Taking the HIGHWAY to Save Lives on Lake Victoria

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Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-20-0290.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

Abstract

Up to one thousand drowning deaths occur every year on Lake Victoria in East Africa. Nocturnal thunderstorms are one of the main culprits for the high winds and waves that cause fishing boats to capsize. The HIGHWAY project was established to develop an Early Warning System for Lake Victoria. Prior to HIGHWAY, weather forecasts for the lake were overly general and not trusted. Under the HIGHWAY project, forecasters from weather service offices in East Africa worked with leaders of fishing communities and Beach Management Units to develop marine forecasts and hazardous-weather warnings that were meaningful to fishermen and other stakeholders. Forecasters used high-resolution satellite, radar, and lightning observations collected during a HIGHWAY field campaign, along with guidance from numerical weather prediction models and a 4.4-km resolution Tropical Africa model, to produce specific forecasts and warnings for 10 zones over the lake. Forecasts were communicated to thousands of people by radio broadcasters, local intermediaries, and via smartphones using the WhatsApp application. Fishermen, ferry-boat operators, and lakeside communities used the new marine forecasts to plan their daytime and nighttime activities on the lake. A socio-economic benefits study conducted by HIGHWAY found that ~75% of the people are now using the forecasts to decide if and when to travel on the lake. Significantly, a 30% reduction in drowning fatalities on the lake is likely to have occurred, which when combined with the reduction in other weather-related losses, generates estimated socio-economic benefits of $44M/year due to the HIGHWAY project activities; the new marine forecasts and warnings are helping to save lives and property.

Capsule: High-resolution observations, new marine forecasts, and hazardous-weather warnings are reducing fatalities and protecting livelihoods on Lake Victoria.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

1. Introduction

Lake Victoria in East Africa (EA) is one of the deadliest bodies of water in the world due to the dangerous weather that occurs over the lake. Earlier studies estimated 3000-5000 drowning fatalities occur annually on the lake (IFRC 2014), although there exists little recorded data for these figures and numbers have been falling. More recent studies (Watkiss et al. 2020) indicate an estimated 1500 deaths occur annually, of which two-thirds are estimated to be weather-related (1000 deaths). Recent surveys of inhabitants along the lake suggest that the majority of drownings happened to fishermen and small boat lake travelers (Kobusingyea et al. 2017; Whitworth et al. 2019). Stormy weather and lightning, strong winds and waves, and boat overloading (Tushemereirwe et al. 2017) are the most frequently cited factors that cause the boats to capsize.

Lake Victoria (LV) is a critical freshwater resource for the region as Lake Victoria Basin (LVB; Fig. 1) supports an estimated population of 5.4 million, including 11% of the population who live on lake islands and rely on marine transport. Every day, approximately 217,000 fishermen go out on the lake in small boats (DiFR 2017; Sobo et al. 2017) and less than half of the fishing boats have an outboard motor. On any given day, fishermen, small-boat operators, ferry-boat passengers, and other lake travelers may encounter life-threatening weather that produces strong winds and waves. These winds and large wave heights are believed to be caused by high-impact weather such as microbursts, downbursts, thunderstorm outflows (gust fronts), or waterspouts. Land-breeze fronts, mountain-valley drainage flows, and strong southerly mesoscale winds also play a substantial role in generating high waves in non-convective situations. Although lake transportation peaks during the day, the majority of fishing occurs at night when the fishing is

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

optimal, but it can be difficult to see and avoid threats from nocturnal thunderstorms. Every day, fishermen must decide whether to take their boats out on the lake, knowing that hazardous or severe weather may occur later over the lake. However, they do not have much choice, as the lake is their livelihood. Thus, there is a desperate need by local inhabitants for accurate marine forecasts, nowcasts, and warnings of high-impact weather so that they may plan appropriately for their daily activities and their safety.

Despite the great loss of life due to high-impact weather, LVB lacks an effective advisory and warning system for the population that depends upon the lake for their livelihood. The World Meteorological Organization (WMO) led a 3.5-year project from September 2017-March 2021 called the **HIGH** impact **W**eather l**A**ke s**Y**stem (HIGHWAY) with the objective to improve resilience and reduce the loss of life and property damage in EA through the increased use of weather information. Under this project, funded by the UK **F**oreign, **C**ommonwealth and **D**evelopment **O**ffice (FCDO), through the **W**eather and climate **I**nformation **SER**vices for Africa (WISER) program, we embarked on four key activities towards development of a pilot regional Early Warning System (EWS) for LVB, expanding upon other projects[1] in the region. The term EWS, as used throughout the HIGHWAY project and in this paper, may cause some confusion to the reader as it includes both 6-24 h marine forecasts and convective outlooks for hazardous weather over LVB. Traditionally, the use of the term warning[2] is reserved to alert for impending or occurring severe weather where immediate action should be taken to save lives and

[1] These projects include the Multi Hazard Early Warning Systems (MHEWS) in Tanzania, WISER's DARAJA project in Kenya, WMO's Severe Weather Forecast Project (SWFP), and the HyVic, MOYA and HyCRISTAL experiments.

[2] See the American Meteorological Society's Glossary of Meteorology definition for warnings. A warning falls within the time period defined by the WMO as nowcasting.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

property. The terms outlook, watch and advisory more accurately represent the types of forecasts included in the HIGHWAY EWS.

The four key activities discussed in this paper are 1) we ran a year-long field campaign (FC) to collect data for research on thunderstorm evolution over LVB and to provide forecasters with higher-resolution observations; 2) forecasters were provided with convection-permitting Numerical Weather Prediction (NWP) forecasts and new nowcast products for use in producing marine forecasts over LV; 3) forecasters and leaders of fishing co-operatives participated in workshops to co-design actionable, understandable marine forecasts, and relevant EWS products; and 4) a socio-economic benefits study was undertaken to assess the value of the new marine forecasts and warning products to the LVB population for saving lives and property.

In the process of conducting these HIGHWAY activities, a significant outcome was achieved. The EA National Meteorological and Hydrological Services (NMHS[3]), responsible for hazardous-weather warnings for LVB, collaborated for the first time to build consensus, develop regionally harmonized, marine-weather forecasts and issue specific hazardous-weather outlooks for users of the lake. This is a major step toward the development of a regional EWS for LVB that is helping to reduce fatalities on the lake.

2. Weather over Lake Victoria Basin

[3] The EA NMHSs discussed in the paper are from Kenya, Rwanda, Tanzania and Uganda.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Field Campaign

We ran the Field Campaign (FC) remotely from 1 March to 31 December 2019 with a domain centered over LVB. A fixed period was designated for the FC to create an urgency in the rehabilitation of existing instrumentation and to gain access to all operational datasets for scientific analyses. Figure 2 shows the locations of the ground-based instrumentation within the LVB; their data-collection location, periods of operation, and update frequencies are listed in Table 1.Observations were archived as they became available, as not all datasets were accessible in real-time, and images of the data were provided to all HIGHWAY participants on a dedicated web site. The Tanzania Meteorological Authority's (TMA) dual-polarimetric radar, well situated on the south shore of LV, is crucial for collection of high-resolution radar reflectivity and Doppler velocity data on storm growth and intensification, and winds and wind shear over the lake. Forecasters who had access to these data in real-time had some knowledge in interpretation of radar reflectivity data, but limited understanding in the interpretation of Doppler velocity and dual-polarization fields. Consequently, forecaster training was conducted during the FC on radar interpretation and use of the radar data to nowcast high-impact weather (see sidebar).The Rwanda Meteorology Agency's (RMA) dual-polarimetric radar in Kigali provides coverage of the western portion of LVB, but because it is located 150 km from LV, it is unable to provide low-level radar coverage over the lake. A Uganda National Meteorological Authority's (UNMA) dual-polarimetric radar was installed on the north shore of LV at Entebbe Airport in late June 2019. The only data available for analysis from this radar were collected in 2020 after the FC had concluded.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

One of HIGHWAY's core activities was the rehabilitation of NMHS Upper Air Stations (UASs; see Fig. 2) and Automatic Weather Stations (AWSs).The Kenya Meteorological Department's (KMD) UAS in Nairobi became operational in August 2019 and UAS in Lodwar by mid-October 2019.With just a few of the NMHS AWSs reporting to the WMO Global Telecommunication System (GTS), we relied on surface-station data provided by the Trans-African Hydro-Meteorological Observatory (TAHMO) and by the University Corporation for Atmospheric Research's 3D-Printer AWSs (3D-PAWS; Kucera and Steinson 2016). The stations provided higher spatial and temporal-resolution measurements along the northern and eastern shores of LV where many storms form. Other data collected during the FC include total lightning (in-cloud and cloud-to-ground strokes) from the Earth Networks Global Lightning Network (ENGLN) and imagery and products for nowcasting from the EUMETSAT geostationary satellite (Table 1). Unfortunately, no NMHS buoys were available for deployment on the lake to provide *in-situ* measurements of temperature, winds, and wave heights, preventing opportunities to understand the impact of the lake attributes (e.g. variable water depth across the lake, temperature gradients, convergence of currents, and wave heights) on thunderstorm initiation and intensification. Real-time monitoring of wave heights by forecasters and use of the buoy measurements for comparison with radar observations of low-level winds and with other NWP/nowcasting products was also not possible.

Diurnal Weather Patterns

Unlike mid-latitude convection, diurnal solar heating and the resulting lake and land breezes dominate the evolution of thunderstorms in the LVB. The result is fewer daytime thunderstorms

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

occurring over the lake (between 12-19 Local Time (LT[4])) and a late night/early morning maximum between 02-12 LT. During this nocturnal thunderstorm maximum, many fishermen are on the lake when the fishing is optimal.

The processes associated with this diurnal variability were first recognized by Flohn and Fraedrich (1966) using infrared satellite data. Numerous studies since have shown this regular diurnal variability using cloud and precipitation data from satellite, and more recently using lightning network and radar data (Albrecht et al. 2016; Thiery et al. 2016; Yin et al. 2000; Waniha et al. 2019; Virts and Goodman 2020). This diurnal variability is illustrated in Fig. 3 using lightning-flash density data for the period from 1 September 2014 - 1 March 2020. Most notable is the daytime peak in lightning to the north and east of the lake and the nocturnal maximum directly over the lake.

Our first examination of the FC data suggests that although storms that initiate over land are numerous and very intense, they nearly always dissipate before moving over the lake. The land storms regularly form in the lee of the mountains to the east and northeast of the lake. Visible satellite data suggest that as they move west toward the lake, these storms and their gust fronts briefly intensify as they collide with the lake-breeze front but then rapidly dissipate before reaching the lake owing to the ingestion of cool lake breeze air that cuts off the thunderstorm's updraft. There is some evidence by Thiery et al. (2017) that frequent afternoon thunderstorm occurrence over land during the day indicates there will be frequent thunderstorms that night

[4] LT=UTC + 3

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

over the lake. This may be due, in part, to general large-scale instability and convergent airflow over LVB that is favorable to storm development.

Radar Observations

Surprisingly, when examining the Mwanza radar data, we observed a large number of boundary-layer convergence lines (boundaries) over the lake. Observation of these boundaries is possible because of the large number of insects over LV. The insects are carried by the wind, thus mapping the wind field (Wilson et al. 1994) and the regions of converging flow. Previously, insects have not been observed over such large bodies of water because they typically resist traveling over water (Russell and Wilson 1996). These convergence boundaries are clearly visible on radar as reflectivity thin lines that mark the location of the low-level convergence and the resulting updrafts (Russell and Wilson 1997). Numerous studies have documented the relationship between these reflectivity thin lines and the resulting initiation, growth, and decay of storms (Wilson et al. 1998; Atkins et al. 1995; Wilson and Megenhardt 1997; Roberts and Rutledge 2003). Observing these same convergence lines over LV make it possible to detect and monitor thunderstorm initiation and evolution, especially at night when visible satellite imagery is not available. Figure 4 shows examples of the convergence lines observed over LV associated with gust fronts, land breezes, gravity waves, and boundaries of unknown origin.

