Assessment of a Ground-Based Lightning Detection and Near-Real-Time Warning System in the Rural Community of Swayimane, KwaZulu-Natal, South Africa

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ABSTRACT: Climate change projections of increases in lightning activity are an added concern for lightning-prone countries such as South Africa. South Africa's high levels of poverty, lack of education, and awareness, as well as a poorly developed infrastructure, increase the vulnerability of rural communities to the threat of lightning. Despite the existence of national lightning networks, lightning alerts and warnings are not disseminated well to such rural communities. We therefore developed a community-based early warning system (EWS) to detect and disseminate lightning threats and alerts in a timely and comprehensible manner within Swayimane, KwaZulu-Natal, South Africa. The system is composed of an electrical field meter and a lightning flash sensor with warnings disseminated via audible and visible alarms on site and with a remote server issuing short message services (SMSs) and email alerts. Twelve months of data (February 2018–February 2019) were utilized to evaluate the performance of the EWS's detection and warning capabilities. Diurnal variations in lightning activity indicated the influence of solar radiation, causing convective conditions with peaks in lightning activity occurring during the late afternoon and early evening (between 1400 and 2100) coinciding with students being released from school and when most workers return home. In addition to detecting the threat of lightning, the EWS was beneficial in identifying periods that exhibited above-normal lightning activity, with two specific lightning events examined in detail. Poor network signals in rural communities presented an initial challenge, delaying data transmission to the central server until rectified using multiple network providers. Overall, the EWS was found to disseminate reliable warnings in a timely manner.

SIGNIFICANCE STATEMENT: Thunderstorms and, more specifically, lightning are life-threatening severe weather phenomena that can result in damage to infrastructure, physical injury, and loss of life (human and livestock). South Africa's lightning mortality rate is said to be 4 times the global average. Despite significant progress in lightning detection and monitoring on a national scale, rural communities remain vulnerable and continue to live without any lightning warning. In an attempt to improve lightning detection on a local scale, this study developed and assessed a community-based lightning early warning system. The system has a monitoring and early warning capacity to improve the preparedness of rural communities to lightning, thus mitigating losses.

KEYWORDS: Climate change; Decision support; Emergency preparedness; Lightning; Nowcasting

1. Introduction

Studies of natural hazards and disasters across the world continue to garner media and public interest due to the magnitude of risks associated with these events. The natural phenomena, lightning, despite being necessary and beneficial for the purpose of nitrogen fixation (by nitrogen oxides) (Drapcho et al. 1967), is an example of one such significant yet underestimated hazard (Dlamini 2009; Cooper et al. 2016; Gomes 2017; Cooper and Holle 2019b). The damaging characteristics are a result of the immense naturally occurring electrical discharges/currents that are generated according to the power of a lightning flash (Bhavika 2007; Blumenthal et al. 2012). Many fatalities as well as minor and major injuries (muscle aches, severe burns, cardiac arrests, nerve injury keraunoparalysis, and temporary paralysis, among others) to human beings and animals may occur by primary and secondary mechanisms (Gomes 2017), as further detailed by Cooper et al. (2016) and by Cooper and Holle (2019b). Lightning also leads to significant economic losses varying from livestock deaths to direct lightning strikes that may result in structural and vegetation fires, explosions, or detachment of materials that may

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fall, causing injury and rendering people homeless and damaging infrastructure (Kithil 1995; Blumenthal et al. 2012; Gijben 2012; Gomes 2017). Indirectly, lightning currents can also result in temporary or permanent damage to electronic and communication equipment, which can lead to significant data and operational time losses as well as damage to equipment/appliances that are used for the purpose of providing medical support, storing food, among others (Cooper et al. 2016; Gomes 2017; Cooper and Holle 2019a; Cooper and Holle 2019b). Consequently, lightning represents a major natural disaster and risk to the public, power companies, aviation, and the agriculture and forestry sectors (Price 2013). Cooper and Holle (2019b) further elaborate on the economic damages that occur among the various sectors of the economy as a result of lightning.

Further complications have been attributed to lightning, whereby in several places across the world, humankind often views lightning (thunder) in great awe and associates it with traditional and religious beliefs (Dlamini 2009; Cooper et al. 2016; Cooper and Holle 2019a). In developing countries, many people are also unaware of lightning-induced human hazards, since most incidents occur in remote locations that lack media coverage, while a prevailing high illiteracy rate, poverty, lack of protective shelters, and other factors are also responsible for the high vulnerability among rural people (Cooper et al. 2016; Gomes 2017; Cooper and Holle 2019a). These factors hinder necessary precautionary measures in many countries, increasing the vulnerability to lightning.

A study by Albrecht et al. (2016) reveals that there are lightning hot spots within each major continental landmass. "A total of 283 of the top 500 spots with the highest lightning frequency occur within Africa," with South Africa displaying moderate flash rate density (up to 30 flashes per kilometer squared per year) in some areas (Albrecht et al. 2016). In South Africa, the annual number of lightning-related deaths amount to between 1.5 (urban) and 8.8 (rural) per million of the population (McKechnie and Jandrell 2014). Annually, up to 100 lightning-related fatalities occur in South Africa (Blumenthal et al. 2012). The increased number of fatalities among the rural population is due partly to the lack of lightning-safe structures, fewer available fully enclosed, metal-topped vehicles, a lack of awareness with regard to the dangers and precautions of lightning, myths and belief systems, affordability concerns (e.g., unable to afford lightning protection systems), unavailability and delays in receiving proper medical treatment, a high rate of labor intensive subsistence farming/agriculture, and population density, among others (Cooper et al. 2016; Gomes 2017). In addition, many more rural cases may often be underreported due to poor communication systems (Cooper and Holle 2019b).

Climate change projections are an added concern for the country as they indicate increased lightning activity (Price 2009; uMngeni Resilience Project 2014). South Africa is particularly vulnerable to climate change impacts because of the prevailing high levels of poverty and the country's heavy reliance on climate-sensitive economic sectors as well as extreme weather conditions coupled with climate variability (Turpie and Visser 2013). However, in an attempt to mitigate the impacts from lightning risks, recent technological and scientific developments have provided the opportunity for more reliable ways of monitoring lightning activity at various spatial and temporal scales. By doing so, approaches to warn of lightning risks and tracking severe weather are possible.

During the past decade, a vast amount of research has led to greater knowledge on the spatial and temporal patterns of global lightning and thunderstorms from both ground-based observations and satellites. The development of these modern lightning detection instruments has been driven by a variety of practical and research needs (Cummins and Murphy 2009). This has provided avenues to expand knowledge and understanding of lightning as well as for monitoring and providing early warnings for severe weather phenomena. The most commonly used techniques for obtaining lightning data remain ground- and space-based lightning detection networks (Rudlosky and Fuelberg 2013). The ease with which lightning can be monitored from great distances using these techniques has been beneficial for tracking changes in significant climate parameters and to monitor severe weather (Williams et al. 1989; Goodman 1990; Kane 1993; Williams et al. 1999; Gungle and Krider 2006; Bonelli and Marcacci 2008; Feng and Hu 2011; Price 2013; Galanaki et al. 2018).

South Africa has made significant progress in the field of lightning research at a national level. Currently, the detection of lightning occurrences across South Africa has been undertaken by the South African Weather Service (SAWS) (Gijben et al. 2016). In 2005, SAWS installed a state-of-the-art cloud-to-ground lightning detection network across the country. The South African Lightning Detection Network (SALDN) supersedes the Lightning Positioning and Tracking System (LPATS) operated by Eskom (South Africa's electricity public utility) and the Fault Analysis and Lightning Location System (FALLS) (Peter and Mokhonoana 2010). This new detection network, SALDN, is based on Vaisala sensors (LS 7000 and LS 7001, Helsinki, Finland) and is the first to provide high spatial resolution, uniform coverage, and high detection efficiency measurements on the distribution of lightning across South Africa (Gijben 2012). Furthermore, the network presents new opportunities such as exploring lightning in thunderstorms and identifying lightning risk priority areas. Despite this progress, the SALDN operates at a national level without dissemination at a community-based level. Agencies and institutions such as the Lightning Interest Group for Health, Technology and Science (LIGHTS), the African Centres for Lightning and Electromagnetics Network (ACLENet), the Earthing and Lightning Protection Association (ELPA), and the University of Witwatersrand currently drive a strong lightning interest and research in South Africa.

