uganda, and Kenya. The Lake Victoria basin (LVB) supports millions of people. Boating accidents associated with the marine industry cause at least 1000 deaths every year (Roberts et al. 2022; Watkiss et al. 2020), which represents a significant percentage of the approximately 217,000 fishermen and travelers over the lake daily. Many of the fatalities have been attributed to hazardous weather conditions (lightning, hail, heavy rain, and thunderstorm outflows) from the frequent occurrence of nocturnal thunderstorms. Lake Victoria thunderstorms are well known as one of the lightning hotspots on Earth (Zipser et al. 2006; Albrecht et al. 2016), with extreme danger to human life.

This paper is based on data from a polarimetric Doppler radar located in Mwanza, Tanzania, along the south shore of Lake Victoria. The data were available from January 2019 through January 2020 with considerable data gaps. This radar was able to detect and monitor thunderstorms over the entire lake as well as boundary layer convergence lines that influenced storm evolution. A second radar was located in Entebbe, Uganda, that provided data for the month of February 2020, unfortunately following the end of the Mwanza radar collection period.

The purpose of this paper is to understand the initiation and evolution of thunderstorms in the LVB based on radar observations. With this understanding guidelines are developed for nowcasting thunderstorms over Lake Victoria that could be useful to weather service forecasters.

We emphasize that this paper is based only on radar data. Planned future papers would discuss methodologies for improving seasonal wind and severe storm nowcasting and warnings. The mesoscale environment is examined based on 1) soundings from Nairobi and Lodwar, 2) meteorological information over LVB provided by the Met Office, operational high-resolution (4.4 km) regional Tropical Africa (TA4) model, and 3) Doppler radar radial velocities and radar features such as bow echoes, and limited surface station data.

Section 2 provides background on previous studies of Lake Victoria thunderstorms and events leading up to the collection of the Mwanza radar data. Section 3 describes the Tanzania and Uganda radar capabilities, scanning strategies, and coverage of thunderstorms over the lake. Section 4 discusses radar detection of biological targets that makes it possible to observe and track convergence lines. Section 5 documents the different boundary layer convergence lines over LVB. Section 6 discusses the areal extent of thunderstorm activity relative to storm initiation time and location. Section 7 describes the various modes of thunderstorm evolution and section 8 provides guidelines, based only on radar, for forecasters on nowcasting thunderstorms over Lake Victoria and section 9 is future efforts.
2. Background

Flohn and Fraedrich (1966) using infrared satellite data and surface station data were one of the first to discuss processes associated with heavy rainfall over Lake Victoria. They inferred that a nocturnal land-breeze circulation, that produced nighttime convergence over the lake, dramatically enhanced rainfall over the lake. Later studies by Ba and Nicholson (1998) also using infrared cloud satellite data found a similar diurnal cycle. TRMM satellite precipitation radar observations (Burleyson et al. 2011; Semazzi et al. 2011) showed a minimum of precipitation activity over the lake between 1500 and 2100 local time (LT) and a maximum of precipitation activity at the northeastern corner of the lake starting at 0300 LT and spreading southwest over the lake during the next 9 h. Similar diurnal evolution of Lake Victoria precipitation have been shown by lightning strike data (Virts and Goodman 2020).

Early access to the polarimetric S-band radar on the south shore of Lake Victoria at Mwanza, Tanzania, prior to calibration of the radar and second trip removal, facilitated the analysis of two weather events from 2018 to 2019 over the lake, graphically illustrating the ability of the radar to clearly detect and track convergence boundaries and thunderstorm initiation over the lake (Waniha et al. 2019). Improved data quality observations from this radar and an extended period of observations made it possible to significantly improve on the findings in Waniha et al. (2019), and to better understand thunderstorm evolution over Lake Victoria. These findings enable future exploration of new ways to provide warning of dangerous thunderstorm conditions to fisherman and lakeside communities. Some of the highlights from the findings presented in this present paper are included in Roberts et al. (2022).

In 2018 funding was secured for a small field experiment under the World Meteorological Organization (WMO) HIGH impact Weather Lake System (HIGHWAY) project (Roberts et al. 2022) which was supported by the U.K. Foreign Commonwealth and Development Office (FCDO). The HIGHWAY field campaign was not a traditional experiment in the true sense of the word, as only locally available data were collected. Numerous steps were involved to access, collect and archive observations from each East Africa country remotely during the period from January 2019 to March 2020, the HIGHWAY enhanced observation period for the Lake Victoria basin. Figure 1 shows the location of the ground-based datasets that were obtained during the field campaign centered over LVB. Satellite imagery and lightning data were also collected. Table 1 in Roberts et al. (2022) lists the suite of instruments, their location, data collection periods, and data frequency. Data were collected from Kenya, Tanzania, and Uganda National Meteorological and Hydrological Services (NMHSs) which bound the lake, and by Rwanda.
The TMA forecast of oration between the authors and the director and engineer at 2017, in preparation for the HIGHWAY project, radar scan-shore of Lake Victoria on a hilltop, 136 m above the lake. In et al. 2019). The radar is located in Mwanza on the south frequency (PRF) Elevation angles (°)