Although the northern end of LV is 300 km from the Mwanza radar, the radar can detect and track nearly all the thunderstorms that occur over the lake due to the extreme heights of the thunderstorms. Comparison of ENGLN lightning locations with storms detected by the Mwanza

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

radar shows that radar reflectivities ≥ 35 dBZ are well correlated with the occurrence of lightning flashes. Comparison of these data also show us that the initiation of lake storms is generally independent of land storms. Days when >50% of the lake was covered by thunderstorms, the mean initiation time was 2120 LT and a majority of those storms formed in a narrow zone of water along the NE and E part of the lake. On days when < 10% of the lake was covered by thunderstorms, the mean initiation time was eight hours later at 0521 LT and initiation occurred in the middle of the lake. The days with the highest percentage of storms over the lake were mostly during the wet season and the lowest percentage days were in the dry seasons.

Prior to HIGHWAY, the strength of the thunderstorm outflows and their potential role in generating increased wave heights hazardous to small fishing boats was unknown. Now, with access to radar data, we can examine these processes. Figure 5a shows an example of an intense thunderstorm detected by the Mwanza radar with near lake-surface winds ≥ 25 ms^{-1} (Fig. 5b). A wind of this intensity is likely to produce waves that would be a serious threat to small boats. Over the next 4 h, we observed this storm on radar as it evolved into a squall line that moved westward across the lake, continually producing very heavy rain and 20-25 ms^{-1} (72-90 km h^{-1}) near-surface winds. Over such a long fetch, there is no doubt large waves (>2.0 m in height) developed. In Figs. 5c, d we see a storm that produced a microburst 11 km south of the UNMA radar and the Entebbe airport. Microbursts are a very serious threat to aircraft on landing and takeoff. They also pose a threat to boats on the lake. The smaller spatial extent of these downdrafts and divergent outflow creates strong wind shear over the lake that can increase waves and cause small boats to capsize. The frequency of microbursts over LVB is unknown; yet

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

HIGHWAY FC observations suggests they may be common[5]. Equally as dangerous are the strong southern so-called “slasher” winds reported by fishermen that occur over the lake when no storms are present. Both transport and fishing boats have capsized during this wind regime resulting in numerous drownings. It is not yet known if these winds result from synoptic or mesoscale forcing. Within close ranges (< 75 km) to the radar, the ability to observe these strong winds is possible, thanks to Doppler radar detection of clear-air winds. Continued research utilizing the many FC data sets should help advance our knowledge of thunderstorm initiation and evolution over the LVB.

3. NWP and nowcast products

NWP

In EA, NMHS forecasters have web-based access to output from a number of global models (e.g., UKMO, NCEP, ECMWF) and use these outputs along with recent observations and local knowledge, as guidance in issuing their local forecasts and advisories. For HIGHWAY, in addition to the UKMO Global Model, the UKMO began running an operational high-resolution (4.4 km) regional Tropical Africa (TA4) model, a convection-permitting version of their Unified Model (Walters et al. 2017**;** Bush et al. 2020) covering eastern tropical Africa. The TA4 is initiated from UKMO global model initial conditions (ICs), and run forward using lateral boundary conditions from the same global model. Data assimilation is used in the global model ICs, but not in the regional model, which can be considered as a “cold start”. The TA4 covers the

[5] Inspection of a few active weather days indicates there can be several microbursts on days when the boundary layer moisture is lower. A specific study has not yet been conducted on the diurnal frequency of microbursts and the total number of microbursts observed during the FC.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

period out to 54 h ahead and runs twice daily at 0600 and 1800 UTC (0900 and 2100 LT). Output is disseminated freely to participants digitally via EUMETCast products broadcast (EUMETSAT 2021) and as images on a UKMO internet portal.

Recent verification (Hanley et al. 2020) of TA4 shows that the higher resolution system provides improved representation of local-scale processes compared to the standard parameterized global model. This is primarily due to the higher horizontal resolution orography, and switching-off the convection parameterization, allowing the regional model to physically resolve convective processes. Over Lake Victoria, comparisons with aircraft observations (Woodhams et al. 2021) have shown that TA4 improves the diurnal cycle of convection, due to the better representation of the lake-land breeze in the afternoon/evening and the land-lake breeze during the night. The TA4 model includes a new lightning diagnostic that has been evaluated in Mittermeier et al. (2021), however a rigorous verification needs to be performed to determine whether the distribution and timing of precipitation follows a similar pattern to the observed lightning climatology in Fig. 3. An initial examination[6] was conducted to see whether the TA4 forecasts captured this diurnal variation in precipitation. The examination was limited to comparing the spatial distribution of TA4 precipitation rate with the radar reflectivity at times corresponding to the observed lightning climatology in Fig. 3. Only the spatial distribution and timing of precipitation are compared because of the difference in units of these two fields. Comparison of these fields in Fig. 6 for 19 October 2019 shows that the model does have skill. In Figs. 6a, b the model predicts rainfall primarily over the lake at 0900 LT and over the land at 1900 LT. The radar images, at these corresponding times (Figs. 6c, d), confirm a similar precipitation

[6] The data set lends itself to a much more rigorous evaluation of TA4

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

distribution. Furthermore, both the model forecasts and radar observations had diurnal maxima over the lake and land that were consistent with the lightning climatology. These preliminary results suggest the high-resolution model forecasts can correctly depict the occurrence of precipitation driven by the lake breeze circulation and provide useful guidance for forecasters, as was additionally confirmed by KMD forecasters who used the TA4 during HIGHWAY.

Not surprisingly, the precipitation patterns in the global model often differed from those depicted by the radar. The availability of the Mwanza, Entebbe, and Rwanda radars provide valuable information in the process of forecasting severe weather at short time scales, as well as in model evaluation as shown above. In the future, radar data also could be assimilated into regional models over Lake Victoria Basin to potentially further improve the performance of NWP forecasts and nowcasts of severe weather at very short forecast lead times of 0-6 h, as rapid assimilation of radar data into forecast models are showing significant progress in placing precipitation in the correct location (Benjamin et al. 2016).

Nowcasting products

Convection in the tropics lends itself to nowcasting applications that use near real-time observations, due to its systematic nature and persistence on hourly timescales. Through HIGHWAY and a sister project, GCRF African SWIFT[7], new nowcasting products were developed using the Nowcasting Satellite Applications Facility (NWC-SAF) software and Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI)

[7] Global Challenges Research Fund (GCRF) supports the African Science for Weather Information and Forecasting (SWIFT) project.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

imagery for the identification and tracking of thunderstorms over LVB while and after storms have initiated. These products[8] include atmospheric stability, Rapid Developing Thunderstorm, and Convective Rainfall Rate (NWC SAF 2019). These satellite-based tools were made available to NMHS offices via EUMETCAST. These tools foster forecaster situational awareness to remain vigilant of evolving hazardous-weather threats. Total, in-cloud and cloud-to-ground lightning density plots derived from the ENGLN data and total lightning forecasts by the TA4 model (Mittermaier et al. 2021a) were made available to forecasters through the UKMO. Although NWP products provide measures of pre-storm, near-storm and current environmental conditions, and thunderstorm characteristics, they provide stakeholders with little actionable information concerning the potential location and timing of convective events occurring in the near future.

To fill this information gap 3-9 hours into the future and provide a continuum of situational awareness between NWP forecasts and real-time radar/lightning/satellite observations, the Lagrangian NearCast model (Petersen et al. 2013) was enhanced and applied over the LVB. The observation-driven model projects multiple layers of full-horizontal-resolution SEVIRI retrievals (see Koenig and de Coning 2008) forward in time and space to better isolate areas where convective destabilization is most (and least) likely occurring. Products are updated twice hourly and are available within 5 min of data collection, and can be particularly helpful in real-time monitoring of NWP performance. Prior to HIGHWAY, training on NearCast, satellite, and lightning nowcasting was provided to forecasters in EA at a WMO-sponsored workshop, on

[8] These products can be found at the following website: https://sci.ncas.ac.uk/swift/resources/view/10622955

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

behalf of SWFP. Through HIGHWAY, these products are now being produced for EA, the first region in the tropics to have access to these data. The Supplement provides examples of NearCast, radar and lightning nowcast products available to NMHS's for 6 March 2019, along with animations of these products and loops of Visible and Infrared imagery that highlight the initiation, rapid development, and propagation of a squall line that moves south down Lake Victoria.

4. Development of an Impact-Based Early Warning System

National and regional workshops

Prior to the HIGHWAY project, there was a lack of trust by fishermen and other end-users in the NMHS forecasts produced for the LVB as they were very general in nature and issued once per day for the whole region. Baseline reports compiled at the start of HIGHWAY estimate that the number of users receiving weather information was less than 5% (Watkiss et al. 2020). Fishermen did not regard the forecasts as useful or actionable, as they contained very little information of relevance to small boat users in LV (Watkiss et al. 2020). Those whose livelihoods depend on the lake need frequently updated outlooks of when weather conditions may change during the day to inform their decision making and to take precautions in planning fishing trips and other small journeys in boats. A major undertaking of the HIGHWAY project was to engage the NMHSs to work closely with LVB stakeholders, community intermediaries, and end-users to develop impact-based early warnings (i.e., outlooks for hazardous weather) that are accurate and useful for lake users. *The use of convective outlooks and impact-based warnings are a new direction for NMHSs in Africa, providing information and advice pertinent to the user, rather than solely offering meteorological information.* Thus, HIGHWAY employed a co-

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

production process (Carter et al. 2019) for the involvement of users, intermediaries, and producers in the development and delivery of marine forecasts and warnings.

Workshops were held in each country with NMHS participants, HIGHWAY communications facilitators, representatives from the user groups, the media, and local government officials responsible for fishery and marine safety. Concepts of impact-based warnings were introduced to gain an understanding of the needs of the users, and to establish local, national, and EA regional networks. During the workshops, stakeholder representatives shared their experiences of how severe weather affected their lives and livelihoods, and how they made decisions related to their work. They discussed the need to get daily marine forecasts with accurate information about wind speed and direction, wave heights, and other weather hazards before the start of each voyage, so that they could plan their route and decide on precautions to take. They wanted forecasts and severe-weather warnings disseminated in manner that was understandable and in their native or national languages[9].

NMHS meteorologists worked with the stakeholders to identify the weather information that was available to meet their needs, and how best to provide high-impact information as well as meteorological variables. The key outputs of the workshops were 1) clear user requirements and guidelines to inform the development of services, 2) impact tables for describing the risks associated with severe weather and recommended mitigation actions, and 3) plans for improved

[9] Native language in south-central Uganda is Luganda; Swahili is the national language for Uganda, Tanzania and Kenya; Kinyarwanda is the national language for Rwanda.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

communication and dissemination, and standard operating procedures (SOP) for production of marine forecasts.

Following the initial rounds of national workshops, two EA regional workshops were held. The purpose was further refinement of forecast products and to increase their impact. These regional workshops were also an opportunity for cross-learning between the countries involved (Chang'a et al. 2020) and sharing best practices. UNMA learned from KMD's experience in co-designing a marine forecast with local fishermen, and ultimately produced a marine forecast very similar in form and content to what KMD was using. TMA also revised their forecast procedure to conform to KMD's and UNMA's to provide marine forecasts that were more actionable, both for fishermen and for commercial shipping. In addition, TMA shared its wave-height forecasting model with KMD and UNMA.

A major outcome of the two EA regional workshops was an agreement among KMD, UNMA, and TMA to divide the lake into 10 marine forecasting zones to enhance resolution, relevance, and effective utility of the forecast products (Fig. 7). *As a consequence of these collaborative actions, and the relationships and trust established between individuals from the different NMHSs, a regional harmonization of the forecasts for LV occurred daily by way of forecaster phone discussions.*

NMHS marine forecasts

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Each NMHS with responsibility for LVB has an SOP comprised of scope, goals, and objectives that include use of forecasting tools, NWP models, real-time analysis, and use of plotted synoptic and climatological charts. Satellite imagery is used for continuous monitoring of the weather. Radar data, upper-air soundings and Tephigrams, AWS observations and Meteograms provide frequently updated information. During HIGHWAY, forecasters used the meteorological data and forecasting tools that were available to them, including the UKMO TA4 model. Forecasters then followed a Marine Forecast Procedure flow chart and filled out a marine template to produce marine forecasts.