People who are outdoors during a thunderstorm face the greatest risk of being killed or injured by lightning (Trengove and Jandrell 2015). While lightning fatalities are generally highlighted, some studies have emphasized lightning injury as being of equal, if not greater, concern (Cooper 1998; Cherington et al. 1999). Lightning injuries range from mild to severe (disabling conditions) (Cooper et al. 2016; Gomes 2017), rendering individuals incapable of returning to work, school, or normal life activities and leading to the destitution of families (Cooper 1998; López and Holle 1998; Cherington et al. 1999; Cooper et al. 2016). In South Africa, the majority of individuals from rural populations are involved in subsistence farming (Trengove and Jandrell 2015), and it is these people, who work outdoors tending the land or herding livestock, who are most vulnerable to lightning (Holle et al. 2007; Holle 2008; Gomes 2011; Cooper et al. 2016). Rural people are also threatened indoors by the risk of lightning as they live in houses without proper lightning protection systems and many do not contain metal plumbing, electrical wiring or reinforcing steel that can provide a pathway for a lightning current to move to the ground (Trengove and Jandrell 2015). In addition, thatched roofs or newspaper are often used to insulate the roof of rural houses, which can easily be set alight by direct lightning and may prevent even the healthiest individual from escaping (Cooper 2012; Cooper and Holle 2012; Gomes 2017). Furthermore, rural houses may also contain stored flammable materials that include, but are not limited to, liquid fuels (e.g., paraffin) as a source of lighting, thereby contributing to an increased risk to lightning. In a study by Ashley and Gilson (2009), it is stated that the number of lightning fatalities appear to be greater near population centers as more people are exposed to lightning hazards at any given one time. This is also valid for rural areas in South Africa as the population per household is usually greater than for urban areas and may result in more people left vulnerable to lightning at one given time. Furthermore, indigenous South Africans are known to attribute lightning to witchcraft or religious beliefs (Cooper et al. 2016), while others may perceive lightning as a ''passive hazard'' (Ashley and Gilson 2009), which often undermines the necessity to take precautionary measures (Dlamini 2009) and results in ''mistreatment of patients and incorrect court testimonies'' (Cooper et al. 2016). The study by Cooper et al. (2016) provides a comprehensive summary of the most common myths and facts about lightning around the world and in South Africa.

Communities, workers, students, and schools in rural areas are also found to lack knowledge about the dangers of lightning and climate change (UNICEF 2011), which could help to dispel misconceptions and myths (Cooper et al. 2016), protect the communities against the dangers of these natural disasters and reduce the number of lightning casualties and fatalities (Ashley and Gilson 2009). In less-developed countries such as South Africa, even once people became aware of lightning injuries, fatalities, and electrical power cuts, they may not have lightning-safe shelters or fully enclosed metal-topped vehicles (Cooper et al. 2016; Cooper and Holle 2019a) and may not understand how to avoid the danger or even be able to afford lightning protection systems due to socioeconomic factors, affordability costs, and literacy rates, among other issues (Gomes 2017). Furthermore, without the aid of lightning protection or early warning systems to provide warnings, many people may misjudge the location or speed of an approaching thunderstorm, resulting in an incompletion of an outside activity or subsistence farming or any other outdoor occupation in time, and may not return indoors in time or may return outdoors too soon, hence, lightning casualties may occur (Cooper et al. 2016).

For these reasons, an interface capable of seamlessly providing rural communities with lightning information that can be used for teaching, learning and as an early warning or disaster management tool was developed and assessed. The main aim of the study was to develop an approach toward reducing the vulnerability of rural communities and small-scale farmers within South Africa to lightning risks. The study investigated the operational implementation of a community ground-based near-real-time (NRT) lightning warning system (LWS) toward building the resilience of rural communities and small-scale farmers in South Africa to the impacts of climate-driven risks and the associated projected increase in lightning activity.

2. Study site description

The research was undertaken in Ward 8 of Swayimane, situated approximately 65 km east of Pietermaritzburg within the province of KwaZulu-Natal, South Africa (Fig. 1). According to several climate change studies (Hewitson et al. 2005), the KwaZulu-Natal Midlands area, within which the uMgungundlovu District Municipality (UMDM) is located, is an area of high climate change risk and is one of three climate change hot spots in South Africa (Department of Environmental Affairs 2013). This is largely owing to its prevailing warmer climate, with anticipated changes in it, and its associated impacts on the environment, the people, and the economies (Stuart-Hill and Schulze 2010). Some of the climate change risks that the UMDM faces include an increased frequency of rainfall, associated with an increase in the intensity and frequency in extreme events that include but are not limited to wildfires, flash floods and storm events (Archer et al. 2010). A projected increase in lightning strikes as a result of the increase in intensity and frequency of storms due to climate change is also a risk to the UMDM. A study by Evert and Gijben (2017) indicated the lightning ground flash density for the province of KwaZulu-Natal to be between 7 and 14 flashes per kilometer squared per year, based on the 11-yr (1 March 2006–1 March 2017) new lightning ground flash density map for southern Africa.

The study area, Swayimane, is located within the UMshwathi Local Municipality and is the largest of the four rural communities (Thokozani, Ozwathini, Swayimane, and Mpolweni). The Swayimane ward consists of both formal and informal housing (Martin and Mbambo 2011; Khumalo 2016). Similar to most rural areas, Swayimane has elements of traditional authority and despite the community adopting modern ways of living to a certain extent, traditional customs are still known to govern the area (Martin and Mbambo 2011; Khumalo 2016).

3. Data and method

a. Lightning warning and notification system

An NRT-LWS was installed at the Swayimane High School in Swayimane on 2 February 2018 (Figs. 1 and 2). The LWS was installed at a height of 5 m with three warn-state categories/ranges of 8, 16, and 32 km. Two of the three warn state categories (8 and 16 km) were based on the National

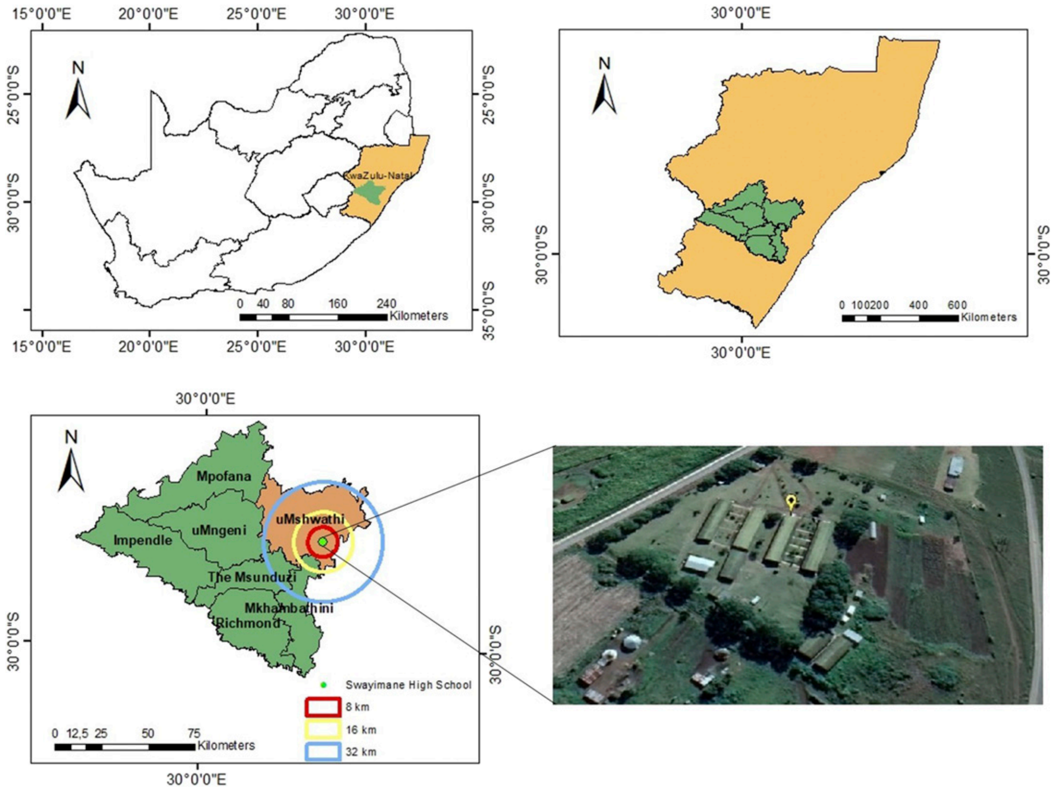


FIG. 1. The Swayimane High School study site located in the Swayimane community of the uMshwathi Local Municipality in KwaZulu-Natal, South Africa. The red, yellow, and blue circles represent the three warn state categories/radius values for which the study area is defined.