<table>
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<tr>
<th>Pulse repetition</th>
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<td>400 0.3, 0.8, 1.5, 2.3, 3.3, 4.5</td>
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<td>1000 0.3, 1.0, 1.7, 2.7, 3.7, 4.7, 7.0, 11.0, 18.0</td>
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The blue circle is the 360-km radar range ring for the Mwanza S-band radar and the green circle is the 75-km range ring for the Entebbe C-band radar. The reasons for the difference in range are discussed later. The Rwanda 5-cm wavelength radar, the western white circle, is not used because of land blocking of the signal toward the lake. The two sounding sites (orange circles) are not used since they are at significantly higher elevation than the lake so the important wind, temperature, and moisture profiles immediately above the lake are not captured. While there are many surface stations (small yellow, purple, green and white symbols), they are not used in this paper because they do not observe convergence lines. The light-yellow lines are country boundaries.

3. Radars

a. Mwanza, Tanzania, radar

The Tanzania Meteorological Authority (TMA) purchased an Enterprise Electronic Corporation (EEC) weather radar in 2015. The polarimetric radar is a state-of-the-art radar with a wavelength of 10 cm (S-band) and a 1° beamwidth (Waniha et al. 2019). The radar is located in Mwanza on the south shore of Lake Victoria on a hilltop, 136 m above the lake. In 2017, in preparation for the HIGHWAY project, radar scanning and data archiving procedures were developed in collaboration between the authors and the director and engineer at the TMA forecast office in Mwanza. These procedures were specifically designed to maximize the means for monitoring storm evolution over Lake Victoria and the basin. This included optimization of scanning to observe clear-air wind convergence features that precede storm initiation. The HIGHWAY scanning strategy, which was repeated every 10 min, is provided in Table 1.

A low and high pulse repetition frequency (PRF) are used. The unambiguous range of the high PRF (1000 pulses per second) scan is 150 km. The purpose of this PRF scan is to obtain high resolution measurements of the vertical reflectivity and velocity structure of storms. The high PRF scan provides a higher unambiguous velocity than the low PRF scan, greatly improving interpretation of the velocities. The low PRF scan, with an unambiguous range of 360 km, covers the entire lake although only the upper portion of tall storms are detected at farther ranges.

Mwanza radar data were available for about one year from January 2019 to January 2020. However, there were numerous gaps in the collection for a variety of reasons, mostly because of hardware malfunctions and limited staff support for data collection. Impressively, given these constraints, there were 148 days of near 24-h coverage. These data were used in the analyses discussed in this paper. Figure 2 shows days of data collection. The majority of days occurred from July through November. Figure 2 also shows for each collection day, the percent of the lake covered by echoes ≥ 35 dBZ. Thunderstorms occurred over the lake in all but two days. This is based on the field which contains the maximum reflectivity at each grid point for a 24 h period. The computation is then the percent of these points that are ≥35 dBZ. The days with the maximum percentages occurred during October and November, East Africa’s second rainy season of the year (www.cpc.ncep.noaa.gov/products/assessments/assess_97/africa.html). Caution should be exercised in generalizing these results to other years and locations since the dataset is limited and 2019 was a wet year particularly during November (Wainwright et al. 2021). The typical wet seasons are from March/April to June and from October to December.

b. Entebbe, Uganda, radar

The Uganda radar was purchased from Vaisala and installed on the north shore of Lake Victoria in Entebbe, Uganda, in 2019 for use by the Uganda National Meteorological Authority (UNMA). The polarimetric radar has a wavelength of 5 cm (C-band) and a beamwidth of 1°. An official opening ceremony marking the installation of the radar occurred at the beginning of July 2019; however, data were not recorded and archived until 31 January 2020. Because of the delay in data collection, there are no times of overlapping observations with the Mwanza radar. Nevertheless, some excellent observations were obtained by each radar, which will be shown later.

The Entebbe scanning strategy was installed by the factory engineers. The scan sequence was repeated every 10 min. The sequence contained four volume scans, each with a

![Fig. 2. Dates of Mwanza radar data collection vs the percentage of the lake covered that day by radar reflectivity ≥ 35 dBZ.](image-url)
different PRF and varying sensitivity between and within the radar volume. The choice of scanning strategy was not useful for weather surveillance and only likely by chance the fourth volume provided data useful for analyses. This volume had 7 elevation angles, the lowest of which was $0.5^\circ$, and a PRF of 2000 s$^{-1}$, giving a maximum unambiguous range of 75 km. Unfortunately, if there had been a useful lower PRF the maximum range could have been much larger. The limited maximum range meant that at times there was considerable second trip echo.