As an outcome of the national and regional workshops, the NMHSs developed bi-lingual reference guides for fishermen to interpret weather forecasts. This guide emphasized the meaning of standard terms used to describe the weather and explained the icons used. For example, a strong wind defined in meteorological terms as 41-60 km h^{-1}, is translated for local fishermen as "the wind that causes large trees to sway, can cause large waves and make navigation conditions difficult for small boats." Similarly, meteorologists define the height of moderate waves on LV as 1.0-1.5 m. This does not mean much to most fishermen. However, comparing the wave to the height of a man communicates the information clearly (see Fig. 8); a wave icon indicates danger when the wave height (indicated by the orange dashed line) is at or higher than a man's neck (Fig. 9). Waves > 1.5 m in height from crest to trough are considered dangerous for open canoes that catch fish and transport goods and passengers on the lake. Waves of this size can fill the boat with water and cause it to capsize (e.g., see WhatsApp sidebar). Forecasts and icons were provided by each NMHS (e.g., Figs. 8 and 9) in English and in the

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

local languages commonly used by fishermen, enabling them to understand the forecast information easily, even if they cannot read English.

For each zone (Fig. 7), a weather-forecast summary is given twice a day, based on the NHMSs 12 and 24-h forecasts, SOP real-time observations, and analyses. Each NMHS produces its own set of 12 and 24-h weather forecasts that are issued at ~03:00 and 15:30. The early morning forecasts provide fishermen with the latest information on wind speed and direction, and any severe weather expected prior to the start of their daily voyage so that they can plan their routes and decide which precautions to adopt. The mid-afternoon forecasts are for the fishermen who fish at night.

The marine forecasts are distributed to fishermen in various formats and vary slightly for each country, but in general, provide outlooks for wind strength, wind direction, wave height, weather, rainfall, visibility, and hazards. A key to the hazard warning colors (red, orange, and green) is also provided (Fig. 9). Intermediaries, such as staff from Beach Management Units (BMUs), are trained to provide guidance to fisherman in understanding forecast icons and hazard warnings (Fig. 10). Advice to small-craft users, for a particular zone, is given as follows.

Red warnings are for fishermen to postpone their boat trip until weather conditions improve and large waves have subsided. Conditions on the lake are expected to be dangerous and life-threatening. There is a high risk that small boats may capsize, break, or sink.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Orange[10] warnings are for fishermen to seriously consider postponing their boat trip until weather and lake conditions have improved. If fishermen do go to the lake, check that the boat is seaworthy and of standard length (≥ 28 ft). Ensure that everyone on board is wearing a life jacket and it is fastened. Carry a large metal anchor and plenty of strong rope. Ensure that the boat's emergency phone is charged with power and air time. Avoid overloading the boat and ensure that cargo and passengers are well balanced. If the boat has an engine, carry plenty of spare fuel, as motor boats use more fuel in rough weather.

Green warnings are to notify fishermen that no severe weather is expected.

Improving communication and dissemination of forecasts and warnings

Weather forecasts and severe-weather warnings are broadcast to fishing communities in Kenya and Uganda daily in their native languages. In Tanzania, radio stations broadcast the TMA marine forecast in the national language Swahili, which is understood clearly by nearly everyone. About half of the 50 or so local and regional radio stations that broadcast to lakeside and island communities in Kenya, Uganda, and Tanzania carry the marine forecasts. Radio stations provide vital and accurate information on weather conditions on the lake before the boats leave their landing sites in early morning and late afternoon. Radio broadcasters were trained to understand and interpret the new marine forecasts and how to script concise bulletins that contained all the essential weather information needed by their listeners. David Agangu, a presenter on Nam Lolwe FM in Kisumu, Kenya (Fig. 11a), notes that *"The information that is being sent to us by the Kenya Meteorological Department is in simple language. This makes it*

[10] Tanzania and Uganda issue Orange warnings; Kenya issues this same level of warnings but uses an Amber color.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

easy for us to understand and for me as a presenter to do the translation in order to transmit it in my local language. The illustrations which accompany the text help us to broaden our explanation to the listener."

With the advent of the WhatsApp social messaging application, which is free to users, and increasing use of smartphones in LVB, the HIGHWAY project set up dedicated messaging of marine forecasts for LV to community intermediaries at landing sides (Fig. 11b), radio journalists, government officials and influential individuals. Recipients of the marine forecasts then immediately forward the forecasts to dozens, sometimes hundreds, of other people in the WhatsApp group to which they belong. This cascades the weather information rapidly to thousands more people. PDF-formatted documents and images, such as the marine graphics forecasts (e.g., Fig. 8) attached to the WhatsApp message, can communicate much more weather information than the SMS messages that are not free for users. Forecast users can also give immediate and spontaneous feedback on the accuracy of weather forecasts, on weather hazards over the lake or accidents that have occurred on the lake (see WhatsApp Communications sidebar for examples).

Increased trust in the twice-daily forecasts has made people confident about using the weather information to plan fishing trips and other journeys in small boats and take severe weather warnings seriously whenever they are issued. Robert Bakaki, a national fishermen's leader in Uganda, who operates fishing boats and fuel supply boats on Lake Victoria, comments that "*The forecasts are always timely, accurate, reliable and easily understood. They help me plan my*

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

daily activities, minimizing fuel costs and eliminating potential risks and dangers to both my crew and my boats."

5. Socio-economic benefits

New forecasts and impact-based warnings are now reaching the lakeside communities and fishermen. Are they providing value? To answer this, we conducted a socio-economic benefits (SEB) study to assess the reduced fatalities and losses resulting from these new marine forecasts and warnings for LV. The method for this study is based on WISER and WMO SEB guidance (WMO 2015; WISER 2017) and prior examples (Clements et al. 2013). The methodology involves identification of baseline conditions, and then the analysis of the change (the benefit) with the new weather and climate service in place. These include tangible benefits, such as the reduced loss of boats. It also includes intangible (non-market) benefits, including reduced fatalities.

At the start of HIGHWAY in 2018, the SEB study (Watkiss et al. 2020) conducted new analysis to assess the number of fatalities each year on the lake. It is extremely difficult to get baseline fatalities, as reliable statistics on drownings and boat accidents do not exist across all three countries, and because many incidents simply go unreported. The baseline analysis conducted surveys and interviews with relevant local representatives, and complemented these with local focus group discussions, along with re-analysis of previous studies (Kobusingye et al, 2017; Tushemereirwe et al. 2017; Whitworth et al., 2019). These analyses indicated that the number of people who die on the lake is likely lower than the previous 3000-5000/year estimates, estimated at 1500/year, due to more routine use of life jackets, the trend towards larger boats and reduction

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

of boats going out in bad weather. Also, not all drownings are due to weather-related events; some are due to other reasons. Based on the limited information on causes of drowning from surveys in the literature, an indicative estimate was made that two-thirds of fatalities were weather related. Given this new data, the baseline estimate for weather-related fatalities on the lake was estimated to be 1000/year. Furthermore, it was estimated from existing reports, that < 5 % of users were getting relevant lake weather information. With these baseline metrics, we analyzed the benefits arising from HIGHWAY project activities across the value chain (Fig. 12) using a combination of desk analysis, field research, interviews, telephone, WhatsApp discussions, and focus groups. Fifteen focus groups were held for the study in Uganda and Kenya, at different landing sites and BMUs to gather information on the communication, perceived accuracy and application of the HIGHWAY regular weather forecasts and severe weather warnings. Our study focused on Kenya and Uganda where the marine forecasts had been up and running for a year. Data was extrapolated to assume similar benefits in Tanzania. The findings (Watkiss et al. 2020) for each activity in the value chain (Fig. 12) are as follows.

Foundational activities, which include advances in the science, investment in meteorological instrumentation, meteorological staff training and capacity building, have led to improved forecasts, with higher resolution and accuracy for the lake. Field research showed high levels of awareness and use of the forecasts in fishing communities. Focus-group discussions at landing sites (Fig. 10b) in all three countries found that *most participants estimated the marine forecasts were useful on about five of the seven days in the week, that is, about 70% of the time.*

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Tailored lake forecasts and improvements in the way weather information was communicated to lakeside and island communities has dramatically improved the reach and impact. The forecasts were targeted to selected local radio stations, with training to translate the forecasts into local languages, along with guidance on the times to broadcast weather bulletins. HIGHWAY piloted the use of WhatsApp to disseminate the forecasts. *Findings from focus groups in Kenya and Uganda in mid-2020 indicated high levels of awareness and usage of the marine forecasts among fishing communities. At some landing sites where community outreach initiatives had taken place to raise local awareness of the forecasts, they influenced ~75% of the lakeside population.* However, field research in Tanzania in December 2020 found much lower levels of awareness and usage of the TMA marine forecast in the Tanzanian sector of LV, partly because it was only being broadcast by two local radio stations.

Communication and uptake of lake-weather information at selected landing sites through the use of community intermediaries, weather flags, and weather noticeboards (Fig. 10b) have led to greater use of information. The focus groups at landing sites indicated that *75% of those who receive weather information use it to inform their decision making.*

In response to the new marine forecasts and severe weather warnings, fishermen and small passenger boat operators are wearing life jackets, wet-weather gear and taking extra fuel, and if severe weather is forecast, they are postponing or cancelling trips. Boat owners and skippers secure vessels at the landing site to prevent damage from high wind or large waves. Interestingly the surveys found new use of the weather information. Skippers use wind and wave information from the forecast to adjust their routing to reduce fuel consumption and save money. Silver-fish

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

dryers and traders cover fish to protect them from rain, and alter their fish purchasing strategy if rain is forecast. Other stakeholders, such as lake travelers, subsistence farmers, tourism operators, and a local electricity and water supply company in the Ssese Islands, use the marine forecasts to inform their decisions.

Importantly, a new analysis was done through the SEB study (Watkiss et al. 2020) to estimate the benefits of the new service, based on the new baseline of 1000 deaths per year described earlier, and the survey results presented above. *The SEB study estimates that the HIGHWAY marine forecasts are avoiding 312 deaths/ year and leading to approximately a 30% reduction in weather-related deaths on the lake.* This claim was supported by the interviews. The available statistics gathered from the interviews and analysis, before and after the service had been running, indicate that drownings have fallen by around one third to one half in both Uganda and Kenya.

The economic value of the reduced impacts has been calculated. For the valuation of fatalities, the focus is on valuing the change in the risk of mortality. There are different approaches that can be used for valuing such changes. For this study, the SEB analysis (Watkiss et al., 2020) used the value of statistical life (OECD, 2011), transferred to the relevant East Africa context using the approach from Cropper and Sahin (2009) and from Milligan et al. (2014). The impact on dependents was captured by applying an uplift to these values. The additional benefits of material losses associated with the reduced loss of boats and gear, as well as the benefits from improved fuel efficiency and reduced fish drying losses, were estimated based on the survey and

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focus group information and local cost data. *Adding all tangible and non-tangible benefits together, the study estimates that the economic benefits of HIGHWAY activities are $44 million/year (central value).* The valuation from reduced fatalities dominates all the values contributing to this total.

6. EWS Vision 2025

Once small-boat users are out on the lake, they are unable to receive weather information in real-time, thus new effort needs to be directed toward producing location-specific severe-weather warnings (Mittermaier et al. 2021a, b) and maps that indicate areas of particularly high risk. Currently, marine forecasts underestimate the wave height on the open water; there is no capability to forecast waterspouts; and research is still needed to improve forecasts of adverse weather conditions that are known to disrupt the navigation of larger transport vessels.