Weather Service's "flood watch" and "flood warning" forecasts, while the 32-km warn range was guided by a strike guard sensor's maximum detection range. All the site recommendations and requirements of the sensors contained within the system were considered. The LWS system consists of two sensors to alert and detect the threat of lightning.

The vertical atmospheric electric field ($\mathrm{V\,m^{-1}}$) was measured (accuracy within 5%) by a downward-facing electric field meter (Campbell Scientific, Inc., model CS110) positioned at a height of 4.05 m above the surface ground. A clear sky with dry conditions value of approximately $-80\ \mathrm{V\,m^{-1}}$ was accounted for, as specified by the equipment supplier. The electric field meter (EFM) measures both positive and negative electric fields but converts all the values to absolute values in order to assess the magnitude of both positive and negative measurements for warning state assessment. The presence of nearby electrified clouds that are capable of producing lightning discharges can be detected within a 40-km radius (maximum). The EFM radius of influence is typically variable, and therefore only the magnitude of the electric field was considered to contribute to the warning classification.

A lightning flash sensor (Wxline Strike Guard SG000) was also installed in conjunction with the EFM, at a height of 5.05 m. According to the manufacturer, the SG000 receives and processes the optical and radio emissions of lightning discharges within 0 to 32 km of the sensor. The SG000 reports the most significant lightning event detected within a two-second window. If therefore, within 2 s, two events are detected, the most significant one (closest) will be reported as a flash. Individual lightning strikes are therefore not accumulated. These discharges detected include intracloud (IC) and intercloud (CC) flashes as well as cloud-to-ground (CG) strikes. While CG lightning can affect humans and infrastructure, IC and CC can provide valuable information on thunderstorms and convective activity by providing an indication on the growth rate and intensity of thunderstorms (Cummins and Murphy 2009; Poelman 2010). IC and CC flashes usually precede the first CG strike in most thunderstorms and this lead time is invaluable toward providing lightning warnings as a storm develops overhead (Cummins and Murphy 2009). On the other hand, for warning systems, the inclusion of cloud flashes may trigger warnings that may not have an impact on individuals on the ground. Since the SG000 sensor does not differentiate between flashes (IC and CC) and strikes (CG), the term "flashes" in this paper will include strikes. Serial data obtained by the SG000 was transmitted to a datalogger (Campbell CR1000) via a fiber-optic link. The SG000 regularly performed a self-test of sensor functions, which includes communication and battery charge levels to ensure the system performs optimally during a lightning event.

One-second measurements from both sensors were recorded with averages or totals calculated every 1 min, every 5 min,

FIG. 2. The LWS located at the Swayimane High School, Swayimane. The CS110 EFM, the SG000 lightning flash sensor, the siren, and strobe beacon lights are visible in the inset image.

and every hour (see section 3b systems design for details). The 1-min data were used in all interpretations within this manuscript, while the 5-min and hourly data were used for providing more coarse summaries of lightning occurrence. A siren and a single set of three strobe lights/beacons (Campbell Scientific model RA110) indicated the lightning warning status and was located on the outside of one of the school buildings for good visibility to the surrounding community (audibility and visibility also benefitted a nearby taxi rank, a community hall, and a clinic) (Fig. S1 in the online supplemental material). Further details about the instrumentation used are available online (https://www.campbellsci.co.za/lw110).

Three possible states or categories were set to represent the measurements of the atmospheric electric field and lightning flashes. ''All clear'' (level 1) indicated no lightning warning and was represented by a blue strobe beacon. ''Caution'' (level 2) indicated an imminent threat and was represented by a yellow strobe beacon and ''alarm'' (level 3) indicated dangerous conditions and was represented by a red strobe beacon. Presently, there are no existing universal warning criteria for the electric fields. The 1000 $\mathrm{V\,m^{-1}}$ (caution) and 2000 $\mathrm{V\,m^{-1}}$ (alarm) electric field magnitudes were used according to the Naval Seas Systems Command (NAVSEA) and the National Aeronautics and Space Administration Launch Pad Lightning Warning System as thresholds to guide the activation of the three states (Clulow et al. 2018). The absolute electric field measurements (1- and 10-min running averages) were used in conjunction with SG000 measurements (flashes detected as they occur) to ascend into higher warning states (Table 1) and to descend to lower warning states (Table 2) (Clulow et al. 2018). Level 4, or alarm state 4, was added to systems outputs, but was not represented as a separate physical alert category and was considered an alarm state 3 (Table 1), and hence there is no criteria for descending out of level 4. Level 4 is initiated by the SG000 only and occurs when flashes within 8 km are detected, while level 3 accounts for flashes detected within 16 km and/or electric field magnitudes of $> 2000\ \mathrm{V\,m^{-1}}$, and includes those flashes detected within the 8 km radius. Level 4 measurements provided useful information to assess just how close the threat of nearby lightning flashes occurred as it shows the proximity of the lightning to be within 8 km of the school. It should be noted that a ''caution'' (0–32 km) may include flashes within 16 km, whereas an ''alarm'' (0–16 km) provides much higher certainty that flashes have occurred within 16 km.

When in an alert state, the system only descends into an ''all clear'' state when there have been no flashes for 30 min and the electric field outputs has decreased below the stipulated exit threshold. The 30-min duration for the flashes is based on the U.S. National Oceanic and Atmospheric Administration 30/30 rule, instructing people to remain in a sheltered area for 30 min after the last lightning flash. The system enters a state = 0 (all beacons are deactivated and emails are sent to alert the system operator) to indicate problems such as low battery voltages, high internal relative humidity, or sensor failure.

The analysis of 1-s, 1-min, and 5-min data outputs were conducted over a 12-month period to assess the electric field levels and the occurrence of lightning flashes. The 12-month (from 2 February 2018 until 2 February 2019) study period was also considered a suitable period to assess the performance of the NRT-LWS, since the summer rainfall period, when most lightning is expected to occur in that part of South Africa, was included in the dataset. However, the analysis of lightning events extended beyond the 12-month initial assessment period as the system was still in operational. To investigate the

TABLE 1. Interpretation of data from the electric field meter and strike guard with respect to understanding the increase of warning levels from 2 to 4 (downward in the table).

State	Beacon color	EFM	Strike guard
2 = Caution	Yellow	1-min running average of the absolute electrical field > 1000 V m^{-1}	Flash detected within a 32-km radius
3 = Alarm and siren	Red	1-min running average of the absolute electrical field > 2000 V m^{-1}	Flash detected within a 16-km radius
4 = Alarm and siren	Red	Does not trigger a state 4	Flash detected within an 8-km radius

temporal behavior of lightning, lightning events, and the dissemination capabilities of alerts at the study site, time series analyses were conducted. In addition, simple descriptive statistical calculations were also undertaken to assess the operational performance of the LWS. These can be found in the results section. All times in the study are reported in central African time [CAT (UTC + 2 h)].

A differentiation between the two terminologies, namely, alarm activation and alarm escalation were made. Alarm activation is used to describe the fulfilment (and repetitive fulfilment measured every minute during an alarm) of alarm state 2 or greater, whereas escalation was used to describe the fulfilment of alarm state 2 or greater but always with an increase to a higher alarm state (Clulow et al. 2018).

b. System design

The LWS used a global system for mobile communication (GSM) modem (Sierra Wireless) for communication of data by General Packet Radio Services (GPRS) every 1-min facilitated by Campbell Scientific Africa (Pty.), Ltd., through a call-back service to a server computer located at the University of KwaZulu-Natal (UKZN) (Fig. S2 in the online supplemental material). The Campbell datalogger automatically opens a transmission control protocol (TCP) communications socket to the hosted UKZN LoggerNet server. The URL of the UKZN Campbell LoggerNet server effectively becomes the "fixed" URL to connect to the LWS, provided that the LWS has a unique Pakbus address. The datalogger was also hardwired to a relay controlling the lights and the 30-W siren at the school.

The server is a virtual machine (VM) on the UKZN network responsible for scheduled data downloads (Campbell Loggernet) and publishing (CSI webserver) the data to a web page. Direct connection by administrators of the LWS is also possible through an internet connection using the Campbell Loggerlink application on a smartphone or using Loggernet on a Microsoft Windows computer or by the remote desktop connection to the VM. Direct connection is beneficial for immediately determining faults before going to the site. Public access to the data and warning status is available online (http://agromet.ukzn.ac.za:5355/Sw_lws/index.html).