Second trip echo is a spurious echo that occurs when echo return is received from a pulse prior to the present pulse and then gets plotted at the wrong range (Figs. 7c and 7d are examples). Importantly, while the Entebbe range was limited, the data had good sensitivity, providing excellent detection of boundary layer features.

c. Thunderstorm coverage over Lake Victoria

Because of the tall height (generally $\geq 15$ km) of the thunderstorms in the Lake Victoria region, they are routinely detected on the $0.3^\circ$ radar elevation angle in the low PRF scan over the entire lake. The height of the $0.3^\circ$ scan at the farthest range of the lake (360 km) is roughly 12 km. Figure 3 compares the Mwanza radar reflectivity of convective storm echoes with lightning strikes observed by the Earth Networks Global Lightning Network (ENGLN; Virts and Goodman 2020). It can be seen in Fig. 3 that lightning was typically observed with storm reflectivities $\geq 35-40$ dBZ (yellow reflectivity is 40 dBZ). Note that this was even the case for storms near the north end of the lake over 300 km from the radar. This is consistent with observations made elsewhere over the years showing convective storms with radar reflectivity $\geq 35-40$ dBZ contain lightning (Dye et al. 1986; Vincent et al. 2003; Yang and King 2010). Comparison of reflectivity and lightning images, similar to those above, throughout the field campaign, mostly verified that 35–40 dBZ reflectivity was the lower reflectivity threshold for lightning. Therefore, we feel confident that when the Mwanza radar observes a precipitation echo $\geq 35-40$ dBZ, on the $0.3^\circ$ radar elevation angle, the storm contains lightning. In addition, it is most likely that any storm with lightning extends to a height greater than 12 km. It follows the Mwanza radar is observing the large majority of thunderstorms occurring over LVB and that the Mwanza radar can be used to study the initiation and evolution of thunderstorms for the entire lake. For simplicity, we will use the word thunderstorms instead of reflectivities $\geq 35$ dBZ in the remainder of the paper.

4. Biological echo

The paper by Waniha et al. (2019) described the clear air radar echo over Lake Victoria and its usefulness for identifying convergence lines over the lake. The clear-air echo was attributed to backscattering from insects and birds. Following the Waniha paper and during the field campaign, radar data quality algorithms supplied by the radar manufacturer, were applied to the Mwanza data that reduced ground and second trip echo substantially thus enhancing the ability to more clearly observe convergence boundaries. The Waniha et al. (2019) paper further discussed the importance of these convergence lines over the lake and the role they play in thunderstorm initiation.
There is extensive literature on weather radar observation of insects and associated clear air echo (e.g., Drake and Reynolds 2012) and their usefulness for detecting boundary layer convergence lines (Wilson et al. 1994). Previous research studies (Wilson and Schreiber 1986; Russell and Wilson 1997; Alexander et al. 2018) and operational nowcasting practices (Roberts and Rutledge 2003) have shown that boundary layer convergence lines, that are visible as clear-air features on the radar, often trigger convective storms in conditionally unstable and unstable environments. Typically, insects mostly fly over land and not over large bodies of water (Russell and Wilson 2001). Thus, it was surprising, even if the concentration of insects overland is very high, to observe significant clear-air echo return over Lake Victoria, indicating that insects are often being carried by the land breeze over the lake and persisting over the lake. Close examination of the clear-air echoes revealed many different boundary layer convergence lines that are directly correlated to convective storm initiation and thunderstorm evolution over Lake Victoria.

Figure 4 shows examples of biological, clear air radar echoes extending to radar ranges ≥ 150 km. The Lake Victoria region is known for its exceptionally high concentration of insects and birds (Corbet and Corbet 1958). While we suspect that much of the radar return is from insects it is likely that ground clutter, birds and sea clutter are also present. In fact, the concentration of lake flies at certain times of the year can be so dense that the lakeside communities catch them in large quantities to make fly burgers for consumption that are exceptionally high in protein (en.wikipedia.org/wiki/Kunga_cake).

There is considerable variability in the extent and intensity of the biological echo from day to day and during the day. Particularly over water a minimum in biological echo occurs in the late afternoon and dramatically increases after sunset. The spatial extent of nighttime biological echo tends to be greater than that observed during the daytime. In Fig. 4, the pockets of high reflectivity just offshore along the west shoreline may be where the swarms become very dense and deep as part of their mating ritual. There likely are different insect and bird species between day and night. Jatau and Melnikov (2018) make the argument that insects have high differential reflectivity (ZDR) values and birds have low values and since high ZDR values are observed during the day and low values at night, they conclude that insects dominate during the day and birds at night. Their studies were conducted in the central United States. Over Lake Victoria both during day and night we observed very high ZDR values (at least 8 dB) as well as low and even negative ZDR values. Without a specific study that includes visual identification of the echo, it is unknown at any time whether the echo is birds or insects. Over Lake Victoria most likely they are both present at any one time. The birds, just like the lakeside people, find the insects a good meal.