Proposals were drafted by each NMHS on the activities they should pursue at the conclusion of the HIGHWAY project. These proposals were consolidated into an agreed-upon vision for a regional EWS with an implementation pathway through 2025.This EWS Vision 2025 plan is supported by the East African Community (EAC). The EAC and NMHSs propose to enhance existing marine weather information and expand its coverage to other regions of EA and lakes impacted by severe weather such as Lake Tanganyika and Lake Kivu. It calls for the siting of a new radar near Kisumu in western Kenya, which will provide better radar coverage of the NE corner of LV and complement radar coverage of the lake by the Mwanza and Entebbe radars.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Vision 2025 anticipates the installation of weather buoys in the Kenyan, Tanzanian, and Ugandan sectors of LV to provide near-surface wind speed and direction, water temperatures, and wave heights on the lake. The plan also includes installation of additional automatic weather stations on islands in the lake. With the launch of EUMETSAT's Meteosat Third Generation (MTG) satellite in late 2022, the new Infrared Sounder (IRS), Flexible Combined Imager (FCI), and Lightning Imager (LI) will serve as sustained data sources to diagnose and characterize the pre-convective environment and monitor storm initiation, development, and evolution over the region (Holmlund et al. 2021). MTG will be a transformational advancement for weather services throughout Africa providing 10 min full-disk multispectral imagery, 30 second total lightning, and 6-hourly soundings over the LVB region. New satellite products will combine the lightning, imager, and sounder into a "seamless" 4-D data cube that can be combined with NWP and radar.

Under Vision 2025, EAC and NMHSs propose to enhance regional cooperation with pooled resources, harmonize practices and knowledge exchange to deliver impact-based early warnings across East Africa. Long-term funding will be essential to maintain and access all of the observational platforms, to support a repository of necessary replacement parts and consumables, and support technicians, engineers, and scientists to maintain these instruments and utilize these observations. Avenues of long-term funding from international donor foundations and high-level ministries in each country will be the crucial next step, beyond the HIGHWAY project, towards the sustainability of a regional EWS.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

7. Summary

The HIGHWAY project was charged with developing a pilot regional Early Warning System for LVB that would reduce the loss of life and property damage through the increased use of weather information and improved marine forecasts. The EWS developed during HIGHWAY included 6-24 h forecasts, convective outlooks, watches and advisories that allowed fishermen, lake travelers and lakeside communities *to take action to plan* their diurnal activities. The EWS did not include warnings, as used in the traditional sense, as an alert for impending severe weather where *immediate action should be taken* to save lives and property.

The HIGHWAY project was highly successful under the FCDO funding and leveraging of other ongoing projects (e.g., WISER MHEWS, WMO SWFP, SWIFT, HyVic, NASA and USAID SEVIRI projects), in development of a pathway for an EWS for LVB, laying the foundation for a sustainable, regional EWS and instigating transformational change in the region. The success of the project was also possible through the leadership of the WMO and its mandate in coordinating the NMHSs in this regional activity. Initially, there was little buy-in into the project by the NMHSs. However, through the collaborations established by forecasters and managers during the regional and national workshops, trust was established between key individuals in the different NMHSs that led to the division of LV into ten agreed upon forecasting zones and the regional harmonization of the marine forecasts for LV. Consultations now occur daily between KMD, TMA and UNMA to align the EWS content and coordinate severe weather forecasting in EA as a whole.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

NMHS offices now issue specific weather forecasts twice daily for the zones on the lake. These marine forecasts are shared with the LVB community in their local languages by radio broadcasters, BMU managers, local intermediaries, and WhatsApp reaching thousands of people. From the cooperative process of producing and communicating user-actionable marine forecasts and products, fishermen and boat operators now have increased trust in the forecasts and hazardous-weather warnings. Fishermen, lake travelers, and lakeside communities now take action and precautions to travel safely on the lake and protect their livelihoods. There is also safer navigation on the lake, financial benefits from fuel savings, and avoided losses (damage to boats, lost nets, and lost boats). *As a result, a 30% reduction in drowning fatalities is likely to have occurred, which when combined with the reduction in other weather-related losses, generates estimated socio-economic benefits of $44M/year. These are substantial outcomes from the HIGHWAY activities discussed in this paper.*

As further evidence of transformational change in the region, forecasters now (or soon will) have ready access to the TA4 model guidance and nowcast products, frequently updated observations from the EUMETSAT MTG LI total lightning, IRS sounder, and FCI imager data, twice-daily upper-air soundings, and rehabilitated surface stations that are being added to the GTS. EUMETSAT's cooperation with Africa is part of its strategic objective to expand the user base for EUMETSAT data, products and services. It reflects a long-term commitment that facilitate sustainability of the investment made at user level to exploit the data and generate regional or national weather and climate services in support to various socio-economic sectors (https://www.eumetsat.int/work-us/support-africa). Further, the Abidjan Declaration, signed in September 2018, illustrates the strengthening of capacities in Africa and preparing access to and

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

exploiting data from the MTG satellites. This declaration encourages the creation of an African Meteorological Satellite Applications Facility (AMSAF) aimed at generating African-tailored products that meet specific regional needs across Africa. The SWIFT project also increases the availability of the EUMETSAT SAF Nowcasting products to users through satellite product training and developmental testbeds to foster the early use and adoption of the new satellite products (https://africanswift.org/2021/04/26/european-satellite-data-key-african-nowcasting/).

The TMA Mwanza and UNMA Entebbe radars have opened up exciting new opportunities for forecasters to understand severe-storm initiation and evolution, and as a foundation for time and place-specific nowcasting, detection and warning of severe weather. Forecasters have clearly benefited from HIGHWAY radar and nowcasting training as those in Uganda are now actively using their radar to produce 0-2 h nowcasts and warnings of severe thunderstorms and strong winds for lake users (Fig. 13); nowcasts that can be included in the regional EWS.

The Vision 2025 plan includes strengthening observation skill, modelling and developing 0-6-h nowcasts and warnings that use the high-resolution observations to provide location-specific information of imminent hazardous weather. Sustainability for a regional EWS is being pursued through high-level political buy-in and identifying overseas financial assistance. HIGHWAY has promoted a significant shift in how EAC Ministers, NHMS offices, and key stakeholders are approaching an integrated regional Early Warning System for East Africa, saving lives and property

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

8. Acknowledgments

We gratefully acknowledge the support provided by Estelle de Coning, Tim Oakley, Alessandro Chiariello, Hugo Remaury, Paolo Ruti and Josephine Wilson of the WMO throughout the HIGHWAY project and for WMO support for the publication of this manuscript. We are indebted to those who shared their data: Frank Annor and Nick van de Giesen (TAHMO), Paul Kucera (UCAR; 3D-PAWS), EarthNetworks for the ENGLN, Vaisala for the GLD360, Pascal Waniha and Benedicto Katole for TMA radar data, and Christopher Amechu for UNMA radar data. Lightning data from Earth Networks and Vaisala were made available to project participants by the NASA Global Hydrology Resource Center Distributed Active Archive Center (GHRC DAAC). Data sets used in this study are available from the Met Office and NCAR. We thank Scot Loehrer, Carol Costanza and Greg Stossmeister (of NCAR) for writing software to display FC data on the NCAR/EOL field catalog (http://catalog.eol.ucar.edu/highway), Daniel Megenhardt for ingest of data into CIDD, and Mike Dixon for installing CIDD at TMA. NCAR staff were supported under the UK Met Office/WMO contract ABEJ-XP6A6B and UCAR/NCAR contract 20180035. Funding for the University of Wisconsin-Madison was provided by the UK Met Office award MSN217865. Steven Goodman was supported in part by the NOAA GOES-R satellite program, Met Office PO #P105101, and by WMO SSA #13946-20/GS/PEX. Katrina Virts was supported by the NASA Post-Doctoral Program and the GOES-R satellite program. We thank Marianne Koenig for her support in development of the project while at EUMETSAT. We especially acknowledge Paul Joe for his formal review of this paper and for spearheading the initial discussions with the EA NMHSs, prior to HIGHWAY, on developing a nowcasting system for Lake Victoria. The HIGHWAY project was made possible

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

with the financial contribution of FCDO through the WISER programme, and the participation and support of James Kivuva of the EAC and the NMHS Directors: Agnes Kijazi (TMA), Festus Luboyera (UNMA), Stella Aura (KMD), and Aimable Gahigi (RMA).

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10. Sidebars

Sidebar 1. Forecaster training

Training and dissemination of knowledge was an ongoing thread throughout the HIGHWAY project and has built a longer legacy to its outcomes.

The WMO provided training to East African forecasters, engineers and technicians on launching radiosondes (Fig. SB1) following the rehabilitation of the Nairobi and Lodwar UAS equipment midway through the Field Campaign. The training was held at KMD, Kenya and was also attended by forecasters and technicians from other NMHSs in the region.

Two training workshops were provided by radar meteorologists from the National Center for Atmospheric Research for forecasters on radar interpretation and thunderstorm nowcasting. One of these workshops was held at TMA's central forecast office in Dar es Salaam, Tanzania using

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Mwanza radar data, and the other workshop (online due to COVID) was hosted by UNMA's Entebbe Numerical Meteorological Center using data from the recently installed Entebbe radar (Fig. SB1). Forecasters were taught to identify squall lines, severe thunderstorms, strong low-level winds, microbursts and potential waterspouts in the radar data and anticipate their evolution and propagation. Feedback was positive. The forecasters appreciated the training and requested more of this hands-on type of training on radar meteorology and nowcasting techniques in the future.

Training was also used to disseminate the knowledge generated under the science component of HIGHWAY. UKMO scientists and international meteorologists working for the HIGHWAY project, in conjunction with WMO and GCRF-African SWIFT, ran several training events for forecasters across East Africa. In Entebbe, Uganda on January 2019, training on nowcasting and numerical weather prediction, as well as training on the use of MODE-S receivers, was delivered at the same time as the HyVic-pilot flight campaign (Woodhams et al. 2019) to take advantage of Met Office science staff already visiting the country. A separate training event was held in Nairobi in February 2019 to train forecasters in how to use and interpret model products and produce warnings. This was followed up in April 2019 with a forecasting testbed (led through GCRF African-SWIFT), also in Nairobi, where these products were used in real time to forecast, monitor, and evaluate severe-weather events occurring across East and West Africa.

Towards the end of the HIGHWAY project, an online (due to COVID travel restrictions) SWFP event was held. This was coordinated by the WMO and attended by Kenya, Uganda, Rwanda,

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Burundi, Tanzania, Ethiopia, and South Sudan. Training on NWP was delivered alongside a more interactive session aimed at capturing forecaster needs, which will help inform future requirements for product development.

As a result of these training workshops, forecasters cited a desire for a platform or mechanism to facilitate collaboration, peer-support, and transfer of knowledge between experts and forecasters amongst East African organizations. Forecasters also indicated a willingness to be involved in research projects in the future, demonstrating that training has an additional benefit in that it stimulates interest in research amongst operational meteorologists, breaking down barriers, and creating a more active and engaged international community.

Sidebar 2. Communication of Marine Forecasts on WhatsApp

Using the WhatsApp social media tool, fishermen and other users provide comments to the weather services on their experiential impressions of forecast accuracy, establishing a feedback loop for forecast improvements. Examples of two of these types of exchanges of a BMU chairman and a lake traveler with the UNMA NMC forecaster group are shown in Fig. SB2a. Forecast users can also give immediate and spontaneous feedback to those in their NMHS marine forecast WhatsApp groups on weather-related hazards over the lake, life-threatening weather, and accidents that have occurred on the lake, as illustrated in Figs. SB2b, SB4, and SB5 respectively. The location of these March and May 2020 events are shown in Fig. SB3.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

The capsizing of the waterbus catamaran ferry on Saturday, 2 May 2020, occurred within KMD's Zone IX (Open Lake – Siaya, Busia), close to Kenya's marine border with Uganda (Fig. SB3). The KMD marine forecasts for Zone IX on 2 May (Fig. 8), indicated that only small waves, light winds, moderate rain and no weather hazards were expected. The UNMA Zone X (Buvuma and Northeast; Fig. 9) immediately west of KMD's Zone IX, showed an orange warning for 2 May, with moderate winds, widespread thunderstorms, and moderate (1.0-1.5 m) wave heights expected. Neither of the forecasts predicted the 2.0 m wave heights that did occur. Because of the uncertainties associated with any forecast, particularly in predicting wave heights, fishermen and other groups that rely on marine transport and smaller informal transport are members of both the KMD and UNMA marine forecast WhatsApp groups.