Email and short message service (SMS) warnings were initiated from the VM when values exceeded certain thresholds as illustrated in Table 1. Warnings were displayed graphically on the website, and emails and SMSs were sent from the VM to key individuals located within the 8-km radius of the study site, indicating warning states with an instructional message stating the need for precautions to be taken. This was carried out to ensure that immediate knowledge of adverse conditions could be made available to the key personnel (ward councilor, local youth leader, local tribal chief, educators, heads of departments, and principals of nearby schools) within the community. The warnings were sent out to the aforementioned selected personnel as a trial run of the system.

Data are freely available and were easily downloaded from the internet; from these data, seasonal trends could be analyzed. [LWS data are accessible online (http://agromet.ukzn.ac.za:5355/Sw_lws/index.html) (Fig. S3 in the online supplemental material).] A large screen [56-in. (1.4 m) monitor] was installed inside a secure metal housing within the corridors of the school displaying the NRT-LWS and climatic data for teaching and learning purposes (Fig. S4 in the online supplemental material).

The warning system operated automatically, minimizing the potential for human error. Initially, because of communication network failures, there were data losses. However, in the event of a communication network failure preventing warning disseminations, the audible and visible alarm systems continued to function.

The internet was a critical consideration at the site for transmission of the data to the VM and the dissemination of the warning messages. To ensure that the NRT screen at the school could operate, a long-term evolution (LTE) modem was installed to enable communication with the UKZN server. The LWS used a GSM modem (U-blox) operating with independent subscriber identification/identity module (SIM) cards. A 12 direct voltage current (VDC) 24 A h battery [with 220

TABLE 2. Interpretation of data from the electric field meter and strike guard with respect to understanding the decrease of warning levels from 3 to 1 (downward in the table).

State	Beacon color	EFM	Strike guard
3 to 2 = Caution	Yellow	1- and 10-min running averages of the absolute electrical field < 1000 V m^{-1}	No flash detected within a 16-km radius for 30 min
2 to 1 = All clear	Blue	1- and 10-min running averages of the absolute electrical field < 500 V m^{-1}	No flash detected within a 32-km radius for 30 min

alternating current voltage (VAC)] was used for the CS110 and SG000, with a capability of operating for approximately 24 h on the battery supply. To monitor the SG000 communication and failures, an internet protocol (IP) fail count was monitored, which was displayed on the web page. The IP fail count was based on the ping time-out of 1500 ms and provided an indication of communication quality.

A detailed LWS alert communication and response procedure/protocol documents the procedures, which are required to be followed to monitor, detect, communicate, and respond during lightning events. Response to the various levels of lightning warning (alarm state 2 or 3) depend on the context. When outdoors, for example, all activity ceases for an alarm state of 2 or 3 and people should move to safe shelters (a fully enclosed earthed building/permanent, substantial earthed buildings) or enclosed vehicles (a fully enclosed all metal automobile or school bus). The practice of assuming the crouch position is also encouraged if no alternative safe option is available when caught outdoors. Normal activity can resume when the warning siren is silenced and/or when the warning strobe returns to a warning state of 1 (the blue strobe beacon flashes; see Table 1).

c. *Automatic weather station*

An automatic weather station (AWS) was also installed at the Swayimane High School in March 2016 (Fig. S5 in the online supplemental material). The AWS was installed at a distance of approximately 200 m from the LWS. The use of the AWS's data was beneficial to the study for situational awareness during the analyses of alarm states and for the confirmation and assessment of detected lightning events.

Measured climatic data included rainfall (Texas Electronics, Inc., model TR252I), air temperature and relative humidity (Vaisala, Inc., model HC2S3 L), barometric pressure (Campbell Scientific model CS106), solar irradiance (Li-Cor, Inc., model LI-200SA), and wind speed and direction (R.M. Young Co. model 05103) as well as a solar panel (for backup power supply). Measurements were made every 10 s with statistical summaries output as hourly and daily data from the datalogger (Campbell Scientific model CR3000). [Data are freely available online (http://agromet.ukzn.ac.za:5355/Sw_weather/index.html) (Fig. S6 in the online supplemental material).]

The sensors were installed in accordance with the World Meteorological Organization (WMO 2008) recommendations, with the rain gauge orifice at 1.2 m and the remaining sensors at 2 m above the ground. Additional sensors included three measurements of volumetric soil water content (Campbell Scientific model CS650) at depths of 0, 15, and 30 cm and a dielectric leaf wetness sensor (Meter Group, Inc.).

4. Data analysis and results

a. *Diurnal pattern of lightning distribution/lightning activity*

The average diurnal cycle of lightning over Swayimane, produced with NRT lightning flash data for the period February 2018–February 2019, is illustrated in Fig. 3. The diurnal flash count, as a function of the local time, shows the typical lightning frequency variations. There was an increase in lightning over Swayimane starting from 1000 CAT to a maximum in the midafternoon (approximately 1600 CAT), which decreased from approximately 2000 in the evening (Fig. 3). The greatest number of lightning flashes occurred during late afternoon and early evening, with some lightning detected in the early hours of the morning. Approximately 80% of the lightning incidences occurred between 1400 and 2100. The period between 0200 and 0900 had the least lightning activity.

b. *Alarm state escalation*

From a total of 269 escalations, the highest number of escalations were from a state of 1 to 2 (total of 124 escalations) and the least number of escalations were from 1 to 4 (total number of 6 escalations) (Fig. 4). Of the events that escalated to a caution state of 2, the majority (79 events) progressed further to a warning state of 3. The number of events that thereafter escalated from a state 3 to state 4 was 36. The remaining number of escalations from 2 to 4 totaled 13 and there were 11 escalations from 1 to 3. For the study's measurement period, the average time taken to escalate to a state of 3 (warning state indicating immediate danger) was 1.5 h.

The alarm escalation frequency peaked during the late afternoon and continued through until late evening (1300–2200) before decreasing. Escalations were at a minimum during the early morning hours until midday (0000–1200). There were no escalation events observed between 0300 and 0400. The increases in escalation events that occurred from 1300 to 2200 concur with the development of convective thunderstorms in the late afternoon and early evening, as observed to occur in most places around the world and in South Africa.

The progression from an "all clear" to the highest alarm state (stage 4) without progression through the other alarm stages as illustrated by the darker shade in Fig. 4, were reached less frequently during the morning hours, than the afternoon and evening. Furthermore, the highest states were very often reached between 1300 and 0200, with the peak occurring between 1800 and 1900, coinciding with the period when many people will be returning home from their daily routines.

c. *Alarm state activation*

All three-alarm states (2, 3, and 4) were found to have occurred primarily due to the flashes detected by the SG000 (Table 3). The strike guard was solely responsible for 57.6% of the escalations to an alarm state 2, while 37.8% of the escalations were solely due to the EFM. For the escalations to an alarm state 3, the strike guard was solely responsible for 45.6% of the escalations to alarm state 3 and the EFM was solely responsible for 43.7%. On a few occasions, both sensors caused an escalation simultaneously (4.5% to alarm state 2% and 10.7% to alarm state 3). Only the strike guard can trigger an alarm state 4 (Table 1); hence, flashes were responsible for all of these escalations. There were a large number of flashes (3600 flashes) detected within the 8-km radius (alarm state 4) of the school (these flash count data are not shown). "False alarms" represent those suspicious and potentially false warnings that occurred without any local lightning detected by the system in the immediate vicinity; hence, those escalations

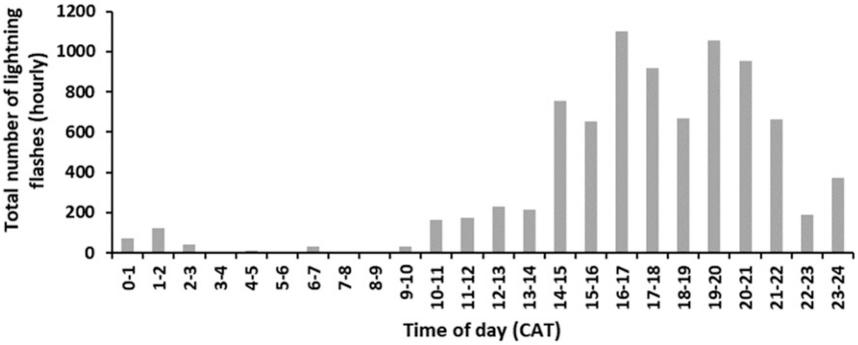


FIG. 3. Diurnal cycle of lightning for the study period (February 2018–February 2019), expressed as a count of the hourly totals summed over all three warning category detection ranges. Time corresponds to Central African Time.

occurred without the EFM and SG thresholds having been met. No obvious false alarm escalations were triggered by the NRT-LWS during no lightning periods and during stable weather conditions (such as clear-sky and low wind conditions, among others), as observed by the onsite AWS. There were no time lags between the cases, since the time criteria that were used for flashes and for the EFM for escalating to each level is immediate. The escalations were analyzed for each alarm state at every 1 min interval.

d. Warning duration

The maximum monthly duration of warning for the study period was 60.9 h during December 2018, while the minimum (0.0 h) occurred in June (Fig. S7 in the online supplemental material). There was a spike in warning duration during August 2018, which may be as a result of a frontal weather system. The warning duration in January was unusually low, which may have resulted from a stable atmosphere, however, continued measurements and comparisons with the country's national network may be required.