As explained in Russell and Wilson (1997) and Wilson et al. (1994) boundary layer convergence lines appear on the radar as enhanced thin lines of reflectivity. This is a combination of insects being caught in converging wind and insects resisting being carried aloft by the line of updraft associated with the line of convergence. This then results in a concentration of insects along the convergence zone and higher reflectivity values than in the surrounding clear air return. A thin line of reflectivity then marks the line of updraft generated by the low-level convergence. While the Doppler velocity may show, at low levels, a line of converging winds, the convergence line or convergence boundary is generally better observed in the reflectivity field. This is because the Doppler velocity shows the convergence of insects occurring at low levels along the boundary. The convergence creates a line of updraft above the convergence extending to higher levels. The insects tend to resist being carried to higher heights increasing their number in the updraft (Russell and Wilson 1997). Thus, the reflectivity will indicate a line of enhanced reflectivity associated with the updraft extending above the low-level convergence. Other reasons for the boundary location being observed better in reflectivity than Doppler velocity are: 1) at longer radar ranges the horizontal convergence of wind is shallow and below the radar beam, while the high reflectivities associated with the updraft extends above the low-level convergent wind where it is intercepted by the radar beam, 2) the radar-viewing angle is oblique to the converging wind and thus only sampling a small component of the velocity, and 3) the converging wind is horizontally narrow and not well resolved by the radar.

5. Boundary layer convergence lines

Boundary layer convergence lines are easily observed visually as thin lines of enhanced radar reflectivity. As mentioned above they are particularly notable over Lake Victoria. Figure 5 provides examples of four different boundary layer convergence lines, observed as thin lines of radar reflectivity, over Lake Victoria. The boundaries in these four examples are within 100 km of the radar. While occasionally, boundaries are observed out to 150 km, more typically they are observed within a 100-km range; the range is dependent on boundary height. Identification of boundary type is based on years of experience, time lapse of the images, and for land and lake breezes, by the time and location of the boundary. A gust front, for example, would be based on time lapse of the reflectivity and/or the velocity images to see that the front initially emerges from a convective cell as a thin line in reflectivity or with Doppler velocities moving away from the cell. Without a formal count gust fronts are easily the most commonly observed boundary, followed by unknown boundaries and then land breezes. Gravity waves were only clearly identified in the example shown in Fig. 5c. Lake breezes are seldom observed; this is likely the result of insects being lifted over the advancing lake breeze and not being concentrated near the ground (or lake surface) at the leading edge of the lake breeze front. The Mwanza radar being located on the south coastline of Lake Victoria is well positioned to observe the

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1 Polarimetric radars measure both the horizontal and vertical reflectivity. The ratio of the horizontal to vertical reflectivity is defined as differential reflectivity (ZDR). Horizontally elongated features like most insects will have ZDR values greater than 1. Most insects have ZDR values greater than about 5.
land breeze off the south coast which are visible as a thin line, parallel to the coast. As observed in Figs. 6a–c the land breeze typically forms 20–30 km north of the south shore. Similarly, the Entebbe radar is well positioned to observe the land breeze off the north coast. Based on the Mwanza radar the frequency of boundary type and their frequency to initiate thunderstorms are provided in Table 2. Initiation is defined when the precipitation echo on the 0.3° radar elevation scan exceeds $\geq 35–40$ dBZ. The frequencies are computed for November 2019, the wettest month in our dataset and July 2019, a dry period.

It can be seen in Table 2 that while the number of boundaries was similar, storm initiation (CI) was much less common in July compared to November. Because of the fewer CI events there were also many fewer gust fronts in July. The much-reduced frequency of CI in July is most likely because of the large-scale dryness and greater convective stability compared to November that is shown in the precipitation climatology

FIG. 4. Examples of biological echoes over Lake Victoria. (a),(c) Radar reflectivity and differential reflectivity (ZDR) at 0541 LT 29 Sep 2019 and (b),(d) $Z$ and $Z_{DR}$ at 2041 LT 4 Oct 2019. The radar range rings are at 50-km intervals. The red cross marks the radar location. The ZDR signal in (c) and (d) is primarily positive between 2 and 8 dB suggesting the targets are biological. It is believed, at this particular time, that the majority of the echo is from lake flies although birds are certainly feeding on them. The echo extending along the entire west coast in (b) and (d) extends as high as 5 km.
LV is at the equator, so the mesoscale dynamics and terrain likely play a larger role than synoptic forcing. Table 2 also shows that while there are more gust fronts in November compared to July the opposite is true that more land and lake breezes are observed in July. This may be that the storm activity in November disrupts land-to-lake temperature gradients thus the reduction in land and lake breezes. Planned future papers will discuss the mesoscale environment, using soundings, satellite, and NWP model data in relation to storm severity and winds and seasons.