11. Tables

Table 1. Lake Victoria Basin observations[1] from the HIGHWAY Field Campaign.

Instrument	Organization	Location	Data collection	Data frequency
10-cm dual-pol radar	TMA	Mwanza, TZ	5 Mar–31 Dec 2019	10 min
5-cm dual-pol radar	RMA	Kigali, Rwanda	1 Mar-31 Dec 2019	10 min
5-cm dual-pol radar	UNMA	Entebbe Uganda	31 Jan-2 March 2020	10 min
UAS (63741)	KMD	Nairobi, Kenya	9 Aug–31 Dec 2019	00 and 12 UTC

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UAS (63612)	KMD	Lodwar, Kenya	29 Oct-18 Nov 2019	00 and 12 UTC
UAS (63705)	UNMA	Entebbe, Uganda	Intermittent	Once daily
Synoptic AWS Surface Stations	KMD, TMA, UNMA	LVB	5 Mar – 31 Dec 2019	1 and 3 hourly
TAHMO Surface Stations	TAHMO	Uganda, Kenya and Tanzania	1 Mar – 31 Dec 2019	5 min
3D-PAWS Surface Stations	UCAR	14 stations in Uganda and Kenya	12 Feb-25 Aug 2019	15 min
Total, IC and CG Lightning	EarthNetworks	Receivers in LVB	1 Mar–31 Dec 2019	Continuous
Mode-S aircraft	UKMO	Entebbe, Mwanza, Kisumu, Nairobi, and Dar es Salaam	Feb-Nov 2019	Continuous
Meteosat Second Generation (MSG-11) satellite	EUMETSAT	Geostationary	1 Mar–31 Dec 2019	5 and 15 min

[1] FC images are posted on the NCAR HIGHWAY field catalog located at http://catalog.eol.ucar.edu/highway

12. Figures

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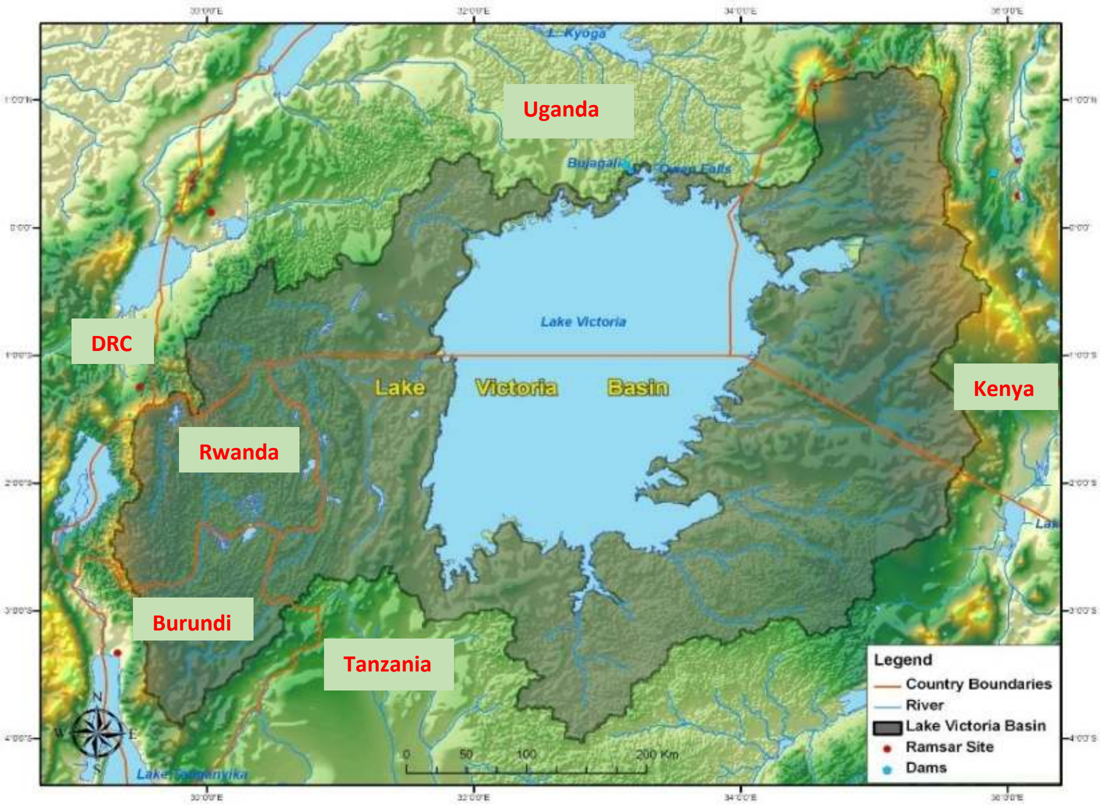

Figure 1. Lake Victoria Basin topographic map. Black polyline shows the horizontal extent of LVB. Orange polylines mark the boundaries of the five countries in the basin: Uganda, Kenya, Tanzania, Burundi, and Rwanda. Courtesy of Amos Christopher Ndoto, Lake Victoria Basin Commission.

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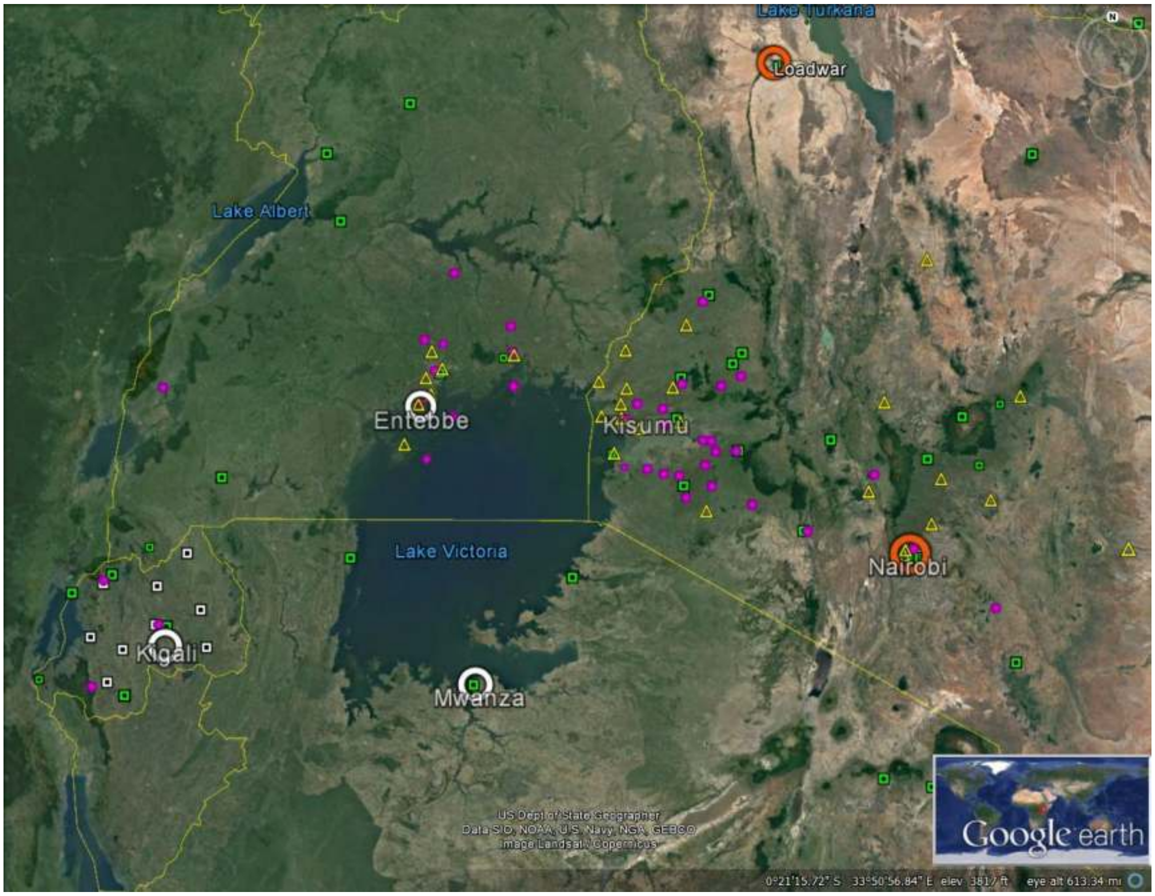

Figure 2. Locations of the ground-based instrumentation available during the FC overlaid onto a Google earth topography map. Instruments shown are dual-pol radars (open white circles), upper air stations at Nairobi and Lodwar (orange circles), 3D-PAWS (yellow triangles), TAHMO stations (magenta circles), NMHS AWSs reporting to the GTS (white and green squares).The yellow polylines mark the country boundaries.

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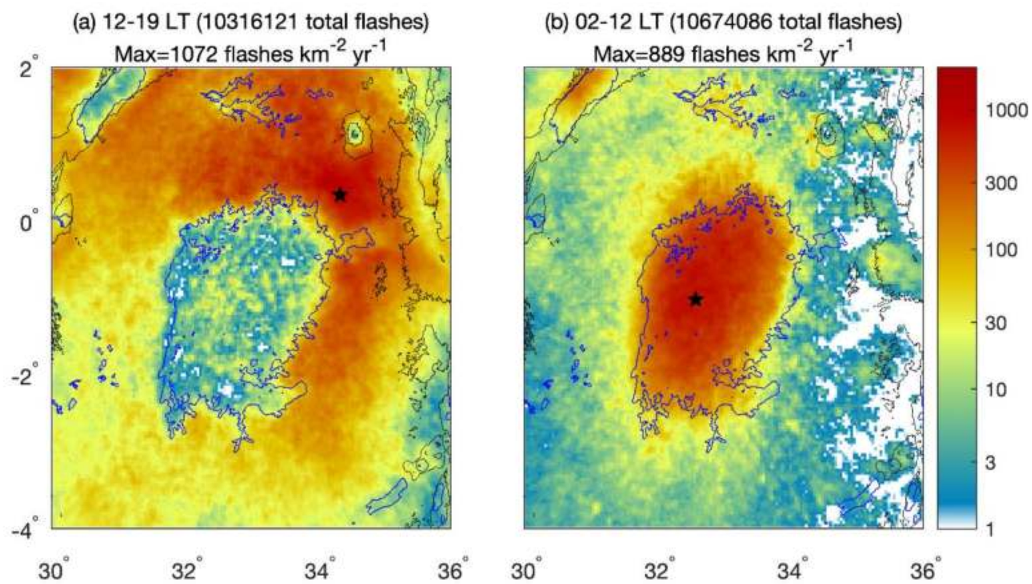

Figure 3. Diurnal comparison of the ENGLN average total lightning density (flashes km^{-2} yr^{-1}) during (a) afternoon and evening from 12-19 LT, 8 hours duration and (b) late night and early morning from 02-12 LT, 11 hours duration, for the period September 2014-March 1, 2020. The total flashes (10 million plus) and the maximum value in the domain is given at the top of each plot. Elevation contours at 1000-m intervals are in black. The black star indicates the location of the maximum flash density during the period (over the complex terrain northeast of the lake during day and directly over the lake at night).