The majority of time for 2018/19 (5965.2 h—95.8%) was spent in alarm state 1 (all clear) (Table S1 in the online supplemental material). Total time spent in alarm state 2 (watch) was 53.2 h, 49.8 h in alarm state 3 (warning), and 60.0 h in alarm state 4. Note that more time was spent in alarm state 4 than in alarm states 2 and 3, indicating lightning flashes were commonly detected in close proximity to the study site (school). An alarm state of 0 indicates a fault with the system. The system spent 5823.0 min (4.0 days—1.6%) in an alarm state of 0, of which most occurred during October 2018, when the system lights were not working because of a communication failure, while the remaining fault period was due to low battery voltages.

e. Lightning event assessment

1) LIGHTNING DATA

Two lightning events were assessed to provide insight into the systems performance and to confirm that SMS warnings were being delivered in a timely manner. They were identified as periods exhibiting above-normal lightning activity. The measured rainfall data were obtained from the onsite AWS. Of these two events, the strongest electrical activity occurred on 3 February 2019, with 260 lightning flashes and 21.4 mm of rain (Table 4). The event with fewer lightning flashes occurred on 20 November 2018, with 117 lightning events and 6.4 mm of rainfall.

In the 9-h-long lightning event on 20 November 2018 (Fig. 5), a large, negative electric field at approximately 1358 was the initial cautionary trigger, causing an alarm state of 2

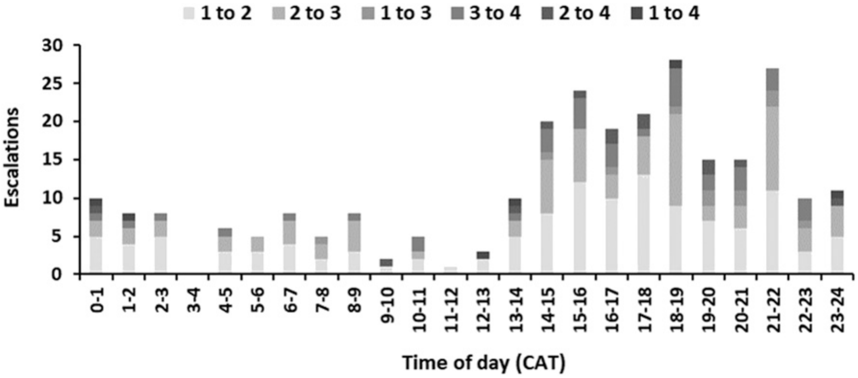


FIG. 4. Annual total diurnal variation in event states displayed as stacked bars.

TABLE 3. Percentage of escalations per alarm state observed by the dual sensor system (SG and EFM). Warnings without any detected local lightning activity are represented by false alarm escalations.

	Alarm state escalations		
Reason for escalation	2	3	4
SG	57.6	45.6	100
EFM	37.8	43.7	—
Both	4.5	10.7	—
False alarm	0	0	0

and thereafter an alarm state of 3 (warning, at 1400). Within a few minutes (at 1407), lightning flashes within 16 km of the study site were detected. Approximately 24 min after the first strike was detected, a strike within the 8-km warn category was observed (1431). Over the following 7 h, there were a number of flashes within 8, 16, and 32 km of the study area indicating the presence of electrical storm activities around the area of interest. After approximately 47 min in alarm conditions (>1), the atmospheric electric field magnitude increased rapidly to a peak of over 6500 V m^{-1} (Fig. 5). During the entire duration there were numerous flashes detected within the span of a few minutes, while a few detected flashes were spaced over several minutes, and the magnitude of the atmospheric electric field fluctuated rapidly, with several peaks detected over 4000 V m^{-1}. Flashes ceased after about 7 h (approximately 2135); however, the atmospheric electric field only stabilized 2 h later (approximately 2344) allowing the system to trigger an ''all clear.''

In the second event, a 2-h-long lightning event (2000–2200) followed 7 h after a brief period of early to midafternoon lightning activity on 3 February 2019 (Fig. 6). The large, negative electric field detected at 1257 resulted in an escalation to an alarm state of 2 (caution). At 1319, a lightning flash within 16 km of the study site was detected and triggered an alarm state of 3 (warning). In the first hour of the lightning event (1300–1400), the atmospheric electric field fluctuated between -2500 and 2500 V m^{-1} and a few flashes within 16 and 32 km were initially observed. Over the following six hours, the electric field was stable around -80 V m^{-1}. Some rapid fluctuations occurred between 2000 and 2200 in which the atmospheric electric field magnitude reached nearly 5000 V m^{-1} and there were numerous flashes observed within the 8-, 16-, and 32-km warn ranges. A total of 260 flashes occurred within this 2-h period of which 137 were detected within 8 km, 49 within 16 km, and 74 within 32 km (Fig. 6). Again, flash frequency diminished first (approximately 2150) and thereafter the atmospheric electric field diminished to around -60 V m^{-1} and stabilized (approximately at 2338). Of the SG and EFM triggers, the EFM kept the alarm in a warning state well beyond 2 h (2.11 h) after the flash warning had ceased.

2) ALERT SYSTEM

SMSs and emails were sent when the threshold for a warning status (alarm state ≥ 3) was reached. An instructional message was included to inform individuals to take the necessary precautions to protect themselves and their assets against the threat of lightning. SMSs and emails were also sent when exiting a warning status (alarm state <3), providing assurance that the risk to immediate danger (within 8–16 km) no longer prevails.

To evaluate the SMS alert system, the time stamps of the SMSs were compared with the EFM and SG data recorded for the abovementioned observed lightning events using 5-min outputs for illustrative purposes. On 20 November 2018 (Fig. 7) and 3 February 2019 (Fig. 8), there were several peaks and fluctuations in the electric field and lightning flashes during the life cycles of both lightning events. Warning SMSs for both lightning events were sent out immediately when a warning state of ≥ 3 was reached. Thereafter as the system approached a caution state of ≤ 2, an ''all clear'' SMS was sent to key personnel within the 8-km radius.

For both lightning events, the SMSs were received in a timely manner based on the trigger conditions (Figs. 7 and 8). The system frequently entered and exited warning thresholds during an event, which may require careful consideration in future. For example, a reviewed log of messages that was sent indicated that some lightning events entered and exited the warning state well over 8 times within a limited period of time. For the lightning event on 20 November 2018, the warning state was entered and exited over 4 times, whereas for the lightning event on 3 February 2019 it was over 6 times. The adjustment of entry and cessation levels for a state 3 may require modification to minimize the number of escalations and de-escalations.

5. Discussion

The analysis of the lightning flashes indicated that a significant number of lightning flashes (3600 flashes) occurred within the 8-km radius of the study site indicating that the area and school was at risk to lightning on several occasions. In contrast, it was observed that a relatively low percentage of time was spent in an alarm state of 4 (Table S1 in the online supplemental material) when compared with an alarm state of 1. These results may elucidate that the community and school is

TABLE 4. Lightning and rainfall data from two lightning events observed in Swayimane.