Figures 6a–c shows reflectivity thin lines, associated with the land breeze, from the Mwanza radar at the same time (0621 LT)² on three different days in August 2019. Figure 6d shows a thin line with the land breeze from the Entebbe radar. The thin lines are observed to form in position 10–20 km off the shoreline; they do not move from the shoreline. There is considerable literature on the lake and land breeze (Hauwitz 1947; Atkins 1995; Miller et al. 2003; Simpson 1987) that discuss both a kinematic and thermodynamic

² All times in the paper are local time, which is UTC + 3 h.
front and when these properties coincide the convergence and updraft are at a maximum. Since the thin line is a concentration of insects it is assumed it is marking the position of the updraft associated with the land-breeze front. In these cases, there is no indication of the thin line moving out from the shoreline rather it is observed to appear near the locations shown in Fig. 6. It is speculated that there is an insufficient number of insects caught in the land-breeze front updraft, to be visible by radar, until the kinematic and thermodynamic front coincide. At this time the convergence and updraft are sufficiently strong that insects have accumulated sufficiently to make the land-breeze front visible on the radar.

Figure 7 provides examples of CI associated with land-breeze fronts. The storms shown in Figs. 7a and 7b evolved into a major east–west squall line that moved north over the lake with reflectivities more than 55 dBZ and velocities of 15 m s⁻¹. The land breeze in Figs. 7c and 7d, from the north coast, moved toward the south and southeast initiating clusters of storms with reflectivities of 50 dBZ and horizontal velocities of 15 m s⁻¹. Because of the high frequency of thunderstorms being associated with boundary layer convergence lines it is most likely that these storms are surface based and have surface-based updrafts.

6. Lake thunderstorm evolution

6.a. Diurnal cycle and origin of thunderstorms

Virts and Goodman (2020) have used the Global Lightning Detection Network (GLDN360) to produce a 5-yr
lightning climatology over LVB. It clearly shows that from 0200 to 1200 LT the lightning is a maximum over the lake and a minimum over land, and from 1200 to 1900 LT there is essentially no lightning over the lake and a maximum over land. The in-between period from 0000 to 0200 LT did have lightning over the lake. Numerous studies have also shown similar diurnal cycle using satellite, cloud, precipitation, and radar data (Albrecht et al. 2016; Thiery et al. 2016; Yin et al. 2000; Waniha et al. 2019).

Visual examination and accumulated notes based on all the Mwanza radar data showed that most thunderstorms initiated over the lake and that those that did not were most likely to advect in from the land from the northeast, east, and south. The Mwanza data also showed that only occasionally were thunderstorms observed to occur over the lake in response to storms or gust fronts moving from land to sea.

The Virts and Goodman (2020) studies also showed the most common mode for thunderstorm occurrence over the lake was for thunderstorms to develop above the lake.

b. Time and location of thunderstorm initiation and coverage

While it is apparent that thunderstorms occurring over the lake primarily initiate over the lake in this section we use the Mwanza radar data to examine the precise time and location of first thunderstorm occurrence over Lake Victoria (FTO). In addition the percentage of the lake and surrounding land covered by thunderstorms every 10 min is calculated from the Mwanza data. FTO could be the result of thunderstorm initiation over the lake or advection of storms from the land. Thunderstorm occurrence is defined as the appearance of reflectivity echo \( \geq 35 \text{ dBZ} \) at the lowest elevation angle of 0.3°. Figure 8 shows for each day3 FTO over Lake Victoria versus the maximum percent of the lake covered by thunderstorms during that day. It can be seen that the greatest likelihood for substantial coverage of thunderstorms over the lake occurs on days when FTO occurs in the late afternoon between approximately 1600–2300 LT. The time of maximum thunderstorms over the lake occurs many hours after FTO. The points in Fig. 8 are color-coded based on the month. Essentially all the days with greater than 50% thunderstorm coverage occurred during October and November (red dots) which is the well-known wet season. The thunderstorm coverage is mostly less than 20% for all the other months. In Fig. 8 there are five cases with thunderstorm occurrence between 1500 and 1900 LT that are during the time noted above by Virts and Goodman (2020) when there is virtually no lightning over the lake. All five of these cases are thunderstorms moving over the water from the northeast or east land areas that dissipate as they move over the water. Thus, the lightning that does occur is close to the shore.

Examination of the Mwanza radar also showed that the location and time of FTO are related to the amount of thunderstorms activity that would follow. This was determined first by recording the time and location of FTO within 6 sections of the lake and 3 land sections adjacent to the lake (see Fig. 9). The time of FTO for a day could occur in multiple sections if the thunderstorms occurred within 30 min of each other. FTO for the land events required the storm to move from land to water without complete dissipation. The time of FTO for a land storm reaching the lake was recorded as the time it reached the lake.