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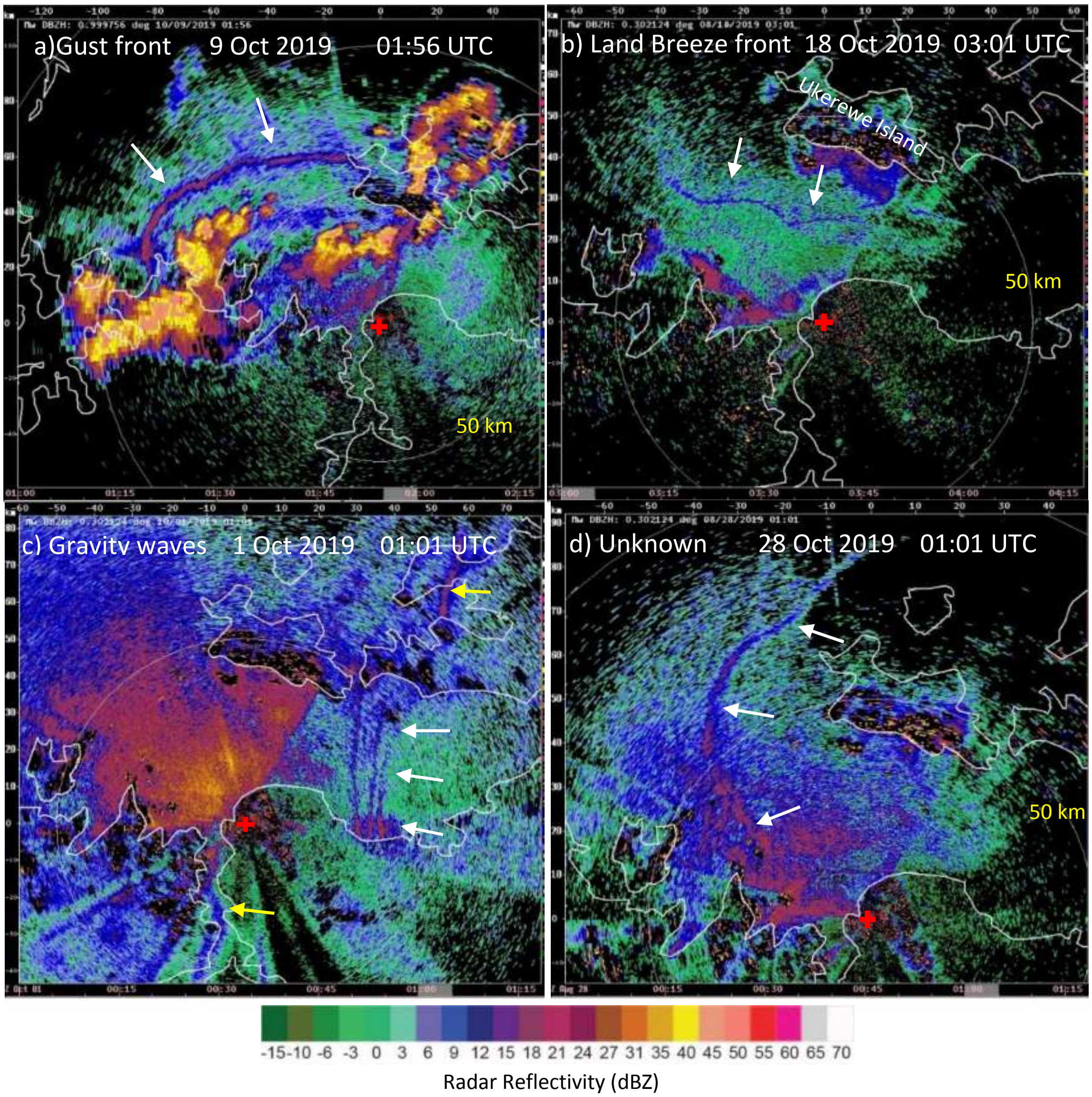

Fig 4. Mwanza radar reflectivity field from four different days (a)-(d) showing examples of thin lines associated with boundary layer convergence lines over Lake Victoria. The white polyline is the southern shore of Lake Victoria. The white arrows point to the boundary location in each panel. The yellow arrows in (c) point to unknown boundaries. All these boundaries initiated storms. The location of Ukerewe island, the largest island in Lake Victoria, is shown in (b).

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Radar range rings (light gray) at 50 km are shown. The red cross is the Mwanza radar location. The large region of 15-35 dBZ echo to the NW of the radar over the lake in (c) is from biological scatters.

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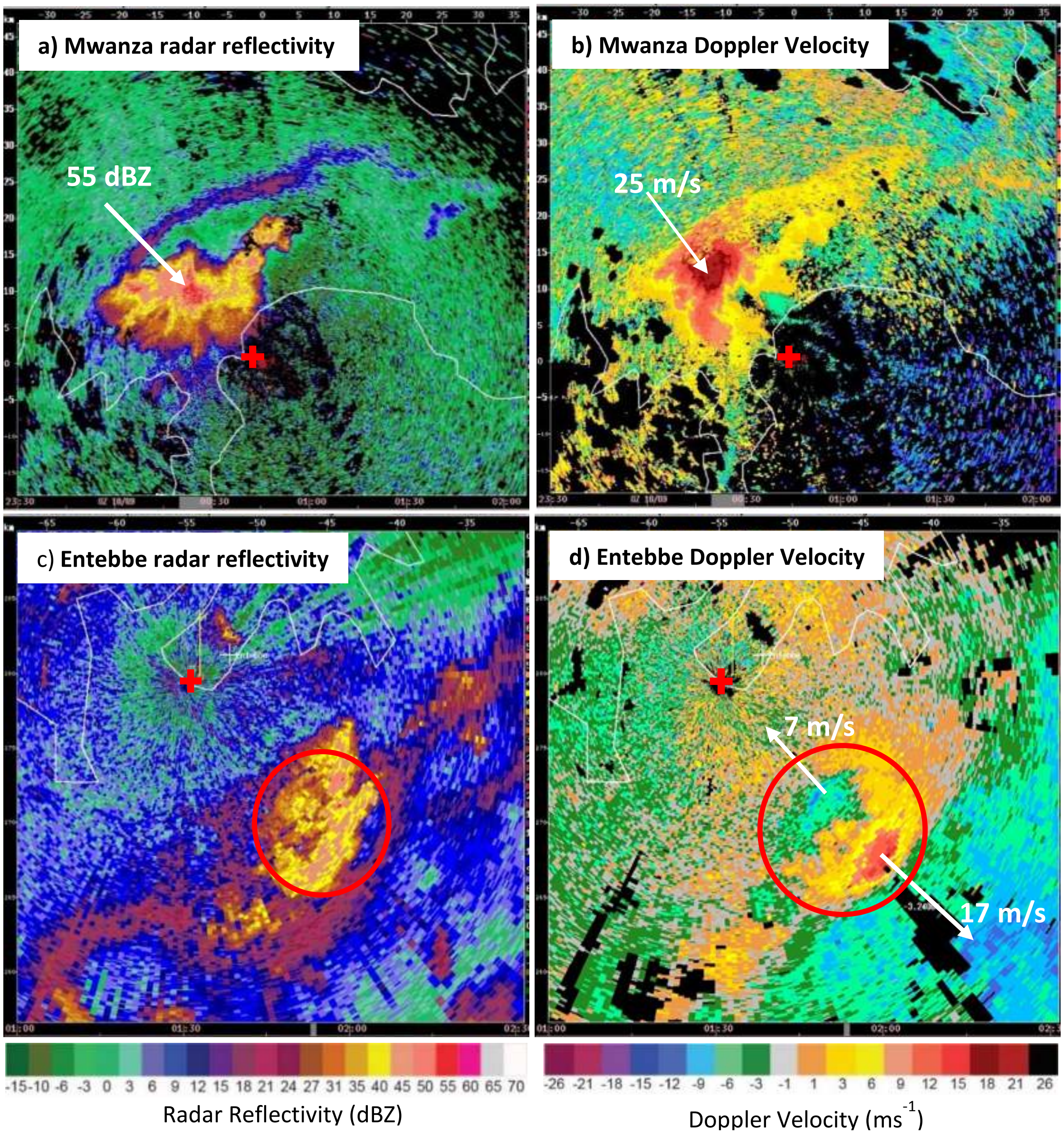

Figure 5. Radar reflectivity (in dBZ) and Doppler velocities (in ms^{-1}) associated with a severe storm and a microburst. Severe storm 15 km NW of the Mwanza radar over Lake Victoria on 9 October 2019 at 00:27 UTC with a) heavy rain (55 dBZ) and b) strong near-surface winds (>25 ms^{-1}). Microburst-producing storm 11 km SE of Entebbe radar (c) on 24 Feb 2020 at 01:53 UTC within the red circle and (d) Doppler velocity showing microburst diverging winds. White arrows

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

indicate the maximum approaching (green and blue colors) and receding (yellow and red colors) Doppler velocities. The red cross in each panel indicates the location of the radar.

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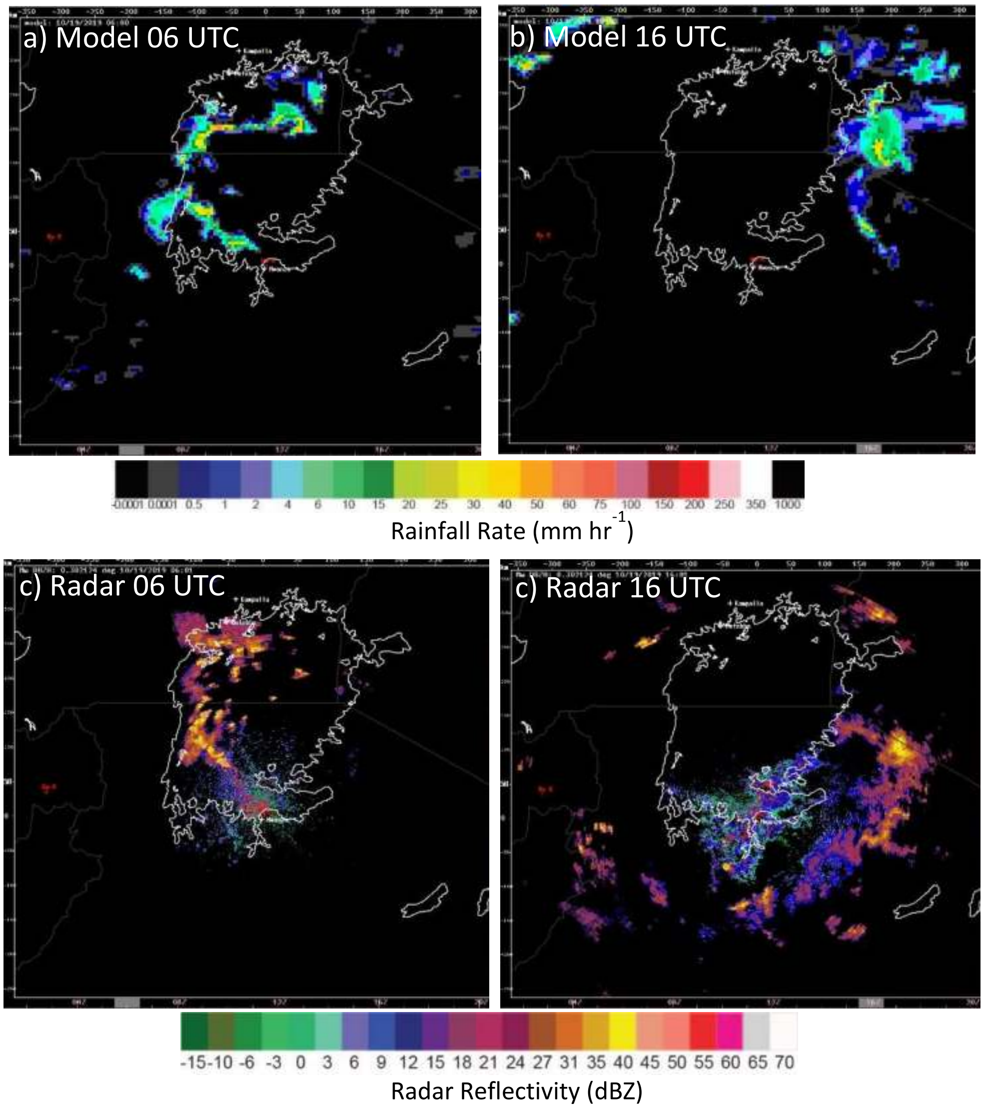

Figure 6. TA4 model precipitation forecasts and Mwanza radar reflectivity over LVB at forecast valid times on 19 October 2019. White polyline represents the lake boundary. Model forecasts of precipitation a) over the lake valid at 06 UTC (09 LT) and b) overland at 16 UTC (19 LT), in agreement with lightning climatology in Fig. 3. Radar reflectivity at c) 06 UTC and d) 16 UTC.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

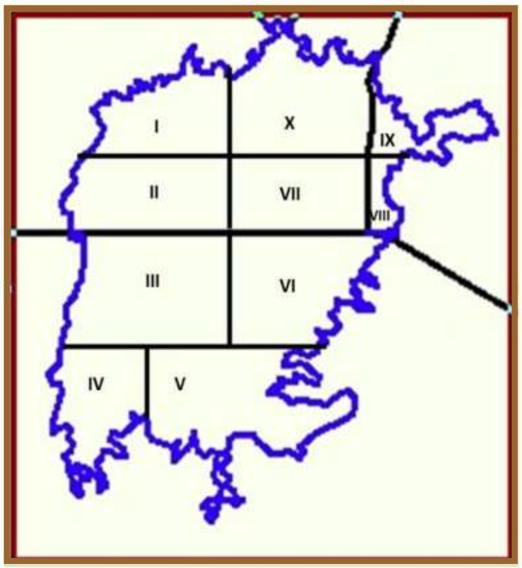

Figure 7. Division of Lake Victoria into 10 marine forecasting zones. Uganda (zones I, II, VII and X), Kenya (zones VIII and IX) and Tanzania (zones III, IV, V, VI) are shown. Thick black lines represent the boundaries between Uganda, Kenya and Tanzania.