		Flashes detected, by warning state category				
Day	Rainfall (mm)	4	3	2	Total no. of flashes	Lightning event duration (h)
20 Nov 2018	6.4	60	33	24	117	9
3 Feb 2019	21.4	137	49	74	260	2

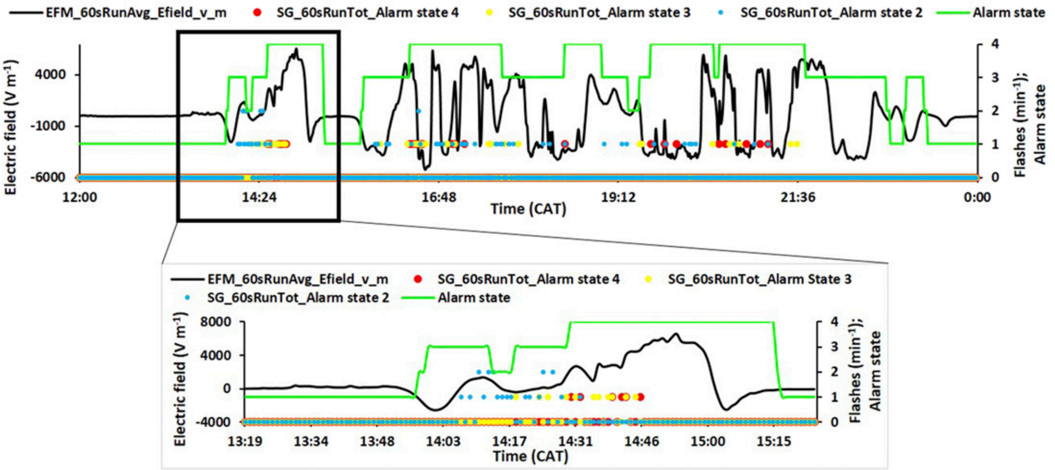


FIG. 5. Temporal progression of the lightning event that occurred on 20 Nov 2018 with observed fluctuations in the atmospheric electric field detected by the CS110 sensor on the primary *y* axis. The secondary *y* axis denotes the lightning flashes detected by the SG000 sensor and the alarm state levels. The red, yellow, and blue markers represent lightning flashes detected within the three alarm state categories (2, 3, 4) of 8, 16, and 32 km the study site, respectively. The outset panel provides a clearer view of the large number of lightning flashes per minute detected within the lightning event.

certainly at threat (i.e., many nearby flashes), however, it is infrequent. Hence, these findings demonstrate the need for early warning systems and also serve as an educational statistic to prevent warning fatigue, or the impression of overwarning.

The diurnal lightning activity in this study is comparable to a number of studies related to lightning diurnal cycle, which include, but are not limited, to studies by Christian et al. (2003), Mach et al. (2011), Blakeslee et al. (2014), and Cecil et al. (2014), among others. The diurnal variations in lightning distribution are often investigated to determine the influences of solar radiation on the development of thunderstorms. Most thunderstorm activity occurs during the afternoon and evening in South Africa (De Coning et al. 2011), but some limited convection also occurs in the morning (Rouault et al. 2013). As observed by the NRT-LWS in Fig. 3, the diurnal cycle of lightning activity for the study site exhibited most lightning during the period between 0900 and 2300 as indicated by Gijben (2016), with peak activity between 1400 and 2100. Results are also in agreement with Collier et al. (2006) who determined that peak lightning occurred at 1700 in the southern region of South Africa, whereas the observed pattern of storms by Preston-Whyte and Tyson (1988) were also found to develop in the late afternoons and early evenings in South Africa. The current results also agree with the findings by Bhavika (2007) who illustrated that the annual average diurnal pattern of lightning displayed maximum lightning activity occurring during the midafternoon and thereafter, decreasing toward the late evening and early morning hours.

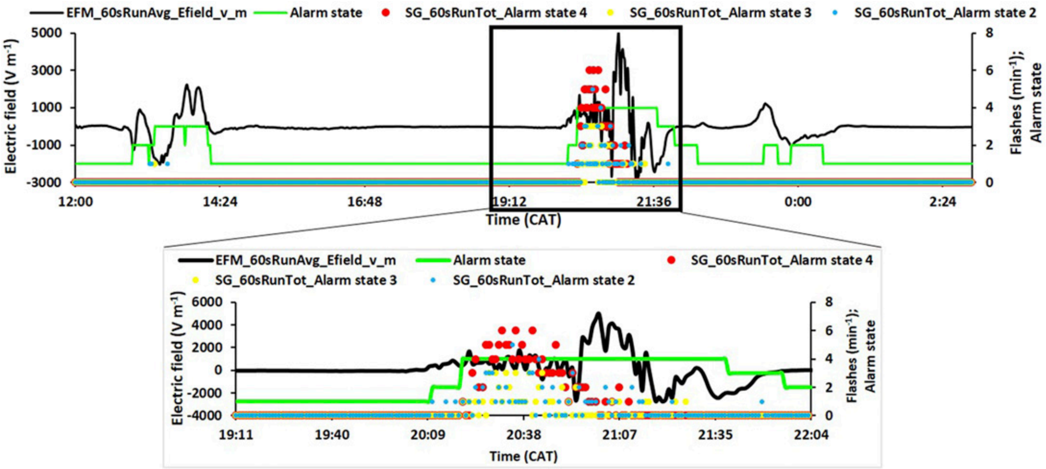
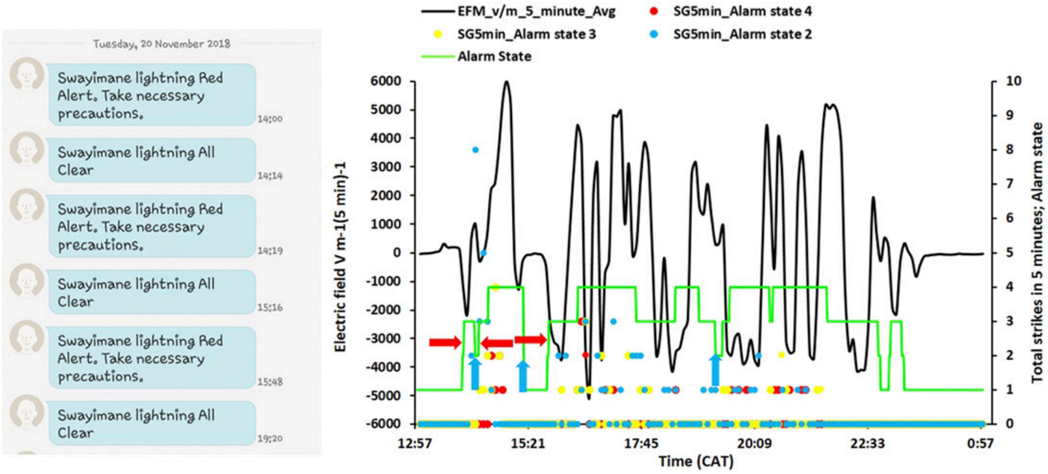


FIG. 6. As in Fig. 5, but for a lightning event on 3 Feb 2019.



Tuesday, 20 November 2018

Swayimane lightning Red Alert. Take necessary precautions. 14:00

Swayimane lightning All Clear 14:14

Swayimane lightning Red Alert. Take necessary precautions. 14:19

Swayimane lightning All Clear 15:16

Swayimane lightning Red Alert. Take necessary precautions. 15:48

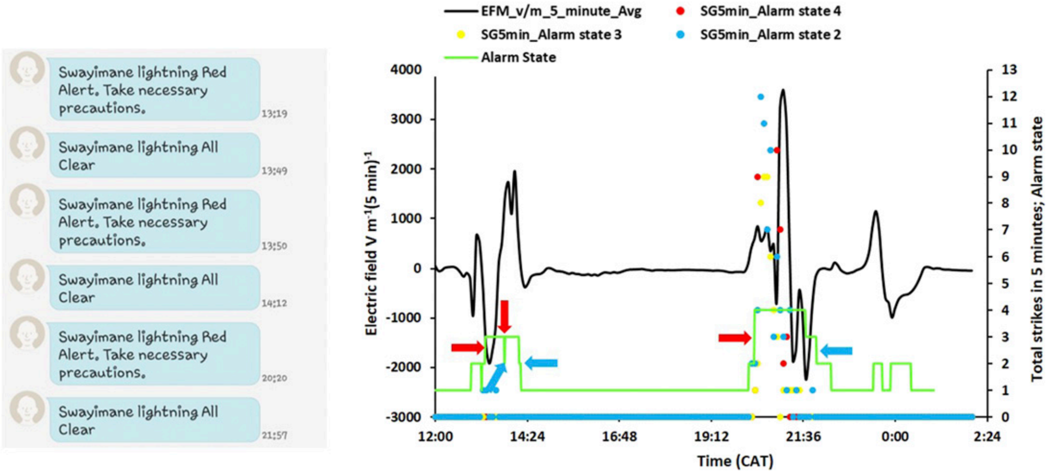
Swayimane lightning All Clear 19:20

FIG. 7. A comparison between the SMS alerts (red arrows—warning SMSs; blue arrows—all clear SMSs) and the recorded fluctuations in the atmospheric electric field detected by the CS110 sensor on the primary *y* axis and lightning flashes detected by the SG000 sensor on the secondary *y* axis at 5-min increments for a lightning event on 20 Nov 2018. The red, yellow, and blue markers represent the lightning flashes detected within the three alarm state categories (2, 3, 4) of 8, 16, and 32 km the study site, respectively. The increase and decrease in alarm state levels (green line) are in accordance with the atmospheric electric field and lightning flash thresholds that determine when the alert messages are generated. The screenshot on the left is an example of the trial run of SMSs.