There were 202 cases in Fig. 9 with FTO in the 135 days4 of radar data collection. Three statistical values are provided for each section. The first is %FTO, which is the percentage of all FTO that occur in the section, the second number (TFTO) is the median time of the FTO for that section, and the third number (Mcvg) is the median of the maximum thunderstorm coverage that occurred for all the events in that section. The earliest times of FTO are from thunderstorms moving from the land (see sections LNE, LE, and LS). These land storms typically result in the maximum number of thunderstorms over the lake; however, they account for less than 13% of the total FTO events. The TFTO from the two eastern lake areas (sections NE and E) average about 2–3 h later than those from the land. TFTO for the remainder of the lake sections (NW, W, C, and S) occurred about 7–8 h later than those from the land. These western and southern lake sections make up just over half the events and result in reduced thunderstorm coverage over the lake, 20%-40% less thunderstorm lake coverage when compared to Mcvg values in the more eastern sections.

Further examination of the most active days over the lake showed that on the days when Mcvg was \( \geq 50\% \) all but two of the events occurred when the FTO was from the land (LNE and LE) or the two eastern lake sections (NE and E). In contrast, days with <10% Mcvg occurred when FTO was over the western part of the lake. In any one section there was considerable variability in TFTO and Mcvg depending on the time of first storm initiation over the lake. The days when Mcvg was >50% occurred in October and November.

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3 The use of day throughout this section refers to the period from the beginning to the end of a lightning episode over the lake, which would generally cover a period from the afternoon/evening of one calendar day past midnight to the morning the next calendar day.

4 It was noted above there were 148 days of Mwanza radar collection. Thirteen days were eliminated because of missing data at time of first storm occurrence.
In summary if first thunderstorm occurrence over the lake is in the afternoon or evening along the eastern or northeastern part of the lake or from land storms moving over the lake, the likelihood is high that lake thunderstorm activity will be extensive covering a substantial portion of the lake and persisting until late night or early morning. This situation is most likely to occur during the wet season. If first thunderstorm occurrence is delayed until after midnight the thunderstorms are most likely to have initiated in the western two thirds of the lake and only a relatively small area of the lake will be affected by thunderstorms.

Thiery et al. (2016), using overshooting cloud top and TRMM satellite data has shown precipitation over land is related to the amount of activity over the lake at night. Specifically, if it is a stormy day over the land it will be a very stormy night over the lake. We have used the Mwanza radar reflectivity data to test this finding, although the land area covered was significantly less than that sampled by the satellite. We compared the percentage of land area5 covered by thunderstorms, from 1200 to 1800 LT, with the percentage of lake covered by thunderstorms, from 0200 to 1100 LT. Figure 10

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5 Land area that was within 360 km of the radar. See blue circle in Fig. 1.
shows that there is some correlation (0.71) between the amount of afternoon thunderstorm activity over the land as a predictor of the activity over the lake the following night. However much of the correlation comes from the situation where there is very little activity over the land during the afternoon (<5% coverage) with <20% of thunderstorm activity on the lake at night. When considering only the events where there was >5% thunderstorm coverage over land then the correlation falls to 0.36. In summary the radar showed that if there is very little thunderstorm coverage (<5%) over land during the afternoon then it is very likely that there will be little activity (<20% coverage) over the lake that night. However, when there is greater activity over land (>5% coverage) there is very little skill (correlation = 0.36) in anticipating the amount of activity over the lake that night.

7. Storm evolution modes

The daily evolution of storms on each day was examined for commonality. There is a large variety from day to day in the location and time of FTO that leads to the evolution of thunderstorms over the lake each late night and early morning. As discussed in the previous section only 13% of the thunderstorms occurring over the lake are the result of land thunderstorms moving over the lake. The remainder are due to thunderstorm initiation over the lake. Six modes of FTO and evolution are defined based on their visual attributes.

Based on where storms initiated and how they evolved it, was possible to place the storms into six types.

The six evolution types are NE Coastal Ring plus Lake TI (Fig. 11a), NE Coastal Ring plus Miscellaneous (Fig. 11b), NE Coastal Ring (Fig. 11c), Lake Miscellaneous (Fig. 11d), South Lake plus Miscellaneous (Fig. 11e), and Center Lake T1 (Fig. 11f). The NE Coastal Ring, as can be seen in Figs. 11a, b, c, d, e, is an area about 80 km wide centered on the shoreline covering both land and water along the north and east coast lines. FTO is frequently located within this zone. The tendency is for these storms to move west and southwest (Roberts et al. 2019; del Moral et al. 2022). Figure 11a shows an example of extensive TI over the lake, 26% of the days fell in this category. On another 26% of the days there was no TI in the “NE Coastal Ring” and TI occurred independently in the “Center Lake”; this area and evolution is shown in Fig. 11f. On 15% of the days TI was only modest or small and confined to the NE Coastal Ring and is shown in Fig. 11c (NE Coastal Ring). On a few days (9%) TI occurred simultaneously in the NE Coastal Ring with TI from a multiple number of other locations and is shown in Fig. 11b (NE Coastal Ring + Misc); When thunderstorms were slow or did not develop in the NE Coastal Ring they developed 11% of the total number of days in the Lake South region as shown in Fig. 11e; and finally there was 11% of the days when TI occurred simultaneously in a variety of lake locations (Lake Misc) and is shown in Fig. 11d.