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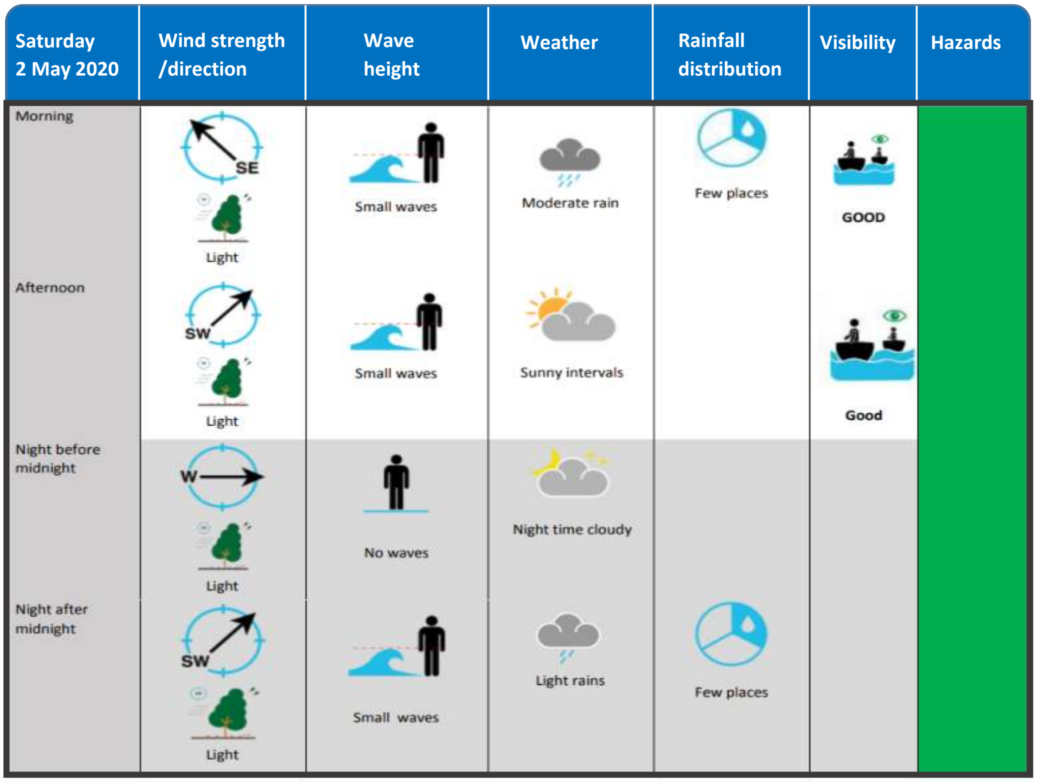

Figure 8. KMD 24-hour forecast for fisherman on Lake Victoria issued at 00:00 LT on 2 May 2020 for Zone IX in Fig. 7 (Open Lake - Siaya, Busia region). Right-hand hazards column shows green color indicating no hazard forecast for this day.

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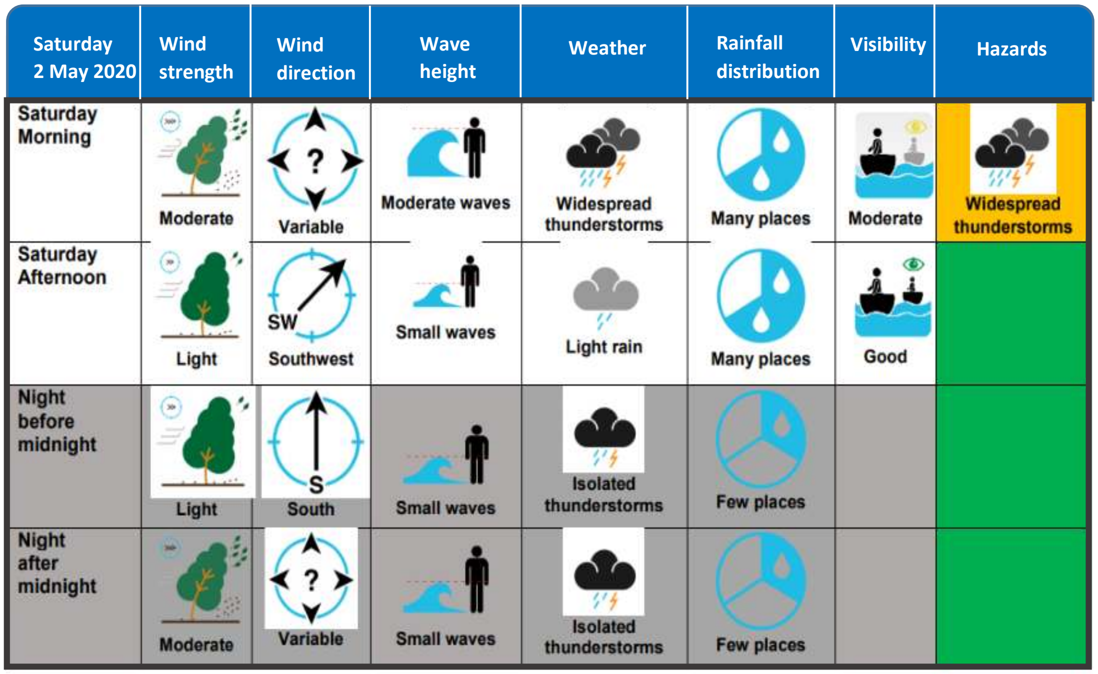

Figure 9. UNMA 24-hour forecast from 06:00 LT on 2 May 2020 to 06:00 LT on 3 May 2020 for fishermen on Lake Victoria. Forecast issued at 03:40 LT on 2 May 2020 for Zone X for (Buvuma and Northeast) in Fig. 7. Right-hand hazards column shows orange warning for fishermen to be prepared for widespread thunderstorms Saturday morning and take precautions.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Figure 10. a) Intermediaries being trained on UNMA marine forecasts. b) Members of the focus group on Lujaabwa Island inspect the newly arrived weather information noticeboard at a landing site in the Ssese Islands. Photo by Christopher Sserwadda.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

Figure 11. Daily dissemination of marine forecasts by radio and social messaging on cell phones. a) Radio broadcaster David Agangu on Nam Lolwe FM in Kisumu Kenya, airs the morning forecast for fishermen twice on his breakfast show. Photo by David Agangu. b) Checking the latest forecast at a landing site in Uganda. Photo by WMO.

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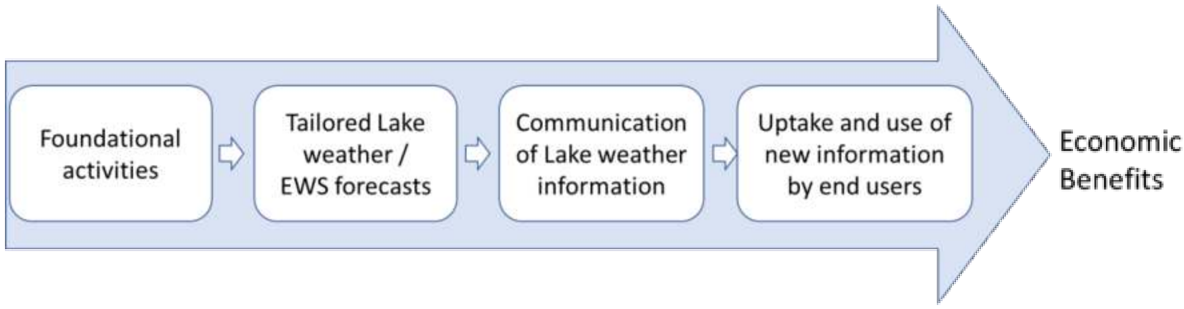

Figure 12. It is the investment along the whole value chain that delivers the economic benefits. The socio-economic benefits study has assessed the improvements from the HIGHWAY activities at each step.

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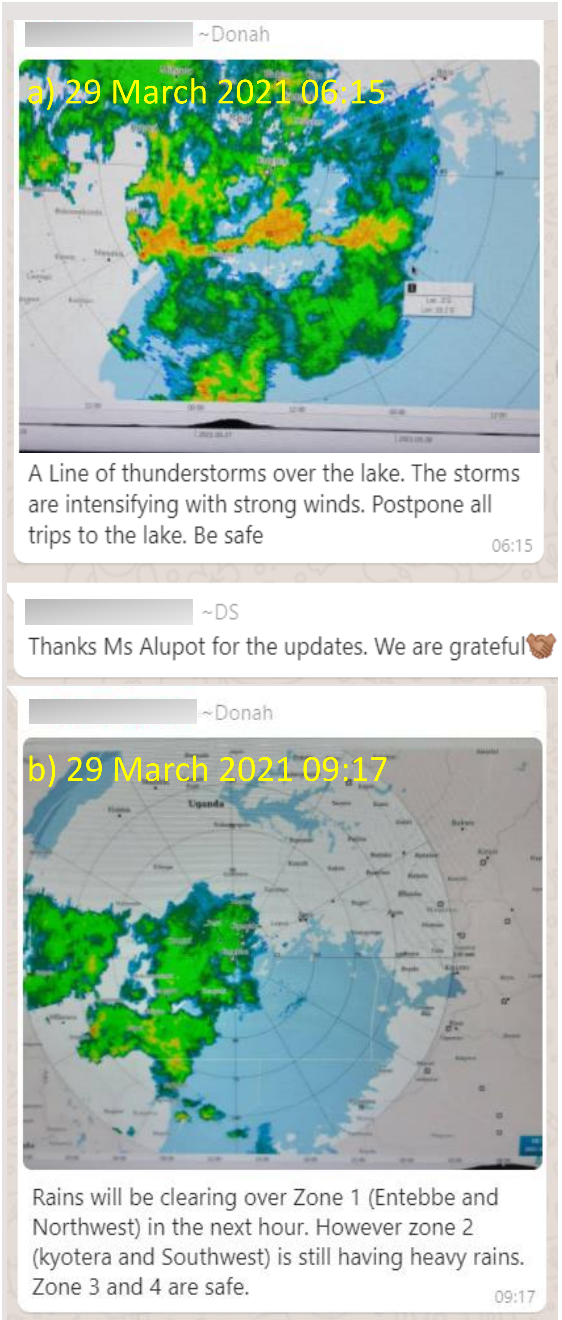

Figure 13. WhatsApp messages containing radar images, very short-term nowcasts, and warnings sent out by UNMA NMC forecaster Donah Alupot to WhatsApp subscribers. (a) Nowcasts issued on 29 March 2021 at 0615 LT for an

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E-W line of radar-detected thunderstorms and strong winds over LV and (b) at 0917 LT for regions of heavy rain and regions of clearing. Benjamin Bahati, KMD Director of Meteorology in Busia County, forwarded these warnings, with clarifications, to ~100 fishermen in Kenya.