Hence, the trends in the diurnal variation of lightning flashes are likely to have indicated the role of convection in lightning incidence.

Approximately 80% of the lightning occurred between 1400 and 2100, during which time students and workers are often returning home and when outdoor sports activities/games are taking place, as well as during the night when individuals are asleep and unaware of the inclement weather, placing the community at risk to lightning injury. The time period during which 80% of lightning incidences occur was found to also be in agreement with several previously discussed studies. The diurnal rate of decay in lightning incidence requires further observation, but current results indicate a low probability of lightning occurrences in the early morning hours. The implication of the early morning lightning increases the value and importance of the system, as most people will not be expecting lightning in the morning, and hence, no precautionary measures are exercised to avoid it. Therefore, the system may be found to be particularly valuable at this time. It is important to note that different data record periods and different measurement systems used may result in different lightning flash results when comparing results presented here with other studies.

While lightning detection by the system was not in itself verified in the study, the reliability of the system to disseminate warnings when lightning was detected by the system and vice



Swayimane lightning Red Alert. Take necessary precautions. 13:19

Swayimane lightning All Clear 13:49

Swayimane lightning Red Alert. Take necessary precautions. 13:50

Swayimane lightning All Clear 14:12

Swayimane lightning Red Alert. Take necessary precautions. 20:20

Swayimane lightning All Clear 21:57

FIG. 8. As in Fig. 7, but for a lightning event on 3 Feb 2019.

versa was undertaken. There was a complete absence of false alarms (verified by the local weather conditions obtained from the AWS), which is important for a warning system and encourages confidence in the meaningfulness of the system warnings. A large portion of events (46.1%) ended at warning state 2, while 53.5% ended at a warning state of 3 (33.1%) or 4 (20.4%). Events ending at a state 2 (caution) may be attributed to lightning cessation or storm cells passing through the periphery of the detection area, whereas those ending at a state of 3 or 4 may be as a result of the propagation of active storm cells near the study area or the presence of charged hydrometeors or charge carries causing a high EFM magnitude and subsequent high threshold and warning state.

Twice as much time (109.8 h) was spent in a warning state (state 3 or 4) than in a cautionary state of 2 (53.2 h), indicating that if there was a state 2 caution, then a state 3 and a state 4 warning seemed likely to follow. From an evaluation of the escalations, it was observed that the SG000 was responsible for the majority of the escalations (57.6% to an alarm state of 2 and 45.6% to an alarm state of 3) when compared with the EFM. However, there were instances when, together with the SG000, and in advance of the SG000, the EFM provided escalations. This can benefit a community by providing additional lead-time to take the necessary precautions before the first flash is detected, thereby contributing toward the predictive capability of the system. Several studies have highlighted this advantage of the EFM in detecting the static atmospheric electric fields and the slow changes in that field during fair weather and during storm conditions (Murphy et al. 2008; Sabu et al. 2017). Despite the fact that not all lightning flashes may be detected by the EFM (Bloemink 2013), the increase in their magnitude fields is invaluable toward predicting the threat of lightning, as charge separation has to occur prior to lightning initiation (Reynolds et al. 1957; Williams 1985; Murphy et al. 2008; Bloemink 2013; Aranguren and Torres 2016; Sabu et al. 2017; Mkrtchyan 2018). This advantage has certainly allowed for some prognostic detection capability in the NRT-LWS through the escalations that were provided by the EFM in the study and justifies the use of the term ''early'' in early warning system. Systems with only lightning detection capabilities and without EFMs may not be early warning systems as observing lightning within a close proximity of a site does not provide an ''early'' warning.

Storms during summer vary in their intensity and duration (Clulow et al. 2018). The time spent in a warning state was higher in the wet season months (November to March), but with variability during these months. Warnings for lightning activity in Swayimane were analyzed using the EFM observations along with lightning flash occurrences. For both lightning events, the atmospheric electric field magnitudes were observed to be well over 2000 V m^{-1} and reaching a maximum of 5000–6000 V m^{-1}. This result is in agreement with Madhulatha et al. (2013), who explain that electric field intensities greater than 2000 V m^{-1} are recognized as thunderstorm activity. The EFM is considered as a good early indicator for detecting the presence of electrified convective systems for local areas providing a warning even before the first lightning flash, and there was an even distribution of warnings initiated by the SG000 and EFM in general.

In the two events assessed, the lightning flashes were found to diminish first while the atmospheric electric field took longer to stabilize at ''all clear'' levels of close to zero. This may be due to the presence of electrification, or lingering charged hydrometeors aloft, during the decaying stages of the storms. Studies by Marshall et al. (2009) and Stano et al. (2010) further discuss lightning cessation based on storm electric fields and have found that the surface electric field below a thunderstorm displays an end of storm polarity oscillation during the storm's decay phase that usually occurs over a period of time. While these factors may provide insight into the prolonged electric field magnitudes that are observed following the last detected flashes, this characteristic of the EFM is also advantageous in ensuring that safety considerations for both lightning initiation and cessation are achieved and that personnel are alerted during the onset of lightning and signaled when the threat has completely passed.

Several past studies have also investigated the relationship between lightning activity and rainfall to understand the behavior of storms. Studies by Kane (1993), Gungle and Krider (2006), and Xu et al. (2010), among others reported on a direct/linear relationship existing between rainfall and the number of flashes. Maximum rainfall was found to coincide with the highest concentration of lightning flashes (Kane 1993), and within mature storms (De Coning et al. 2015). Of the two lightning events assessed in the current study, the event on 3 February 2019 had a higher flash count and a greater rainfall amount, which may support the findings of the research cited above. However, the lightning events from the full data period showed that the highest concentration of lightning does not necessarily correspond to the storms with the highest rainfall amounts (Fig. S8 in the online supplemental material). Since a point-based rain gauge measurement was analyzed in the study, further research between the study's lightning events with a more spatially representative rainfall distribution is required.

The lightning event on 20 November 2018 was further observed to have entered and exited warning thresholds rapidly, whereas the lightning event on 3 February 2019 contained stabilized periods in between entering and exiting the warning thresholds. Despite no verification of whether warnings were issued for all lightning events, as lightning detection in itself by the system was not verified, the reliability of the system to disseminate warnings when lightning was detected and ensuring that they met the desired thresholds was possible. Consequently, the alert notification system was found to correlate well during the onset and offset of lightning activity as evaluated by the fluctuating EFM and detected flashes that met the stipulated thresholds, although there were a number of brief ''all clear'' messages followed by repeat ''warning'' messages during the duration of a storm period, which may be providing mixed signals to community members with regard to the warning status.

On the basis of the reliability of the system to disseminate warnings when lightning was detected and when thresholds were met, the NRT-LWS was observed to successfully detect lightning threats and issue warnings within the warn categories of 8, 16, and 32 km of the study site, proving its worth as a NRT warning system for rural communities. However, given the limitation in its spatial coverage due to the SG000 maximum detection range of 32 km, a network of similar systems could be created to overcome the spatial limitations and achieve greater coverage. On the other hand, future research on the use of the SALDN dataset for local level lightning warning dissemination purposes would prove to be valuable due to the spatial coverage. While the SALDN's flashes dataset could be useful, the SALDN does not consider atmospheric electric field measurements. Within the study, the EFM was shown to be beneficial for not only the detection of electrified convection prior to a lightning flash but also in ensuring that the threat from lightning no longer prevailed at the end of the storm, which is crucial for safety advisories. Future investigations into using the SALDN flashes dataset together with a network of EFMs could be useful for disseminating email and SMSs within a range of any given location. Additionally, the lessons learnt and the process that were adopted in this study for the dissemination of email and SMSs could be mimicked for use over larger spatial scales, which could prove to be an invaluable contribution toward the dissemination of warnings within rural areas.