For each of the six evolution types FTO versus the maximum percentage of the lake that was covered by reflectivity > 35 dBZ...
is shown in Fig. 12. Apparent in Fig. 12, although the scatter is significant, is the decrease in the maximum lake coverage of $>35$ dBZ as the time of FTO increases. Note, the three evolution modes that do not involve the NE Coastal Ring (dark green, gray, and dark brown) tend to have first thunderstorm occurrence over the lake after midnight. While the Coastal Ring evolution modes start as early as 10 h before midnight.

Table 3 lists the six evolution types in order of their first time of thunderstorm occurrence over the lake. Statistics are provided of the median time of first thunderstorm initiation, the median percentage of the of lake covered by thunderstorms, the median percentage of land surrounding the lake that is covered by thunderstorms the previous afternoon and finally the time of year that is most common for each evolution type. This data sample, as can be seen in Fig. 2, has a limited number of cases during the March–May wet period thus the numbers and time of year statistics in Table 3 should be viewed with that in mind.

FIG. 9. Statistics on thunderstorm occurrence and evolution for Lake Victoria divided into six lake sections (black polygons) and three adjoining land areas. The bold black letters in each section over the lake represent Northwest (NW), Northeast (NE), West (W), Center (C), East (E), and South (S). The three land areas are indicated by the thin lines, light green is Land Northeast (LNE), purple is Land East (LE), and red is Land South (LS). See text for definitions of %FTO, TFFO, and Mcvg. The background is the topography.

FIG. 10. Afternoon thunderstorm activity over land as a predictor of the nighttime activity over the lake that night. Coverage is the percentage of the area covered by reflectivity $\geq 35$ dBZ.
In summary, as observed in Fig. 8, Fig. 12, and Table 3 when the first storms in the NE Coastal Ring form early, i.e., late afternoon and early night, the following nighttime thunderstorm activity over the lake will be extensive. This situation occurs almost entirely during the wet season of October and November. In addition, when the first TI does not form in the NE Coastal Ring the tendency is for the thunderstorm activity over the lake to form late and to be less. When the NE Coastal
Ring TI is small with early dissipation. TI occurred primarily in the South Lake region, this most frequently occurs during the relative dry season in August and September. Finally, when there is no TI in the NE Coastal Ring, thunderstorms will eventually form over the central part of the lake during the very late night or morning. Table 3 also shows, as in Fig. 9, there is a tendency for widespread afternoon thunderstorms over the land to be followed the following night by widespread thunderstorms over the lake.

8. Forecaster guidelines

Table 3 and discussion suggests that this type of information would be useful for Lake Victoria forecasters. Presently...
Forecasters have access to web-based global models (e.g., UKMO, NCEP, ECMWF). These models do not assimilate any local data except for limited, occasional data that are transmitted to the WMO GTS. Based on the 12- and 24-h model forecasts, marine forecasts are issued twice daily for fishermen. Because of the lack of any local data these forecasts are very general in nature lacking specific time, place, and storm severity information. However, radar data are available from Entebbe and Mwanza. Forecasters with suitable radar data available and who are trained in the use of radar data could make use of the information in Table 3 to help predict the general timing and amount of storm activity over the lake. Additionally, nowcasts of specific storm location and storm severity could be provided.

**Fig. 11.** (e),(f) As in (a) and (b), but for South Lake + Misc. and Center Lake TI, respectively. The second image in (e) shows the TI moving north and the second image in (f) shows continued TI over center lake.
First of paramount importance is particular care must be taken to maintain the radar and to collect data in a useful manner. Collection procedures should be similar to those provided in Table 1. Based on examination of the complete set of HIGHWAY radar observations, forecaster guidelines are presented below that assume the forecaster has full access to radar displays and radar data.

1) By monitoring the location and movement of thunderstorms over Lake Victoria and surrounding land areas it is possible to use extrapolation to nowcast thunderstorm locations. Some radar manufacturers provide an algorithm to track storms using simple extrapolation procedures. In the absence of an extrapolation algorithm the forecaster can use the “grease pencil” approach where they mark the past locations of the storm of interest on a radar display, determine the direction and speed of storm motion, and extrapolate that motion into the future.

2) By monitoring the location and movement of convergence lines over the lake as well as cloud and precipitation patterns.

FIG. 12. As in Fig. 8, but plotted is the maximum percentage of the lake covered by thunderstorms relative to the time of first thunderstorm occurrence over Lake Victoria. This time the coloring of the dots corresponds to the six evolution modes. Orange is the NE Coastal Ring + Lake TI, yellow is NE Coastal Ring, light green is NE Coastal Ring + Misc, dark brown is Lake Center, gray is South Lake + Misc, and dark green is Lake Misc.

TABLE 3. Comparative statistics associated with the six evolution types. The land median coverage is for the time period from 1200 to 1800 LT and the lake median coverage is the following night from 0200 to 1100 LT. The evolution types are listed in the order of first thunderstorm occurrence over the lake.