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Sidebar images

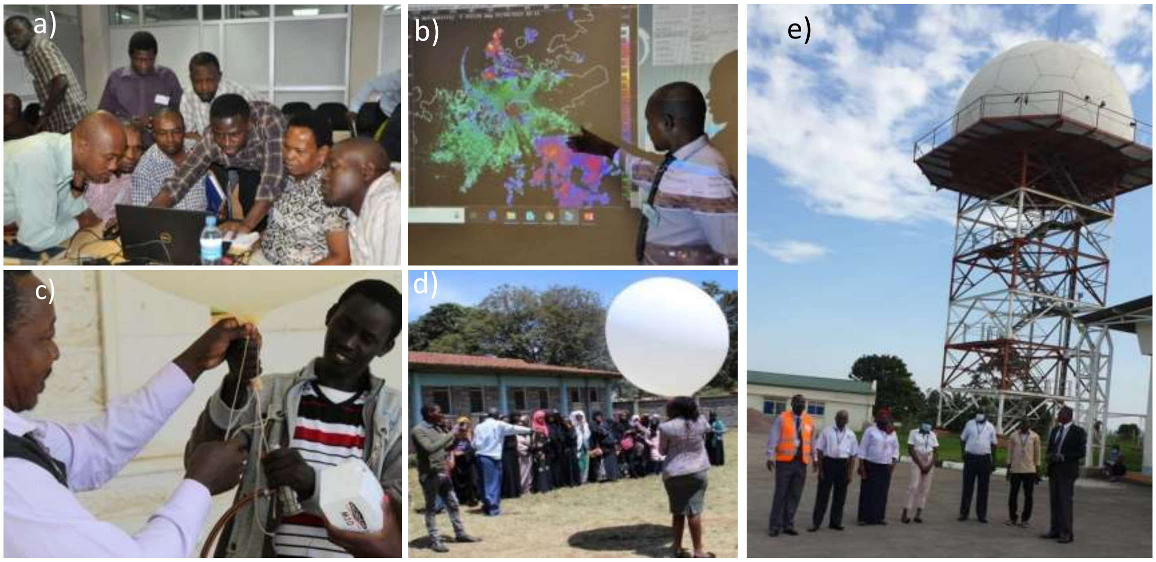

Figure SB1. (a) and (b) Forecasters and engineers are trained on radar interpretation and thunderstorm nowcasting at TMA forecast office in Dar es Salaam in July 2019; (c) and (d) WMO and KMD train technicians on radiosonde launches at KMD site in Nairobi in July 2019; e) Virtual radar and thunderstorm nowcasting training workshop hosted by UNMA at the Entebbe NMC and radar site in September 2020.

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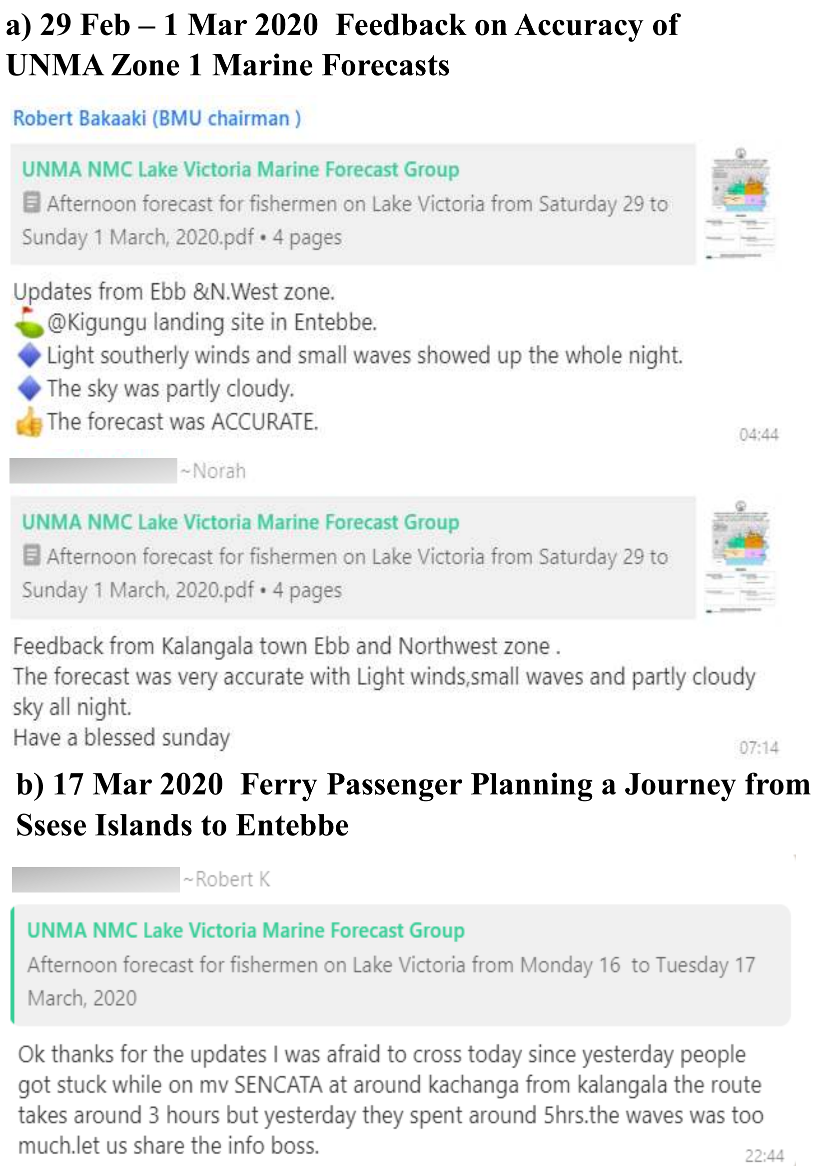

Figure SB2. a) Two different types of feedback on forecast accuracy from a BMU chairman and a passenger on a transport boat. b) Response from an individual using marine forecasts on WhatsApp to help plan a journey from the Ssese Islands to Entebbe (see blue dashed track in Fig. SB3) on a small vessel during bad weather and waves.

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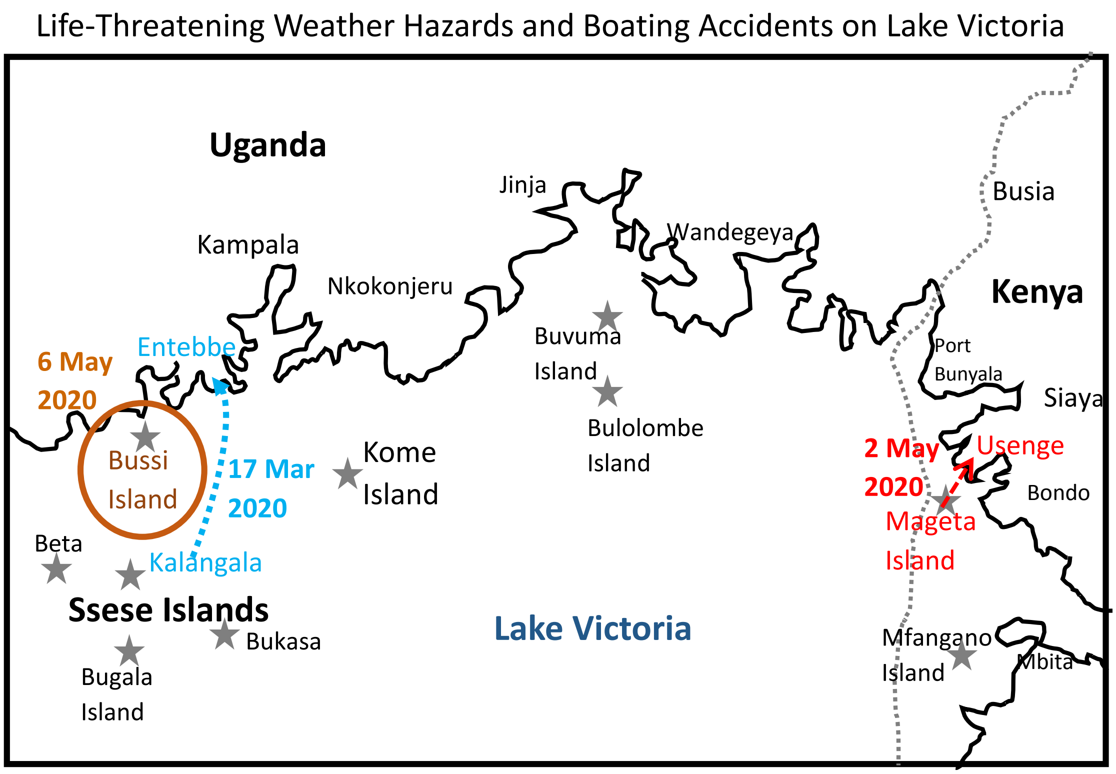

Figure SB3. Northern and northeastern shores of LV outlined in black. Dotted gray line marks the boundary between Uganda and Kenya. Selected cities and islands (located with gray stars) are shown for geographic orientation. Dashed blue line shows the ~5h journey by small vessels from Kalangala Island to Entebbe during high waves and bad weather. Brown circle encloses Bussi Island and surrounding water where two waterspouts occurred. Dashed red line shows the passage of a waterbus catamaran ferry from Mageta Island to Usenge beach that capsized in 2-m waves.

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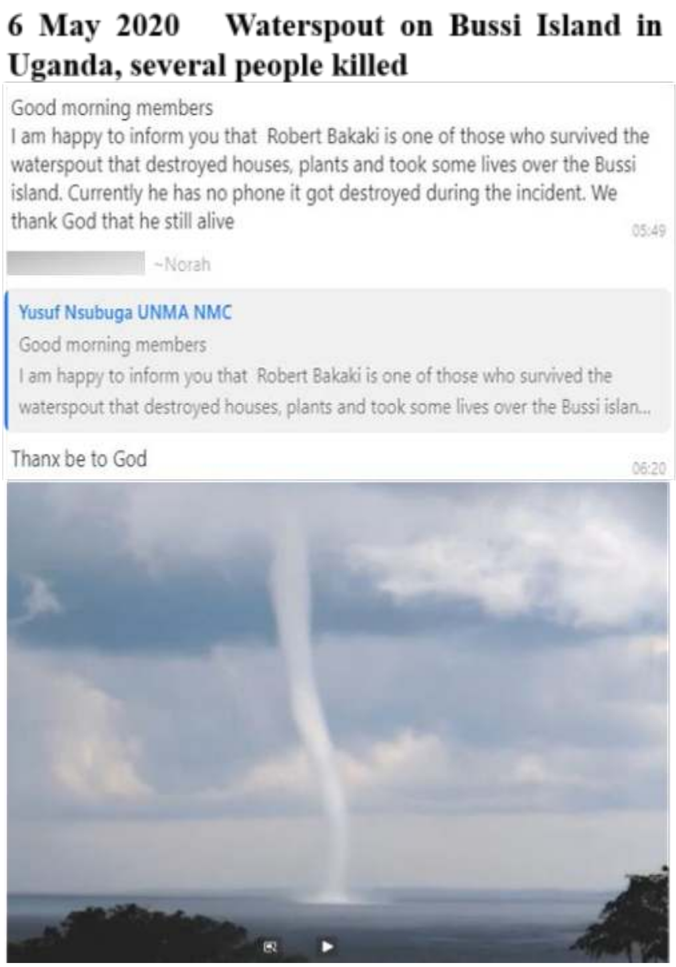

Figure SB4. Two waterspouts occurred in the vicinity of Bussi Island, Uganda, one of them caused lost lives and destroyed property on the island. The location of this island is shown in Fig. SB3. Robert Bakaaki, who is mentioned in the WhatsApp message sent out by a UNMA NMC forecaster, is a Beach Management Unit chairman in Uganda (see Section 4c and Fig. SB2a). Photo credit: ChrisAustria.com.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.

2 May 2020 Waterbus catamaran ferry capsized in 2m waves in Kenyan waters

Figure SB5. Waterbus catamaran ferry capsizes in 2-m waves; above photos were taken by a fisherman and posted on one of KMD's marine forecast WhatsApp groups. People are standing on the hull as ~20 people are being rescued. Location of the boating accident is shown by the red dashed line in Fig. SB3.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-20-0290.1.