The NRT-LWS's information displayed on the monitor at the school was accessible for improved knowledge and awareness of the students, while the audible and visible alarms contributed to the safety of the school students and nearby areas, which include a community hall, clinic, and taxi rank.

6. Limitations and recommendations

Through the application of the local ground-based NRT system at Swayimane over a 12-month period, the major limitation encountered with the system was the research area's variable network signal coverage, which affected the systems communication resulting in some communication failures and data losses initially. Hence, communication interruption of the warning requires careful consideration. In an attempt to rectify the communication failure concerns, the LWS's modem had a second SIM card from a different network provider added, which enabled a second network to activate during failures with the first network. It was also observed that the number of SMSs that were sent during some storm cycles was very high, and there may be a need to revisit the deactivation thresholds. A review of the log messages that were sent showed that some lightning periods entered and exited the warning state well over eight times within a limited period of time. It is recommended that the threshold to trigger the ''all clear'' be modified for warnings that have been in place for more than 60 consecutive minutes in a day, to only trigger when no lightning has been detected within 32 km for 30 min rather than 16 km.

Over the 12-month operating time, there was no damage to any of the system's hardware. Consideration should be given to battery capacity in remote areas where electricity may be unreliable as was the case at Swayimane, but the 24 A h battery installed was sufficient to power the system for 24 h on the battery only. There was considerable benefit in providing warning through the audible and visible alarm systems hardwired to the CS110 and not affected by communication network failures. In addition, the VM at the university was found to be extremely beneficial as it was able to store and back up data. Note that regular inspection is required including cleaning and basic maintenance of the LWS. Spider webs, dust, and replacement of the CS110 desiccant (when relative humidity values $\geq 60\%$) were some of the maintenance required as well as a scheduled calibration and internal battery change of the SG000 after approximately 4 yr.

The purpose of this research focused on documenting and providing insight into the development of a community ground-based NRT-LWS, which could serve as a framework from which similar networks and systems could be developed in the future. As such, the validation of the instrumentation was beyond the scope of the study and warrants a study of its own. The validation of lightning warnings and lightning flashes occurring within the same distances against lightning data from lightning location systems (LLS) and national lightning networks such as the SALDN is required. Consequently, future research questions may include the following (among others):

- What percentage of flashes were undetected?
- What percentage of flashes were accurately detected?
- What is the detection efficiency/error ellipse of the NRT-LWS within the three warn state categories?
- What is the lead time between the detected flashes and the observed fluctuations in the EFM against alerts sent out?

Furthermore, comparative and statistical analyses as well as sensitivity tests of local meteorological data should be investigated to determine if there are lightning–climate relationships that may include but are not limited to direct relationships between lightning frequency and precipitation rate, ice water content and lightning activity correlations, and lightning–radar reflectivity relationships.

In addition, vulnerability assessment and risk mitigation remain an avenue for future research. The NRT-LWS impact on the community and the community's response and perception to the system requires investigation. Future endeavors to ensure successful implementation of the system for the people within the community will continue and include ongoing research within the theme of community education/involvement, seeking answers to the following questions (among others):

- When and what type of educational programs can be conducted to inform the community on how to interpret and react to the siren, beacon lights, and warning alerts, and will such educational programs be successful?
- Will the behavior of individuals change?
- What are the community's social and cultural perspectives with regard to lightning activity?
- What proportion of the community's population see/hear the system during the day and during evening/night near their homes?
- How many lightning-safe shelters are available and within a reachable distance of those at high risk?

- What are the municipal officials plans with the NRT-LWS warnings?
- Will the warnings be incorporated into future disaster management strategies, and how?

7. Conclusions

In South Africa, lightning is a significant threat with a mortality rate that is 4 times the global average of 0.2–1.7 per million of the population (Hill 2006). While global lightning networks and national lightning detection networks such as the SALDN are available for providing lightning detection and warning, rural communities remain devoid of these warnings. This is mainly due to lightning activity being detected at a national level, without warnings being disseminated at a local scale.

An NRT-LWS was successfully implemented in the Swayimane rural community. The NRT-LWS is a community ground-based warning system that consists of visible alarms (beacon lights), audible alarms (siren), and automated warning notifications (via SMSs and email) making it an automated observation, measurement, and warning dissemination system. The NRT-LWS displayed its capabilities as a risk-based warning system through the provision of NRT information for a variety of environmental conditions (emerging storm/potential lightning threat risks) to the onsite school, improving the community and school students' awareness to lightning risk. This information can also be beneficial to farmers, municipal officials, and disaster risk management agencies with measurable thresholds upon which actions can be initiated. The environmental warning system operated automatically, minimizing the potential for human error. In addition to being an NRT warning system, this system automatically measures, stores, communicates, and publishes meteorological conditions for the environment onto a web page for public access. These dissemination capabilities provided even the remote human settlement of Swayimane with the opportunity to react to potentially dangerous meteorological conditions.

The NRT-LWS system combined the detection of flashes and the atmospheric electric field, which triggered 109.8 h in a warning state over 12 months. A large number of lightning flashes (3600) were detected in close proximity to the school, which indicates that a high risk of lightning prevails around the school. Furthermore, the majority of lightning incidences occurred between 1400 and 2100 when students are exiting the school grounds and many people are returning home and hence out in the open. Additionally, at night individuals are asleep and unaware of the inclement weather. With the NRT-LWS located within the school, there is an added benefit of reduced risk to warn the school and its vicinity. Two lightning events exhibiting above-normal lightning activity were also analyzed and SMS warnings were being delivered in a timely manner once thresholds for a warning were reached thereby providing the community with a system that offers reliable warnings to lightning danger and to mitigate the risk of losses.

The dataset provided the first ground-based insights toward describing the characteristics of lightning in the Swayimane area as well as at a local level for South Africa. The results presented confirm that the LWS has been successful in the provision of timely and effective information through the SMSs and emails. This will allow individuals exposed to the hazard the opportunity to act to avoid or reduce their risk. Currently, as a test run of the system, SMSs and emails were disseminated only to the principals of nearby local schools, educators, the local youth leader, the local tribal chief, and the ward counselor. It is envisaged that the notifications be disseminated more widely throughout the community, in the languages that are understood by the community as well as including an instructional message describing how to respond to the warning.

Basher (2006) and Clulow et al. (2018) found that early warning systems require four requirements to be complete and effective. These include (i) knowledge of the relevant hazard, (ii) the ability to monitor the hazard and issue warnings, (iii) the communication and dissemination of warnings, and (iv) the capability for timely response by people at risk and/or relevant authorities. The early warning system discussed in this current research was found to satisfy all four of these requirements. Basher (2006) further discussed that the sustainability of these requirements and the warning system as an entirety requires political commitment and institutional capacities. This is dependent on public awareness and an appreciation of the benefits of effective warning systems and constant interaction with the surrounding community, which is necessary for the full benefit of the system to be realized. Hence, it is recommended that sufficient resources be allocated to interact with the surrounding communities on the issue of lightning and lightning warning.

Future endeavors toward ensuring the successful implementation of the system will continue and include community and school participatory and educational approaches with a focus on the importance and understanding of the NRT-LWS warnings and alert messages, as well as addressing cultural beliefs associated with lightning (workshops, public awareness materials, animated posters, use of local radio, and print media). Other additional future efforts will also include dissemination of alert messages in the local languages, utilizing innovative mechanisms for learning (school art and essay competitions), the dissemination of human-safety lightning guidelines and alert response protocols, which will be tested through mock events at the study site, and installing affordable equipment to stress the necessary precautions that one should take as well as working with the local municipality on locating key lightning safe shelter points and on ways to train the community to follow simple safety procedures.

Future studies focusing on the SALDN and the NRT-LWS to understand the capabilities of both systems and dissemination of warnings from the SALDN's data to communities in South Africa would also be beneficial. A network of similar warning systems (such as the system described) could be installed at schools in similar high-risk areas with a focus on densely populated communities.

Despite lightning systems providing reliable warnings, the community response to the warnings is complex because the only shelter available is often rural housing, which is not necessarily structurally lightning safe. Without lightning-safe shelters in communities, individuals are still vulnerable to the threat of lightning. Future studies therefore need to address the economic feasibility and implication of constructing lightning-safe shelters around rural communities and/or identifying lightning high-risk areas and installing lightning conductors in these areas across South Africa.

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Data availability statement. The data analyzed during the current study are openly available (http://agromet.ukzn.ac.za:5355/Sw_lws/index.html). Alternatively, the data are available on request from the corresponding author.

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