<table>
<thead>
<tr>
<th>Evolution type</th>
<th>Percent of occurrence</th>
<th>Median time of first thunderstorm occurrence over lake (LT)</th>
<th>Median percent of lake covered by thunderstorms</th>
<th>Median percent of land covered by thunderstorms</th>
<th>Time of year when most of the evolution type occurs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE Coastal Ring + Lake TI</td>
<td>26</td>
<td>2189</td>
<td>50.1</td>
<td>23.9</td>
<td>October and November</td>
</tr>
<tr>
<td>NE Coastal Ring + Misc</td>
<td>9</td>
<td>2343</td>
<td>47.6</td>
<td>24.4</td>
<td>75% September, October, November</td>
</tr>
<tr>
<td>NE Coastal Ring</td>
<td>15</td>
<td>0049</td>
<td>20.3</td>
<td>7.8</td>
<td>No preference</td>
</tr>
<tr>
<td>Lake Misc</td>
<td>12</td>
<td>0330</td>
<td>11.5</td>
<td>8.4</td>
<td>No preference</td>
</tr>
<tr>
<td>South Lake + Misc</td>
<td>11</td>
<td>0429</td>
<td>15.9</td>
<td>6.6</td>
<td>No preference</td>
</tr>
<tr>
<td>Center Lake</td>
<td>26</td>
<td>0552</td>
<td>8.1</td>
<td>3.5</td>
<td>79% July, August, and September</td>
</tr>
</tbody>
</table>
growth above them it is possible to anticipate the initiation of new thunderstorms over the lake.

3) By monitoring the amount of thunderstorm activity over the land during the afternoon it is possible to anticipate thunderstorm activity over the lake at night. In particular, if there is little thunderstorm activity over land, there will be little thunderstorm activity over the lake that night and if there is significant afternoon thunderstorm activity over land there will likely be significant activity over the lake. However, the amount of activity over the land provides only limited skill in anticipating how much of the lake will be affected by thunderstorms.

4) By monitoring the thunderstorm activity and timing of thunderstorm occurrence in the “NE Coastal Ring” it is often possible to anticipate the evolution of thunderstorm activity over the lake.

- When the first thunderstorms form before midnight in the NE Coastal Ring the nighttime thunderstorm activity over the lake, approximately 78% of the time, will be extensive (covering >40% of the lake). This occurred entirely during the September to November rainy period.
- When the activity in the “NE Coastal Ring” occurs later and later during the night the thunderstorm activity over the lake will be less and less. However, the scatter is large making it difficult to nowcast the amount of >30 dBZ lake coverage.
- When the thunderstorm initiation in the “NE Coastal Ring” is relatively small and storms are short-lived the primary thunderstorm activity will be in the South Lake region. Maximum lake coverage of thunderstorms will be less than 30%.
- When there is no thunderstorm initiation in the “NE Coastal Ring” thunderstorms will form after midnight only over the central part of the lake during the very late night or morning and >35 dBZ coverage will be less than 20% over 90% of the time.

9. Future

This paper utilized the Mwanza radar data to obtain the first ever, surface-based look at thunderstorm initiation and evolution over the LVB. The paper is limited in scope to the use of only radar and some lightning data. Future research will make use of additional datasets that include synoptic data, surface stations, upper air soundings, and numerical model forecast output. Utilizing these more comprehensive data, methods will be explored for producing specific time and place thunderstorm nowcasts in daily operations that could be used by weather service forecasters with access to radar displays. Future work will also utilize the Doppler velocity and reflectivity data for documenting thunderstorm rainfall rates, prevailing winds and low-level wind velocities that create hazardous conditions to fishermen and lakeside communities.

The forecaster guidelines presented here assume the forecaster has suitable access to continuous, rapidly updating radar displays. Presently this is not the case for most of Africa. The African SWIFT project is using satellite data where radar is not available to nowcast thunderstorms (Roberts et al. 2022; Parker et al. 2022). Significant financial and technical challenges exist 1) to acquire radars and suitable displays, 2) to support engineering technicians to keep the radars operating continuously, and 3) to train forecasters on continual monitoring of radar displays, on radar data interpretation and thunderstorm nowcasting, and 4) to set up communication networks to get radar data to the forecaster in a timely fashion and to disseminate thunderstorm nowcasts to the general public.

Kenya, Uganda, and Tanzania are in the process of obtaining or planning for the installation of new radars. It is important that sufficient engineering and meteorological staff be obtained and trained for maintaining the radars and monitoring and interpreting the radar data. It is also important the data are shared between countries and efforts eventually include the production of radar mosaics to provide a complete look at the weather over the entire LVB region. Accomplishing the above will make possible the saving of many lives and will be a major accomplishment that can set the standard for other African countries to follow.

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Data availability statement. Request for the Mwanza 2019 radar data should be directed to Ladislaus Chang’a, Director of Research and Applied Meteorology, ladislaus.changa@meteo.go.tz

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